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Canada
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Spruce Budworms
Program

Prepared by
Forest Service
U.S. Dept. of Agriculture
Northeastern Forest
Experiment Station
Broomall, PA 19008

GTR-NE-99

1985

Spruce-Fir Management and Spruce Budworm

Society of American Foresters Region VI Technical Conference

SAF 84-07

SPRUCE-FIR MANAGEMENT

AND

SPRUCE BUDWORM

Society of American Foresters

Region VI Technical Conference
April 24-26, 1984
Ramada Inn
Burlington, VT

Sponsors

U.S.D.A. Forest Service
Northeastern Forest Experiment Station
Northeastern Area State & Private Forestry
Canada-U.S. Spruce Budworms Program
Society of American Foresters
Region VI Technical Committee
Vermont Dept. of Forests, Parks & Recreation
SUNY College of Environmental Science and Forestry, Syracuse, N. Y.
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SPRUCE-FIR MANAGEMENT AND SPRUCE BUDWORM

Jack E. Coster

Director, Division of Forestry
West Virginia University
Morgantown, WV 26506-6125

INTRODUCTION

Regional Technical Conferences were initiated by the Society of American Foresters in 1982. Since then there have been 8 of them across the U. S., with 8 more scheduled for 1984, including this conference. The basic idea was to foster dissemination of scientific and technological information throughout the profession of forestry, and to do so at the grass-roots level of professional society.

There are 12 Forest Science Regions and they correspond to the 11 Voting Districts of the Society, except for the large Rocky Mountain-Intermountain District which is divided into 2 Regions for better coordination and travel. Conference planning and coordinating in each Region is done by a Regional Technology Committee composed of at least three members from the State Societies within the Region. Each Region is to hold a Technical Conference every second year.

In this area, Science Region 6, the two State Societies, New England and New York, each have a Forest Science Coordinator. Dr. Tom Corcoran (University of Maine) and Dr. Edwin White (SUNY-ESF), along with the Conference Program Chairman, Dr. Daniel Schmitt (USFS-Northeastern Forest Experiment Station) have taken the lead roles in this Conference.

And a fine conference it looks to be. Management of spruce-fir forests in the face of the persistent spruce budworm is a real challenge to resource managers. The topic cries out for a technical up-dating. The last major conference on spruce budworms was in 1984 at Alexandria, Virginia. The Canadian-USA Spruce Budworms Program (CANUSA) has brought concerted research effort to the problem on both sides of the international border that runs through the insect's territory. Managers and researchers need the latest information on the problem.

The first real-life forest insect problem that I encountered as a forester recently out of the University of Montana School of Forestry was western spruce budworm. Of course in those days there was only one spruce budworm--the spruce budworm. (Life becomes more complicated.) My "almost like new" forest entomology notes revealed the scientific name of the beast. I practiced pronouncing it over and over--Choristoneura fumiferana, Choristoneura fumiferana. Then I went into my District Manager's office to tell him what I had found in our stands. He asked if I might know the scientific name of the insect. "Yes I did", and pronounced the name flawlessly. But my composure was shattered when he said, "You're wrong! It's Tortrix fumiferana." (Another example that things change.)

I have clear recollections of days then when the air in some stands was constantly aglitter with flying moths. And I recall my despair on seeing the effects of the budworm on a young Douglas-fir stand where we had planned a Christmas tree sale for the coming Fall. That was in 1957 and 1958 and spruce budworm was an all too common occurrence for the next few years in southwestern Montana.

The spruce budworm problem has dominated forestry practices in the coniferous forests of eastern North America. It has also become a major social dilemna because of the control practices used against the insect. Traditional cost-benefit analyses fail when applied to the large scales that budworm control projects encompass. The social costs of our projects, particularly the costs related to health effects of spray programs, can be only imperfectly estimated. This failing becomes even more obvious when we look to the long term social costs and benefits of budworm control programs.

Forest management is becoming increasingly complex. Technical forestry principles themselves are more involved not to mention the legal and social environment in which we must manage. Management science has responded to these sorts of complexity with the systems concept. Industrial engineers seem to have been early users of the systems approach, but the idea has spread to many areas, including forestry. Integrated forest pest management is the term often used to indicate use of systems planning approaches for forest insect problems.

The basic elements of integrated forest pest management are that (1) protection planning and implementation are subordinate to forest land management objectives, (2) that the apparent injuriousness of pests must be evaluated within a sound ecological, social, and economic framework, and (3) that complete elimination of naturally occurring pests is not usually a feasible protection goal.

Intergrated management of eastern spruce budworm is not yet a reality; the ecological, social, and economic knowledge needed to develop an integrated management system is not available. And it appears to me that this information will not be available for some time. The problem is too vast and complex for quick and easy solution. But I do believe that an integrated systems approach to the problem is the only way that will lead to satisfactory management of the insect. The integrated approach to research and management ensures that the long term view of the problem is adequately considered and evaluated.

In the short term, the options that foresters can use at this time are limited; spray, salvage, and do nothing. None of these options deal very effectively with the underlying causes of budworm

infestations. And the current long term view of spruce budworm "management" is simply a summation of short term actions over time.

The major topics of this conference include most of the major knowledge areas that need to be included in an integrated management system to deal with the insect. Population monitoring capabilities are essential for prediction of outbreaks. Knowing the impact is necessary for assessing costs and benefits of proposed programs. Understanding the roles of predators, parasites, and weather are key factors in judging budworm population strength. Stand hazard ratings and appropriate silviculture provide the forester with longer term options than are now available.

Integrated forest pest management can be described at three levels: a conceptual level, a philosophical level, and a practical level.

A dictionary tells us that a concept is nothing more than an abstract idea; a thought, a notion. The concept, more properly the concepts, of integrated pest management today reflect the changing ideas of how science, technology, and society view pest problems and their solutions.

Philosophies are more concrete than concepts. A philosophy is a theory regarding a sphere of activity or thought. A philosophy has also been called a system of philosophical concepts. Philosophies are based on logical reasoning and analysis of fundamental beliefs. They eventually must be tested by the appropriate segments of society to determine whether they can serve as the basis for practices designed to meet society's needs.

Where are we now in the evolution of forest pest management? The concept of forest pest management has evolved from one of more or less brute force "control" of pests to one that recognizes that pest management activities must be consistent with broader economic and social conditions. And our philosophy, or framework, of pest management, where does it stand now? Scientists and managers have done a good job of weighing scientific and technological knowledge and theorizing its application to pest management and to the broader scope of resource management. Our state-of-the-art pest management philosophies include the ecosystem approach to research and to population regulation; they incorporate benefits and risk consideration, including those relating to non-market effects; and they consider both long-term and short-term intervention as part of a single over-all strategy. Our philosophies appear sound and provide good frameworks for guiding research to practical application of pest management.

Practical applications. Pest management has evolved up to that level, but insects pests are not managed using all of the marbles yet. The practical on-the-ground ways that we deal with pests are changing as a result of our philosophical changes, however. The first changes in the practical level of insect management were in how we used older existing tactics and practices. The obvious example is insecticides. Schedules have been replaced with timed applications relating to insect densities. The use of some chemicals has been restricted because of environmental considerations and effects on target and non-target organisms.

New tactics and practices also are being included in practical pest management. In the next 3 days we will hear about biorational insecticides, improved detection and monitoring systems, using predators and parasites, and more. Much of this new knowledge is very close to becoming pest management practice.

But the practical level of spruce budworm pest management lags considerably behind where our research philosophy says we could be. This situation should be no surprise to us. Producing new technology, testing it, and adopting it takes time.

There is an intermediate step between our current level of incomplete pest management knowledge and full-fledged pest management system. Resource managers should be able to incorporate new findings into their decision-making system without having to wait for the full and final result. This was the intent of the decision support system for southern pine beetle that I discussed in the compendium on The Southern Pine Beetle (U.S.D.A. Technical Bulletin 1631). Although existing information on the southern pine beetle was not adequate for a full blown pest management system, decision support systems, tailored to fit organizational realities, are feasible and would move southern pine beetle management to a sounder level of practice. Such a system is in reality a subsystem of a more ideal pest management system.

The conference is designed to move us to a higher level of spruce budworm management in the eastern spruce-fir forests. Let's take an upbeat attitude and look for ways that we can use the information that is being transferred to us here.

"BUDWORM! WHAT ABOUT THE FOREST?"

Alan G. Gordon

Research Scientist, Ontario Tree Improvement and Forest Biomass Institute,
Ontario Ministry of Natural Resources
P.O. Box 490, Sault Ste. Marie, Ontario P6A 5M7

The importance of the spruce and spruce-fir cover types in eastern North America is outlined.

Biogeographic history of spruce and fir is explained in relation to distribution during the Pleistocene. Evolution of the genus Picea is discussed with respect to continental drift. White spruce is essentially modern, dating from the Pliocene. Red spruce is an older species dating, with Arcto-Tertiary floral associates, from Tertiary times or perhaps earlier. Some geneco-logical concepts are identified. The genetic distance as related to cross compatibility, particularly in white spruce, is outlined.

The consequences of long selected tolerances not only affected migration and present distribution but also affect management of modern stands. Respective nutrient uptake patterns, productivity and nutrient cycling strategies are demonstrated.

Finally, stand structures and dynamics of white spruce-fir and red spruce-fir forests are related to budworm activity.

Keywords: Spruce-fir; Picea glauca; P. rubens; P. mariana; Abies balsamea; Pleistocene; species assemblages; migration; ecological variation; productivity; nutrient cycling; evolution; paleo-botany; genecology; crown form; hybridization; stand dynamics; budworm.

A year or so ago, I attended a Canada-Ontario Joint Forest Research Symposium in Timmins, Ontario entitled "The spruce budworm problem in Ontario - Real or Imaginary." When I came home, I discussed the meeting in general with my wife Jeanne and a number of the papers in particular. She listened with some comment for about half an hour and finally, in exasperation, breaking in, said, "Budworm! What about the forest?" That remark gave me the title of this presentation, an overview of the spruce and spruce-fir forest.

Extent and Importance of the Eastern Spruce-fir Forest

At the outset, I would like to provide an estimate of the enormous extent of the productive spruce and spruce-fir forest of Canada and the United States. Table 1 indicates the total area and volume for eight central and northeastern states. It may be seen that in this area there are 1,462,000 hectares which are equivalent to about 5,624 square miles. The total productive volume stands at 667,826,000 cubic metres. The productive area for six Canadian provinces from Ontario eastward is 60,667,000 hectares or 234,184 square miles (Table 2). The standing volume carried on this area is 5,121,585,000 cubic metres. Since in a number of Canadian provinces black spruce is not separated from white spruce in inventory data, these data also contain extensive areas of black spruce. Some states and provinces, e.g. Minnesota and Nova Scotia, have a great deal of

Table 1. Area and volume of Stocked Productive Spruce and spruce-fir forest land*

State	Area 1000 ha	Volume 1000 m^3
MAINE	272	368,167
NEW HAMPSHIRE	25	52,620
VERMONT	16	37,581
CONNECTICUT	7	5,494
NEW YORK	319	54,461
MICHIGAN	83	67,800
WISCONSIN	93	36,080
MINNESOTA	647	45,623
Total	1,462	667,826

*data after USDA Forest Service (1982)

Table 2. Area and volume of stocked productive spruce and spruce-fir forest land*

Province	Area 1000 ha	Volume 1000 m^3
NEWFOUNDLAND	7,297	428,629
NOVA SCOTIA[1]	1,751	124,581
P.E.I.	165	22,036
NEW BRUNSWICK[2]	3,197	280,321
QUEBEC[3]	33,027	2,792,854
ONTARIO[4]	15,240	1,473,164
Total	60,677	5,121,585

*data after Bonner (1982)
Supplemental data courtesy:

[1]F. Wellings, Forest Resources, Nova Scotia Dept. of Lands and Forests

[2]W. Clowater, Forest Development Survey, N.B. Dept. of Natural Resources

[3]D. Demerse, Service de l'inventoire Forestier, Québec Min. de Terres et Forêts

[4]J. Osborn, Forest Resources, Ontario Ministry of Natural Resources

their spruce and fir associated with hardwoods and the volumes of spruce and fir per hectare appear somewhat lower since hardwood volume is excluded in summation. The sheer extent, its current production and its productive potential provide an idea of the incredible value of these forests. The budworm, with its propensity for periodic epidemic outbreaks, can cause tremendous losses and, as such, is a major component of management consideration of the spruce-fir forest. In addition to the foregoing, the northern spruce-fir boreal forest or taiga also extends northwestwards through northern Manitoba, all the way to Alaska.

To give you some idea of the extent and nature of the harvest in northern Ontario and Quebec, Figure 1 illustrates about a half mile (0.8 km) of stacked full-tree logs. (In full-tree logging, the stump and roots are left on the site. The tops are usually brought out to a primary landing where branches are removed). These log decks are, in effect, a whole spruce forest turned on its side! The height of the near end of the pile is higher than a bus and it may be seen that the small ends of the logs lie away from the road. Another stack is decked up on the other side. There is a second corridor down the far side of these decks and more logs decked beyond. This whole forest will be cut, brought in to this landing and then moved out to a mill. The landing will be filled up again continuously.

Figure 1. Tree length log decks in northern Ontario.

Pleistocene History and the Migration of the Spruce-fir Forest

Figure 2 provides a diagram of North America during full glaciation illustrating the maximum extent of the glacial sheets at about 18,000 years ago. The important thing to note from this is that if one considers the extent of the ice, it may be realized that, apart from a slight possibility in a small unglaciated corner in southeastern Alberta, there was no part of the boreal forest occurring at that time in Canada. The total boreal forest was located south of the glacial front and entirely in what is now the United States. A large refugium-corridor, connected with Beringia (the unglaciated parts of Alaska, eastern Siberia and the land bridge between them) existed in the central Yukon plain of central Alaska and extended partly into Canada, between the Laurentide and Cordilleran ice sheets. This refugium-corridor was, however, not as convenient as we may wish to presume for the survival of trees and forests.

The area was associated with large ice fronts and the climate was known to be somewhat dry and extremely cold. Flora from pollen diagram and mammalian remains from interior Alaska indicate that the area was essentially a dry steppe-like grassland in some areas, while seemingly a cold steppe tundra in others. While it is known that there were moderate amounts of both white (*Picea glauca*) and black spruce (*P. mariana*), birch (*Betula*) and alder (*Alnus*) in central Alaska during the interstade in mid-Wisconsin times, the climate subsequently became very severe, returning Arctic conditions in late-Wisconsin times. Spruce forests disappeared or were greatly diminished (Matthews 1974). There appears to be no evidence anywhere of any extensive stands from which a great thrust of boreal forest could have re-entered Canada from the northwest. There is also no evidence that any modern spruce species entered North America across Beringia in the Pleistocene or the Pliocene or that any spruce species entered Siberia from North America in this period. There are no white spruce or black spruce anywhere in Siberia or other parts of Asia and there are no *P. obovata*, *P. jezoensis*, *P. koraiensis*, or other Asian species in North American forests. The flora of Beringia in the late Quaternary was essentially that of tundra (Hopkins 1967).

Further inference that the Yukon corridor was utilized by forests migrating northward and not southwards is that there is currently no fir (*Abies*), apart from a few stations of amabilis fir (*A. amabilis*) in southeastern coastal forests in Alaska today, and there is no evidence that there ever was fir in Pleistocene time in continental Alaska. Balsam fir (*A. balsamea*) reaches north-central Alberta from the east, and the range of its close relative, alpine fir (*A. lasiocarpa*), actually makes slight overlapping contact with that of balsam fir in northcentral Alberta. This species extends sparingly into the Yukon from the south, usually at high or moderate elevations, and not reaching the Alaskan border. These firs over their whole ranges grow in association with spruce.

Figure 3 provides an illustration of Pleistocene occurrences of spruce and spruce-fir forests at full glacial and at late glacial periods down to the present Holocene period. Several groups of points may be noted, particularly those on the continental shelf off the coast of New Jersey extending upwards through George's Bank towards Nova Scotia and southwards past Nantucket to Virginia; those in west Texas near the panhandle and northwards along the eastern slope of the Rocky Mountains; and also points in Louisiana and southern Texas. As palynological data continues to be presented, particularly from the northern Great Plains, it becomes evident that there was spruce-fir forest rather continuously all across the whole ice front, extending from the Rocky

Figure 2. North America during full glaciation. Southernmost line represents the maximum extent of ice sheets about 18,000 years ago. Gray area represents ice margin at about 13,000 years ago (Canada 1973).

Mountains and onto parts of the exposed continental shelf of the eastern seaboard. This is not to say that there was a solid, deep spruce-fir forest, only that the type of forest that we have now in the boreal - jack pine (Pinus banksiana) and spruce, as well as fir in the east with extensive areas of fire origin poplar (Populus), and on some landtypes white birch (Betula papyrifera) - extended continuously from west to east in front of the ice. The forest that was present then looks relatively similar to that extant now in the boreal forest from northern Alberta through Ontario to Quebec. This forest was essentially simply displaced southward (Watts 1970; Wells 1970; King 1973). Stand variation, age and composition were related to successional development and site types just as our modern forest is today.

In addition, fossil mammal remains from the Great Plains to New England and the coast indicate that there were many boreal animals including musk-ox as well as several small mammal species from the modern fauna much farther south (King 1973). Also there were species of wooly mammoth (Mammutus sp.) and a wide ranging species of mastodon (Mammut americanum). At one time, mastodons were thought to be exclusively browsers, entirely restricted to spruce forests. More recent information suggests they were utilizing both wooded parkland and boreal forest (King 1973). Wooly mammoths were grazers and browsers feeding on tundra grasses, sedges, and conifer foliage such as spruce, fir and pine.

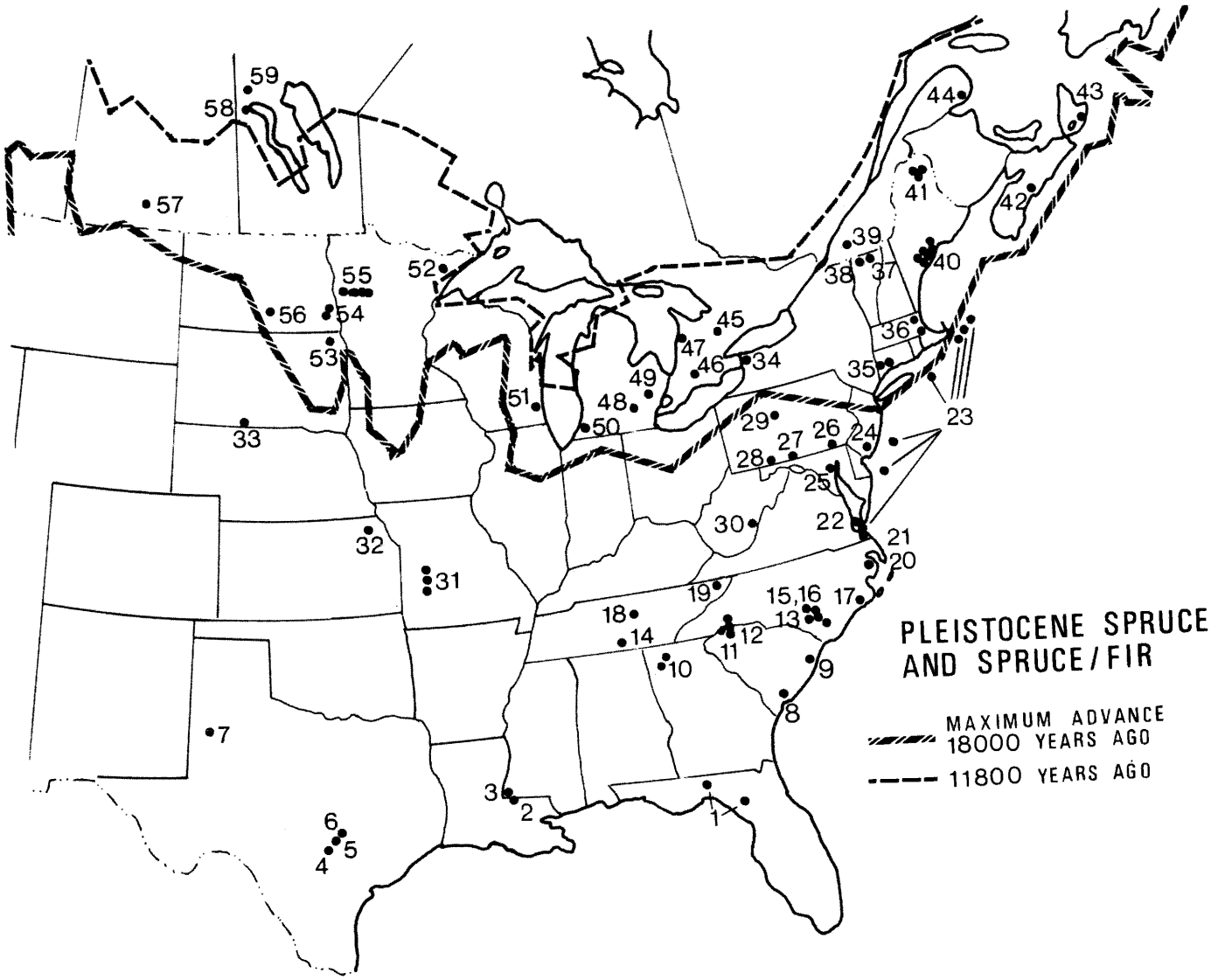

Figure 3. Pleistocene occurrences of spruce and spruce-fir forests at full glacial, late glacial and postglacial periods down to the present Holocene.* Locations: 1. Davis 1946; 2. Brown 1938; 3. Delcourt and Delcourt 1977; 4. Potzger and Tharp 1947; 5. Potzger and Tharp 1954; 6. Graham and Heimsch 1960; 7. Hafston 1961; 8. Leopold 1959; 9. Frey 1952, 1955; 10. Watts 1970; 11. Whitehead and Barghoorn 1962; 12. Cain 1944; 13. Whitehead 1967; 14. Delcourt 1979; 15. Barclay 1957; 16. Frey 1951, 1953; 17. Davis 1963; 18. Delcourt 1979; 19. Buell 1945; 20. Whitehead 1963; 21. Whitehead 1965; 22. Terasmae (in: Harrison et al. 1965); 23. Emery et al. 1967; 24. Potzger 1945; 25. Knox 1962; 26. Martin 1958; 27. Martin (in: Guilday et al. 1964); 28. Schrock 1945; 29. Sears 1935; 30. Darlington 1943; 31. King 1973; 32. Horr 1955; 33. Watts and Wright 1966; 34. Miller 1973; 35. Leopold 1956; 36. Davis 1958; 37. Miller and Thompson 1979; 38. Davis 1965; 39. Terasmae and Lasalle 1968; 40. Potzger and Friesner 1948; 41. Deevey 1951; 42. Livingstone 1968; 43. Livingstone and Estes 1967; 44. Livingstone 1968; 45. Terasmae and Matthews 1980; 46. Mott and Farley-Gill 1978; 47. Anderson 1979; 48. Andersen 1954; 49. Stoutamire and Benninghoff 1964; 50. Potzger 1954; 51. Wilson 1936; 52. Cushing 1967; 53. Watts and Bright 1968; 54. McAndrews 1969; 55. McAndrews 1967; 56. Moir 1958; 57. Ritchie and DeVries 1954; 58. Nichols 1969; 59. Nichols 1969. *Map modified after Stalker (1977).

Their remains have been found in Missouri, Michigan, New England and other places (Stoutamire and Benninghoff 1964; Whitmore et al. 1967).

There were other forest discontinuities along the ice front, occasioned by cold local climates and topography. In New England, for example, there was extensive tundra (Davis 1969). In the southern United States modern interpretation indicates that many southern hardwoods had compressed ranges, and here and there, in different kinds of niches, there was good survival of many Appalachian species (Watts 1970; Delcourt and Delcourt 1977). In the southern Appalachians migration is a little more complex. Early records indicate that the most logical interpretation is that both black and white spruce and jack pine extended southward on both sides of the Appalachian Mountains (Watts 1970).

There were two peaks of spruce, however, and one possible explanation is that the second peak in spruce in the late glacial (Leopold 1956; cf. Terasmae and Lasalle 1968) may have been the expansion of red spruce (Picea rubens) in some areas (Gordon/Leopold 1970, pers. comm.) closely followed by hemlock (Tsuga canadensis) (Potzger and Friesner 1948; Davis 1969). Many of these red spruce sites are not far from current areas of red spruce at higher elevations and in the Maritimes.

While pioneering chronological studies lacked good comparisons with sites of modern pollen rain, studies in more recent times have included comparative modern pollen rain data (Webb 1974) from similar but more northern sites. Correlations have been made, for example, between palynological sites in New England and northern Quebec (Davis 1969); Missouri with Great Lakes and eastern Canadian sites (King 1973); as well as comparisons with standing basal area (Leopold 1964).

As might be expected, there have been some interesting and fairly universal misinterpretations. A number of palynologists have shown that some sites located on the Great Plains indicated the presence of ash (Fraxinus) along with spruce in the pollen record and stated that no such stands were extant today (Baker 1965; Lichti-Federovich and Ritchie 1965; Cushing 1967; McAndrews 1967; Davis 1969; Gordon/Leopold 1970, pers. comm.). The interpretation of this and other observations (e.g. Artemisia and Picea) and even paleontological assemblages such as walnut and spruce led palynologists and paleobotanists to think that such species assemblages had no modern analogues, or that in a paleontological sense, some species had changed their ecological characteristics. In fact, there is no evidence that they have. These species have certain kinds of morphologies which are predicated on selection for certain ecological environments. They are unlikely to keep morphological characteristics constant through great ages of time if they have also been constantly changing their physiological tolerances. The unfamiliarity with species' site tolerances and requirements and with the present boreal forest itself, has also been misleading. In fact, there are a number of places in the north where white spruce does grow in proximity to black ash (Fraxinus nigra)! Figure 4 illustrates such a stand in the boreal forest of northern Ontario. The ash are growing in a site we call an ash flush about 120 m (6 chains) wide and about 0.8 km (0.5 miles) long. It is base rich - flushed with bases at higher concentrations than those of the surrounding physiographic sites. White spruce, balsam poplar (Populus balsamifera) and trembling aspen (P. tremuloides) occupy these adjacent sites. In this figure, a small lake is located in the immediate background. Any pollen rain studies from that lake would give substantial mixes of ash and spruce pollen together in the same diagram. It is a widespread but not a common phenomenon in the boreal forest, and is predicated on species requirements and edaphic limitations.

The soils of the Great Lakes, with their relatively high base status and consequently high pH, are not at all like the acidic granitic tills of the Canadian Shield. But, find occasional

Figure 4. An ash flush in the boreal forest, northern Ontario. The associated stands contain white spruce, balsam fir, trembling aspen, balsam poplar and some black ash.

pockets of like soils in the shield, and there is the species assemblage. Most of the sites from which chronological data is currently being collected have modern counterparts in stand composition and successional stage at a number of places in the current boreal forest or taiga.

The question arises as to how, for example, do we know, from the pollen record, a spruce was red, white or black in the mid-Appalachians. Early studies (Frey 1951) utilized some small differences in pollen size. There was size overlap, however, particularly in the pines, and some palynologists questioned the ability to separate such species as red pine (Pinus resinosa) from jack pine (Whitehead 1964) as well as to differentiate among the spruces with complete certainty. However, more recent studies (Birks and Peglar 1980) have identified other pollen characteristics, undulating cap margins, irregular reticulation in the sacci, etc. as well as the use of discriminant function analysis, all of which have enabled confirmation of earlier findings regarding Picea.

Arguments regarding, for example, the inability to separate pollen of red pine and jack pine due to size overlap did not take sufficiently into account those species' edaphic and climatic requirements and tolerances, their associated species and the presence of nearby macrofossils (cf. Whitehead and Barghoorn 1962; King 1973). When a pine species, red or jack, occurs with black spruce and such non-arboreal northern species as Myriophyllum farwellii, Lobelia dortmanna, Sanguisorba canadensis (Whitehead and Barghoorn 1962; Watts 1970) as well as Arceuthobium pusillum, the pine will be confirmed as jack pine rather than the temperate red pine.

A further point of interest has been the consistent presence of dwarf mistletoe (Arceuthobium pusillum) in the pollen record of the southern Appalachians (Whitehead and Barghoorn 1962) and as far south as Georgia (Watts 1970). Dwarf mistletoe, in host preference, is almost entirely restricted to black spruce. It does occur very rarely on red

spruce, although not presently in the southern Appalachians, and rarely on white spruce. During full and late glaciation, its consistent presence, along with black and white spruce and jack pine, suggests its association is most logically attributed to the boreal spruces.

The confusion among some palynologists with respect to the nature of the boreal forest may have been compounded by a number of phytosociological studies referring to north temperate montane and southern Maritime forests as 'boreal' when they were not. The floristics have similarities but differ in other respects. Still, in some recent literature, they remain described as 'boreal'!

At full glaciation, the boreal forest, dominated by jack pine growing on freely draining sandy plains, and accompanied by the boreal white and black spruces, reached northwestern Georgia (Watts 1970). In the late glacial in Louisiana (Delcourt and Delcourt 1977), southern Texas (Potzger and Tharp 1943, 1954) and probably northern Florida (Davis 1946) the boreal forest outliers were in fact just that. They were not part of a big continuous band of boreal forest extending down that far south, but rather outliers of the boreal such as one finds in parts of New Hampshire today.

Ecological Variation in the Spruce-fir Forest

For the purposes of this overview, a catalogue of phytosociological studies is avoided. Rather, examples of the principal types of spruce and spruce-fir forests are illustrated which demonstrate the wide ecological amplitude embraced by this forest.

The boreal forest or taiga is characterized by few arboreal species. In North America, the principal species are jack pine, which grows on pure stands or associated with black spruce and occasionally trembling aspen, white spruce which grows in cyclic association with trembling aspen or balsam poplar, and in the east, balsam fir. Eastern tamarack (Larix laricina) is widespread. Minor species include several species of alder (Alnus sp.), mountain ash (Sorbus sp.) and willow (Salix sp.). In the north this forest includes the spruce-muskeg as well as the spruce-lichen parklands and spruce ericaceous tundra ecotones; along the southwestern edge, the spruce-aspen-grass parklands; and in the east, enclaves of north temperate forest species.

What is the great spruce and spruce-fir forest like? In northwestern Ontario, white and black spruce are often associated together, along with balsam fir and aspen. This association also occurs in the Green River area of northern New Brunswick, but over much of their range, edaphic controls separate these species out more distinctly, balsam fir being frequently found growing in mixtures with white spruce or red spruce, but not black spruce.

Pollen records from Texas also indicate that, in the Pleistocene, fir grew more with white spruce than with black (Potzger and Tharp 1954). A point of interpretation about the pollen record is that the pollen of balsam fir is heavier than that of spruce, and while it does occur here and there in the pollen record, fir is usually under-represented (Davis and Goodlet 1960). Studies have been done to indicate that spruce pollen in the modern pollen rain is very closely representative of actual basal areas in the surrounding stands (Leopold 1964). Pines are usually much over-represented.

Figure 5 illustrates a subarctic spruce-lichen forest which occurs in the far north of Quebec, Ontario, Labrador and the Northwest Territories. Other associates which occurred earlier in post-glacial time have dropped out. There are great rock and outwash sand plains supporting lichen in a park-like forest which, depending on exposure and moisture regime, is intact in all the depressions. Such areas are much utilized by caribou for both food and shelter.

Figure 6 also illustrates a subarctic spruce forest. This is an upland forest with widely distributed black spruce with an ericaceous heath growing vigorously between all the trees. This forest is widely distributed from northern interior Alaska, across the Northwest Territories to Newfoundland.

A bit farther south - in parts of Alaska, the eastern Northwest Territories, northern Manitoba and Ontario on the Hudson Bay lowlands (Fig. 7) - the first closed boreal forest occurs, consisting of white spruce and aspen on the slightly higher eskers and postglacial beaches, while immense flats of small black spruce are found in the poorly drained intervening areas. These areas are often also associated with long string bogs, frequently without spruce, but rather, with eastern larch.

In interior Alaska (Fig. 8), successional stages of black spruce and ericaceous heath may be found at moderate elevations and following fire (Fig. 8, foreground). These stages are followed on north slopes by continuous and closed stands of black spruce (Fig. 8, background) (Viereck et al. 1983).

Figure 9 shows the south slope of the same area which is occupied by tall aspen, pure stands of white spruce, and mixed white spruce and aspen. The climatic delineation of these two spruces is dramatic in interior Alaska, the north slopes being almost entirely black spruce, and the south slopes largely white spruce (Viereck et al. 1983).

Stands of white spruce of magnificent form - tall linear-crowned trees - are very common in interior Alaska (Figs. 10, 11) (Juday and Zasada in press). The ground vegetation is feathermoss (Hylocomium splendens, Pleurozium schreberi, etc.). Such stands are also common in northcentral Quebec although they are generally considerably younger and are spruce-fir rather than pure spruce.

Figure 12 demonstrates gradual deterioration in interior Alaska. The tall white spruce decline. The stand gradually breaks up with no regeneration

Figure 5. Subarctic spruce-lichen forest (lichen tundra-forest ecotone) in northern Quebec.

Figure 6. Subarctic spruce-ericaceous forest (ericaceous heath tundra-forest ecotone) in northern interior Alaska.

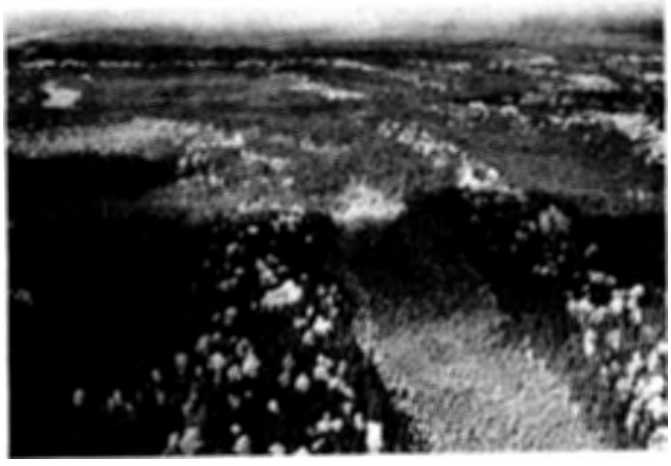

Figure 7. Closed high boreal forest, Hudson Bay lowlands, Ontario. White spruce, aspen and white birch on eskers and beaches, black spruce on poorly drained flats, larch in the string bogs.

Figure 8. North slope black spruce, interior Alaska.

Figure 9. South slope white spruce and aspen, interior Alaska.

and black spruce commence to invade. This kind of stand transformation comes about through nutrient depletion on fresh or moderately drained floodplain sites or paludification on moist or wet sites. These are active processes in Newfoundland and Labrador, northern Quebec and Ontario through to Alaska. The black spruce succeeding on such sites usually become dominant for a rotation or so but are of low quality.

Figure 13 shows a black spruce ecosystem site in interior Alaska with an average age of 120 to 140 years (Viereck et al. 1983). Such stands are sometimes referred to as the 'drunken forest'. The trees are about eight metres high and of very small diameter. They are all leaning in various directions. Similar stands occur at the higher latitudes in northwestern Ontario.

The Green River area in northern New Brunswick is a typical closed boreal forest. Figure 14 demonstrates the massive catastrophic deterioration of white birch and the cyclic replacement by the spruce-fir forest coming up through it. This forest is now

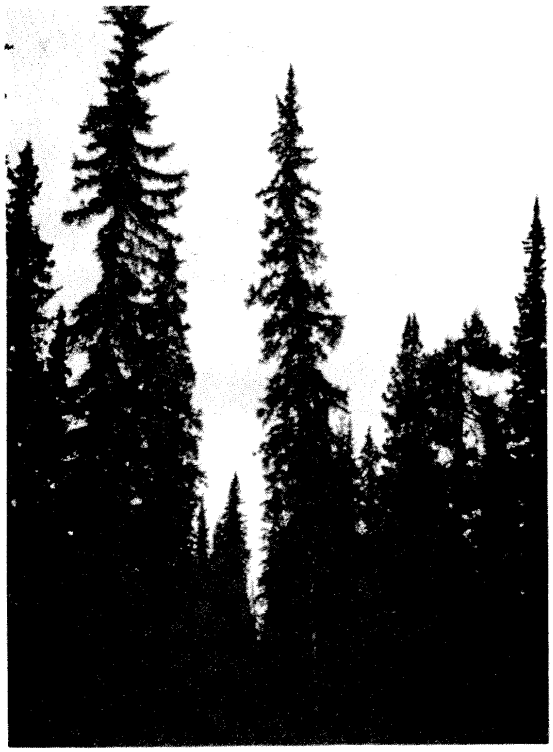

Figure 10. Tall linear-crowned white spruce in interior Alaska.

Figure 12. Interior Alaska degraded white spruce site; black spruce beginning to invade.

Figure 11. Interior Alaskan long-boled white spruce; feathermoss floodplain site. Stand age up to 240 years.

Figure 13. The 'drunken forest'. Mature black spruce growing over permafrost. Interior Alaska.

much more dominated by fir than in former times as a result of cutting and budworm spraying practices.

Where the boreal spruce-fir forest impinges on the north temperate forest the composition of the stands is frequently under edaphic as well as climatic control. Successional stages are also of influence as are the number of species involved and individual species tolerances.

Figure 15 shows such an area in the Algoma region of Ontario. Examples such as this are repeated endlessly across southcentral Ontario,

Figure 14. Green River, northern New Brunswick 1962. Catastrophic dieback of white birch. Rising regeneration predominantly fir with some spruce and white birch.

Figure 15. Algoma, central Ontario. North temperate boreal forest with white spruce and fir.

Figure 16. Red spruce-fir stand in a 'sea' of tolerant hardwoods, southcentral Ontario.

Figure 17. Northcentral Ontario, north temperate forest; hardwood niches in a 'sea' of boreal spruce and fir.

Quebec, northern Vermont and New Hampshire. This is a north temperate forest showing very tall white spruce and good balsam fir, surrounded by other sites which are supporting tolerant hardwoods. There is a ridge in the background with hemlock and white pine (Pinus strobus). This kind of stand is common throughout northern New England. It could well have been the kind of stand that provided the pollen rain for the Louisiana sites during late glaciation, not large, but repeated over and over again with nearby associated hardwood areas.

Figure 16 shows a pure intact stand of red spruce and balsam fir in southcentral Ontario. It is encompassed by a 'sea' of tolerant hardwoods with a few conifers. This is very similar to southern Appalachian stands today. When cooling glacial climates put pressure on temperate hardwoods, the areas they occupied would diminish and conifers would advance out across these hardwood areas. The hardwoods would persist in their own special niches, and to some extent in mixtures, but the general niche of the conifers would expand.

By moving northward two and one half degrees in latitude to the northern part of Algoma in north-central Ontario (Fig. 17), an idea of what that shift would have been like is provided. Here, it may be noted, is a great sub-boreal forest filling all the valleys and sweeping across the landscape. The 'sea' is now composed of mixed conifer stands. The tolerant hardwoods are confined to their niches here and there, and may be noted as light patches on the southwest - facing ecoclimatic sites on the upper slopes. The rest of the country is all boreal spruce and fir.

Moving westward, Figure 18 provides an example

Figure 18. Cypress Hills, southeastern Alberta sub-boreal forest: white spruce and lodgepole pine.

of what some of the boreal forest may have looked like on the Great Plains in the west. This is in the Cypress Hills in southeastern Alberta and southwestern Saskatchewan. These are pure white spruce and lodgepole pine (Pinus contorta) stands. This relatively small block of land is of moderate elevation above the general plain. It demonstrates that the local climate can hold sub-boreal forest here. On the nearby plain on a lower slope, there is another fragment of the same stand as well as examples of spruce-aspen parkland. These are modern stands, but during late glaciation, or presently, given any cooling climatic shift, this stand could expand from here and advance across the visible plains to join up with other stands at great distances. There are no other spruce in this particular instance within 280 km (175 miles), but this is clearly a glacial remnant. Pollen and macrofossil data indicate that such forests were widespread on the northern Great Plains (Wells 1970).

Figure 19. North temperate forest; white spruce-black ash flush, central Ontario.

Referring back to commentary on some of the palynological studies indicating that ash and spruce were not associates, Figure 19 provides an example in the north temperate forest of Ontario where black ash and white spruce are growing well together. Both species are tall, emergent trees. They are in a valley here surrounded by other forest types but the stand will repeat itself in this edaphically restricting site. The regeneration consists both of ash and spruce.

Information is accumulating on the nature of the postglacial migration of white spruce in eastern North America. The first of these is phytosociological data (Löve 1959) which showed that there is a separation of an eastern and western component of floristic associates of white spruce. One group, called the 'eastern boreal element', migrated in a northerly direction from the Great Lakes area into eastern Manitoba and around the north ends of the prairie lakes. A second group of plants, the 'western boreal element', invaded Manitoba from the west. Some members of this western group migrated as far east as James Bay. White spruce were associated with both of these migrations.

Holst (1960) from preliminary provenance studies was the first to suggest the possibility of two clines of white spruce from south to north, one east of the Ottawa valley and one west. Nienstaedt (1968) showed from available provenance material that the southeastern distribution of white spruce was in all likelihood a two-pronged cline extending into northwestern Canada on the west side of Hudson Bay and into Labrador on the east. These findings were further elucidated by Wilkinson et al. (1971) who showed, utilizing cortical oleoresin monoterpene composition of white spruce provenances, that there were indeed northeast and northwest aggregations in white spruce populations. The principal division occurred up the Manitoba-Ontario boundary to the northwest and eastwards to Labrador, similar to the inferences of Löve (1959). There was also a minor division from the southeast up the Ottawa valley.

The immensity of the range of white spruce provides the principal clue to the great ecological diversity and the related genetic selection embraced by this species. A number of ecologically distinct sites and associations, for example, shallow calcareous soils, and even northern alkaline swamps have not been mentioned in this overview.

The place of fir in the forest is also of prime importance. Balsam fir is a boreal species by origin - its prime centres in the east are in the Maritimes and parts of Quebec. Inventory data in Ontario suggests that relative to other species, it represents only a small percentage of softwood volume. It becomes a somewhat weaker competitor as it goes to the northwest in northern Manitoba and Saskatchewan. Its range sparingly overlaps that of its Rocky Mountain variant, alpine fir, in central Alberta (cf. Parker et al. 1981). The latter species, while fairly widely distributed in uplands of the Yukon, does not get into the main part of Alaska, although at high elevation it is present along with spruce and mountain hemlock

(Tsuga mertensiana) in coastal southeastern Alaska. Amabilis fir is mentioned previously.

Balsam fir in the northeastern forests is not nearly as long-lived as spruce and rots out much earlier. However, regardless of its volume as it approaches maturity, its regeneration is extremely aggressive, both in Ontario and eastwards, and much more so than that of spruce. There are always new and rising waves of fir regeneration in much of the northeastern spruce-fir forest. In parts of central and northern Maine and northcentral New Brunswick, it is near the centre of its biotic potential. The best stands of almost pure fir which occur in Quebec and northern New Brunswick might give the impression that this is predominantly what that country has produced. However, historical accounts of much of this area indicate that enormous volumes of spruce have been cut out there in the past, e.g. in the Miramichi area (Long R.D. 51, 1962, pers. comm.). The forests have experienced a marked shift as a consequence of man's activity and in the face of the much more successful regeneration capabilities of balsam fir.

In the Adirondacks (Adams et al. 1920) and in the northern Appalachians, pure balsam fir on the upper slopes of the higher peaks represents a true boreal forest above the temperate montane red spruce, and red spruce-balsam fir mixtures on the midslopes. These balsam fir forests replace themselves through a process described as fir waves. All the trees in an elevational band reach natural rotation age and die about the same time. Regeneration commences in the openings and the whole wave gradually advances upslope in the direction of the wind flow (Sprugel 1976; Sprugel and Bormann 1981). Above the fir forest there may also be scrubby balsam fir and, higher up, black spruce krummholz such as one finds on Mount Katahdin, Mount Marcy and Mount Washington (Löve and Löve 1966).

In the southern Appalachians, balsam fir intergrades with fraser fir (Abies fraseri) (Robinson and Thor 1969), an endemic species of high elevation in the south. Red spruce and fraser fir both have temperate montane characteristics: for example, flushing much later than does balsam fir.

The Productivity, Structure and Functioning of the Spruce-fir Forest

Differences in productivity related to shifts in latitude and to differences in site and forest type are presented in Table 3 (Gordon 1983). In the eastern boreal forest, a very common condition of white spruce stands is that they are usually mixed with balsam fir and white birch, or with aspen. Stands may be pure conifer or mixedwood. The two white spruce mixedwood stands, which are still carrying the shorter-lived species, are on different sites accounting for dry matter productivity differences between 4,742 and 5,755 kg $ha^{-1}year^{-1}$. While these mixedwood sites are quite different from the black spruce sites, the productivities are equivalent. The latter are both Site Class 1 black spruce stands (Plonski 1956).

Table 3. Aboveground productivity (litterfall plus increment) in kg $ha^{-1}year^{-1}$ for five spruce and spruce mixedwood stands.

Lat.	Site	
45°30'N	Red spruce mature - fresh till	8703.7
46°42'N	Black spruce immature - fresh outwash sand	5742.3
49°15'N	Black spruce mature - moist peat	4568.3
49°12'N	White spruce Mixedwood mature - fresh-moist silt, fine sand	5755.0
49°33'N	White spruce Mixedwood mature - fresh till	4742.4

Black spruce also grows, however, on wetter sites than these highly productive sites, and as moisture regime increases (gets wetter), productivity of black spruce decreases. Red spruce stands on the fresh till are much farther south in the north temperate forest and have a higher productivity reflecting better climate. These are measures of very productive forests of spruce and spruce-fir types on sites on their respective moisture catenas. At lower site classes at these same latitudes there would be much lower productivity.

Figures 20 and 21 (Gordon 1983) present examples of nutrient cycles in a north temperate red spruce stand and in a boreal white spruce mixedwood stand. The structure and functioning of these stands are somewhat similar so the cycles are expected to be more similar to one another than they would be to that of other species such as pure hardwood stands or other conifers. There are some differences, however, which are a consequence of the differences in the nutrient status of the sites on which these types grow. Red spruce stands are normally found on more acidic sites than those on which white spruce mixedwood would grow. This red spruce stand is predictably more acidic: compare calcium levels in the reserves - for red spruce 399 kg ha^{-1} vs. 1918 kg ha^{-1} for white spruce mixedwood. More rapid turnover rates are expected in the white spruce mixedwood and more accumulation in the red spruce stand. For nitrogen in the red spruce stand, there is more than one and a half times as much nitrogen in the reserve components as there is in the white spruce mixedwood. However, the amount of nitrogen being cycled as exemplified by uptake is approximately the same.

Both phosphorus and magnesium have substantially greater amounts in the reserve components of the white spruce mixedwood than in the red spruce and this is reflected in the lower amounts involved in uptake in the red spruce stand. These amounts are, nevertheless, sufficient for adequate growth in a less demanding species like red spruce. In the case of calcium, the white spruce has five times more in the reserves than that of the red spruce and yet strangely, the amount of calcium cycling in the red spruce is nearly equivalent to that of the white spruce mixedwood.

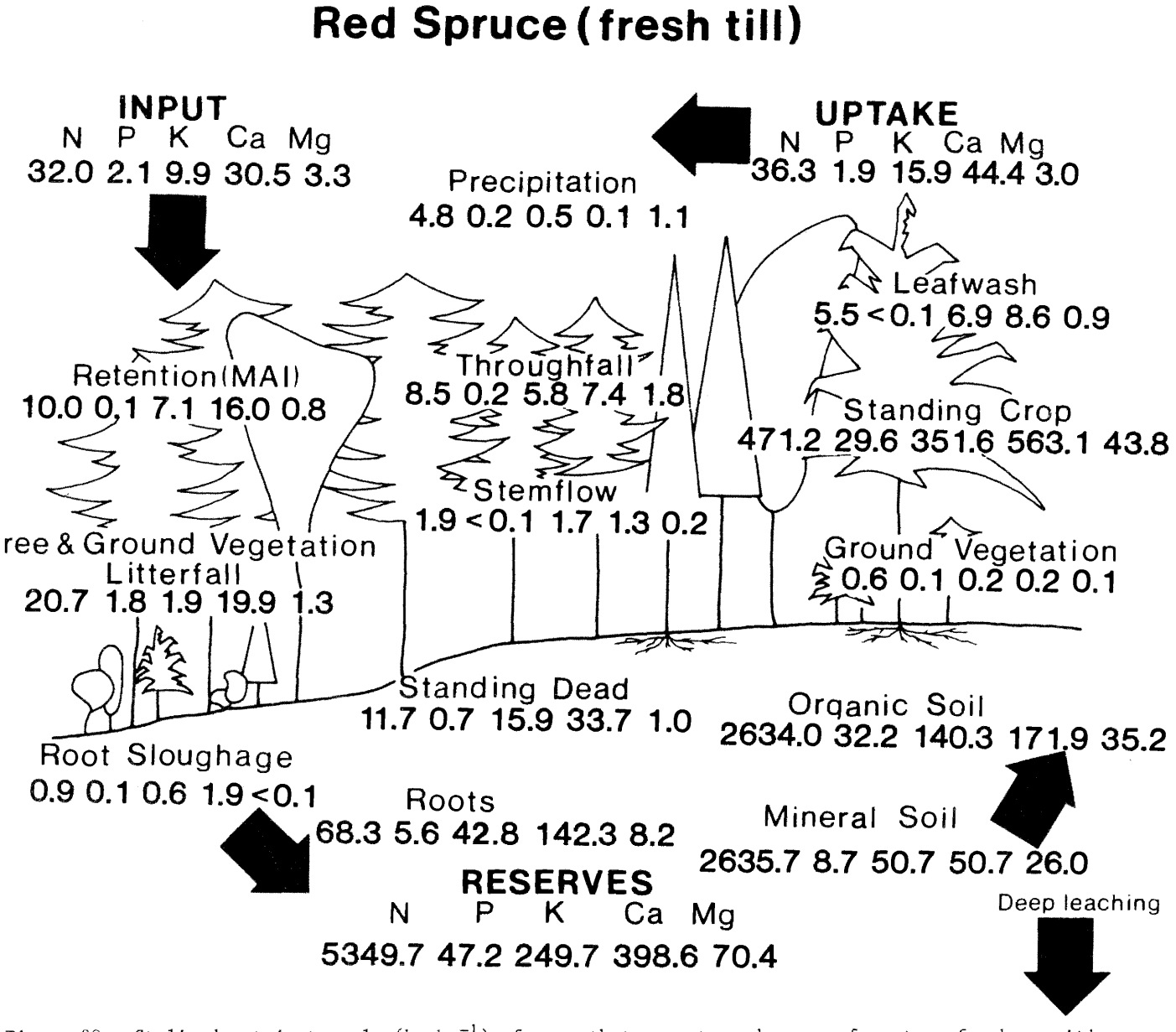

Figure 20. Stylized nutrient cycle (kg ha^{-1}) of a north temperate red spruce forest on fresh granitic till. Species represented are red spruce, balsam fir, eastern hemlock, yellow birch and sugar maple.

For potassium, the amounts in the reserve components are about the same in both stands but the red spruce are getting by with about two-thirds of that of the more demanding species in the white spruce mixedwood stand. Incidentally, balsam fir are present in both of these stands.

Evolution of the Genus Picea

The evolution of the genus Picea and more particularly the origin of white spruce is important since it is the principal and constant constituent of the boreal spruce-fir forest of North America. As recently as 1955, and even later, Beringia, which was exposed off and on from the mid-Pleistocene at least to mid-Wisconsin time, was considered to be the likely route through which spruce entered North America and diversified. At the same time, it was well known to many paleobotanists that there were fossils dating back to much earlier times through the Tertiary in a number of places in North America. As the reality of continental drift (Melville 1966; Wilson 1966) began to become more widely accepted in the late '60s, it became evident that the advent of Picea into North America had indeed taken place much earlier in the Tertiary or even the Cretaceous (65 million years ago) before continental drift had isolated North America (Gordon 1968).

It is generally accepted that conifers originated before the angiosperms (Florin 1963; Sneath and McKenzie 1973) and that the latter were indeed very common in the Cretaceous period. Spruce-like fossils are very rare, however, in that period although pine fossils are fairly common. There are at least two reasons that there are few examples

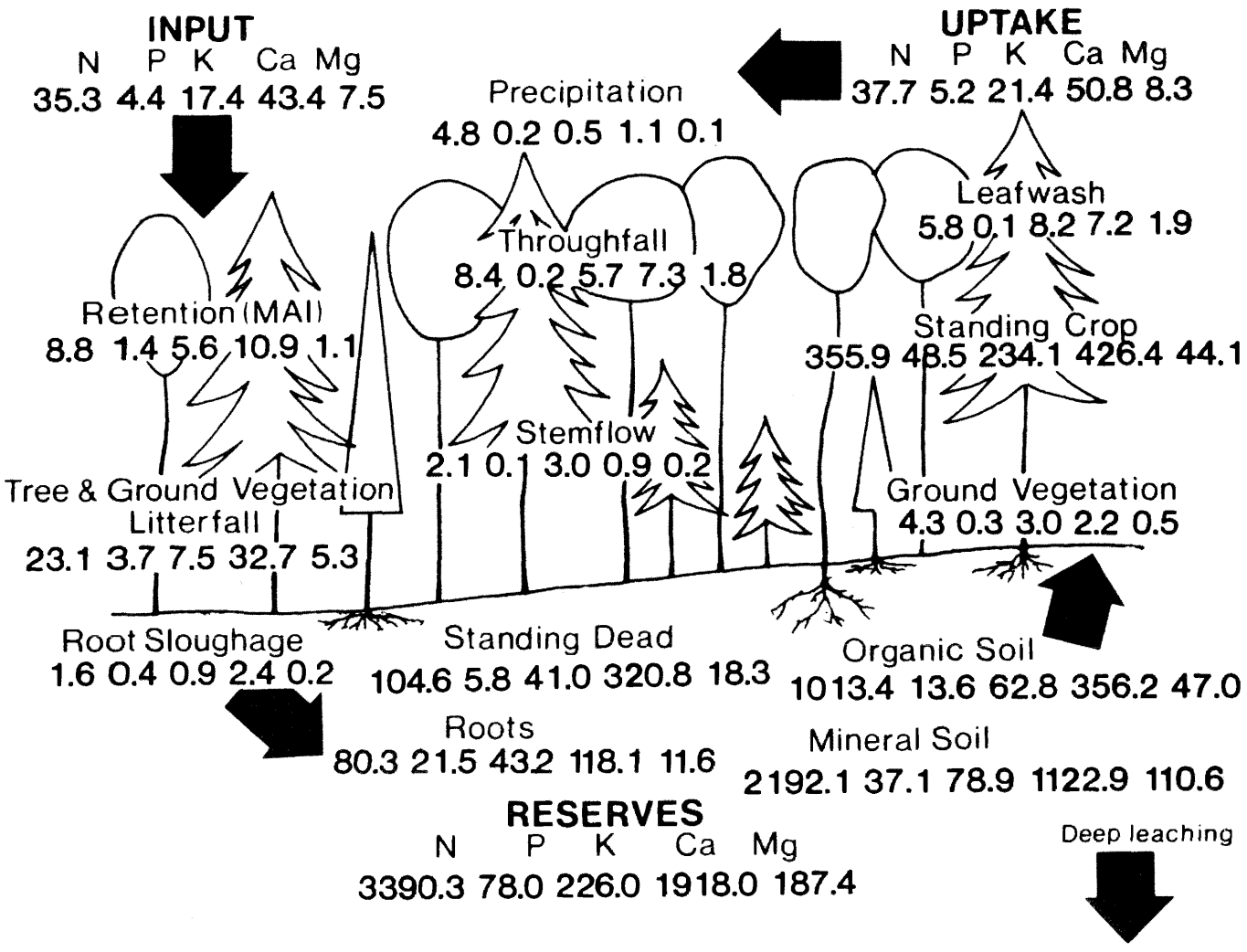

Figure 21. Stylized nutrient cycle (kg ha^{-1}) of a boreal upland mixedwood on silt, fine sand. Species represented are white spruce, balsam fir, trembling aspen and white birch.

of Picea from the Cretaceous. Their origin and radiation from the Pinaceae may not yet have occurred (Miller 1976), and just as likely, the sites on which Picea grew were mostly upland and not near good sites of preservation.

Miller (1976) very thoroughly evaluates early fossil Pinaceae from the Cretaceous and onwards. Floral or fruiting parts of plants are the most constant attribute through time in fossil evaluation. An extremely small number of traits (one or two) involving the number and configuration of resin canals in cone scales of conifers, so far has proven to be of high diagnostic value in relating fossil specimens to different species and genera. The small number of Cretaceous spruce-like fossils thus far found in North America has been disqualified as Picea, and assigned to other extinct genera, although fossil Picea specimens have been obtained from the late Cretaceous in Europe. It is generally accepted that late Cretaceous thus far represents the age of the genus.

The flora of the northern hemisphere has been essentially modern since the Pliocene (about 11 to 2 million years before the present) and have come down to us from that period through the Pleistocene to the present with very little change. More precise information as to when species arose, separated or diversified would aid in our understanding of taxonomic relationships and chemical and genetic bridges and barriers that are being encountered in breeding work. Many of the species involved are from different continents which have been separated for very long periods of time. This understanding, in turn, helps greatly in developing tree improvement strategies.

In the case of North American native spruces, white and black spruce are both modern species. There are no fossils older than the Pleistocene and Pliocene. Red spruce on the other hand appears

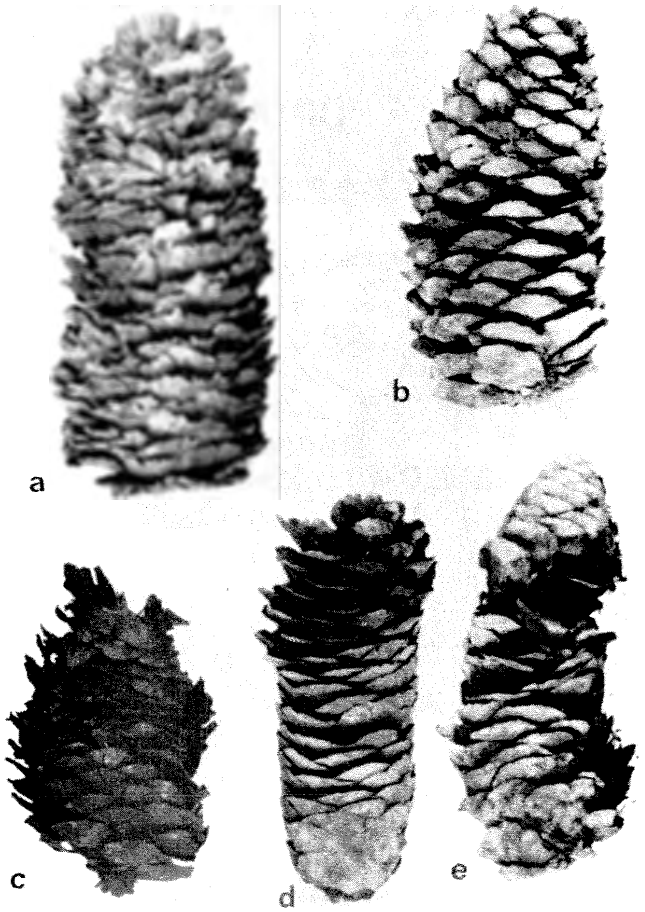

Figure 22. Fossil Picea banksii cones from the late Miocene. Banks Island, northwest Canadian arctic (Hills and Ogilvie 1970).

to be an older species. It grows with flora known as the Arcto-Tertiary flora and has been associated with that flora for a very long time, well back into the Tertiary period. It has affinities with a number of older Eurasian species (Gordon 1976). Many other hardwood species in the southern and central Appalachians have occupied and have been migrating up and down the Appalachians throughout the Tertiary period and since.

Genecologists, in common to some extent with paleobotanists, look upon new and old species as having different attributes. One of these is that in general old species, e.g. Ginkgo, Liriodendron, tend to have no, or fewer, enemies than new species or they have come to terms with those that they have (Wright 1955). Young species tend to have a wider array of pests or enemies and these often occur in epidemic proportions. Also, old species tend to have shrinking ranges.

Apart from common Juniper, and its co-Pleistocene companion species, black spruce, white spruce has a range far greater than any other North American conifer. None other of the Pinaceae have ranges which are anywhere near as large. Its range is much greater than its associate balsam fir. Its present range is with few exceptions restricted to landscapes which have been glaciated. No fossil counterparts extending back beyond the Pliocene have been located as yet. Its closely-related montane counterpart is Engelmann spruce (P. engelmannii) with which it freely hybridizes. This species however has a fossil counterpart, P. lahontense, which is known from a number of sites in Idaho, Oregon and Colorado, back through the Miocene and Oligocene epochs from approximately seven to thirty-eight million years before the present.

One other interesting possibility is P. banksii (Hills and Ogilvie 1970), a fossil species from the late Miocene (Fig. 22). Some of the cones of this species, however, are quite different from those of modern white spruce. White spruce, incidentally, both now and in the Pleistocene (Brown 1938) has cones which vary greatly in size between provenances and occasionally between families (Gordon, unpubl.). Incidentally, the associates of P. banksii were in general those of an eastern mixed forest, equivalents of jack pine, white pine, eastern hemlock, larch, alder, hazel (Corylus), butternut (Juglans) (Hills, L.V. 1969, pers. comm.) such as might be observed in parts of southcentral Ontario today.

Genecology in White Spruce

White spruce shows astonishing variation in crown form. Crown form, doubtless acquired through this species' long migrations as a consequence of the different environments and associates, is now regionally centred. Northern types tend to have crowns which are more linear and columnar; southern ones are usually more broad-crowned.

The important selection pressures would relate to whether or not this species grew in pure conifer stands of spruce or spruce-fir, or in mixtures with hardwoods, such as trembling aspen and white birch or tolerant hardwoods. There would likely be, for example, greater selection for broader crowns among those growing with hardwoods. Similarly, selection pressures would exist relating to whether snowfall was wet or dry, heavy or light; broad-crowned types tending to take the strategy of being able to hold snow up without breakage, narrow-crowned types tending to shed it. While narrow-crowned types do tend to be more uniformly distributed at higher latitudes, there are small populations of tall, narrow-crowned spruce existing as isolates at lower latitudes in the spruce range.

There are also several different types of crowns within the narrow and broad groupings. For example, Figure 23 shows an uncut face of a white spruce stand in Alaska. Of the crowns clearly visible in this picture, all but two are extremely narrow-crowned types, typical of interior Alaskan crowns. Two of them are somewhat broad relative to the others, but by southern standards, not broad.

Figure 24 illustrates an unusually narrow-crowned tree in central Ontario. This crown is sufficiently narrow that some would identify it as black spruce.

Very tall, narrow linear crowns of central Alaskan white spruce are shown in Figure 25. These crowns are so narrow that it leads less experienced people to call them hybrids of white and black

Figure 23. Interior Alaskan white spruce, tall narrow columnar-type crowns.

spruce or even simply black spruce.

A typically broad-crowned type is shown in Figure 26. This is in Site Region 5 of central Ontario in a north temperate forest. This type is very common in New Hampshire and central Maine. This crown type in Norway spruce is known as bürsten-fichte (Priehäusser 1958).

Figure 27 illustrates a broad, pendant-type crowned tree from central Ontario. All the twigs

Figure 25. Long narrow linear crowns of mature white spruce, interior Alaska.

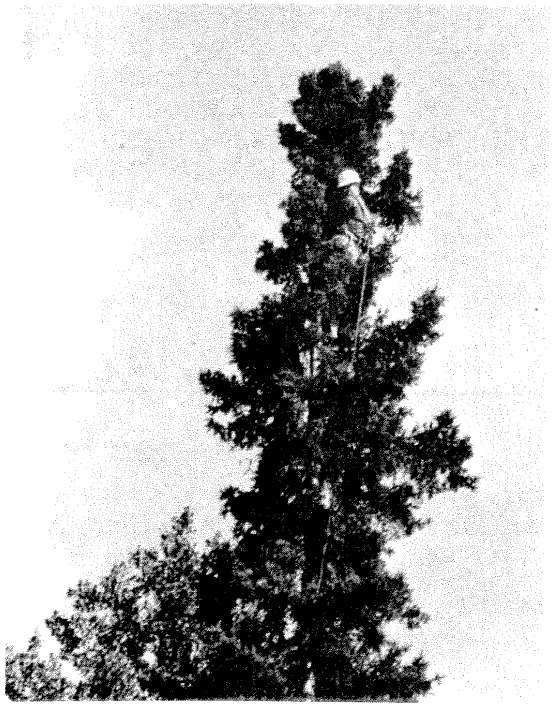

Figure 24. Unusually narrow-crowned white spruce, central Ontario.

Figure 26. Broad-crowned white spruce, north temperate forest, central Ontario.

Figure 27. Broad pendant-type crown, north temperate forest white spruce, central Ontario.

Figure 28. Spike-type, north temperate forest white spruce, central Ontario.

Figure 29. Long linear-crowned, highly productive white spruce, central and northern Ontario.

Figure 30. Pollen collection in superior white spruce.

on this tree hang down. There are first and second order branching, but the second order branching is all pendant. More extreme forms of this crown type are commonly found in Norway spruce and are known as Kamm-fichte (Priehäusser 1958). This tree is broad-crowned and is growing with tolerant hardwoods and hemlock in a north temperate forest.

A 'spike-type' crown is shown in Figure 28. The bole is long and linear with a very narrow taper. There are first order branches going out from the bole but essentially no second order branches at all. There are many small third order twigs growing from, and pointing in all directions from, the first order branches. The crown has an excessively see-through appearance. This crown type also occasionally occurs in Sitka spruce (P. sitchensis).

Figure 29 illustrates a tall, linear-crowned tree, occurring in central and northern Ontario. It would be classed as a rather narrow-type crown but would be still broader than those in central Alaskan trees. This tree is a very desirable type for tree improvement work. Its height-to-diameter ratio is excellent: a long, linear tree with excellent crown form. Figure 30 shows pollen pickers at work in that tree.

With such wide variation in species such as white spruce, genecological questions such as the crown-type strategy are of considerable importance in breeding and tree improvement. These different strategies relate markedly to efficiency and productivity.

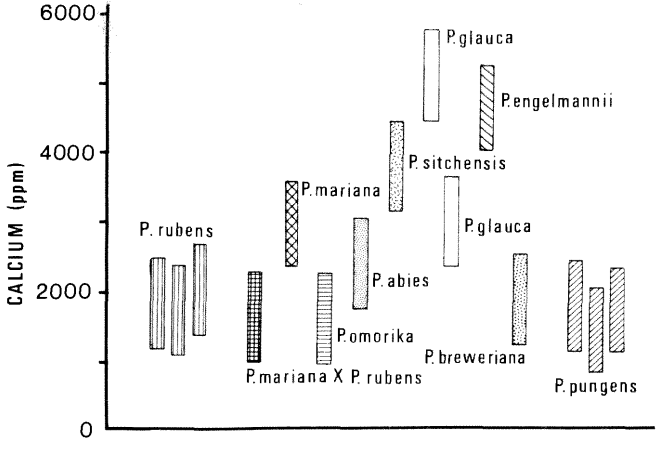

Figure 31. Calcium uptake of different spruce species and family sources, growing on a common, low lime landtype.

Another genecological consideration is nutrient uptake. Figure 31 illustrates calcium uptake in a number of species and family sources of spruce. For the sake of argument, they could be called 'genotypes' of the genus. These trees are growing in replicated plots in a Picetum in southcentral Ontario at latitude 45°30', and are all on the same landtype. The landtype is a deep fresh granitic till and moisture is not limiting. However, the only source of calcium is the granitic petrography, and lime concentrations in the soil are not high. The different patterns of calcium uptake exhibited by various species groupings are of interest. Three populations of red spruce on the left are relatively similar. A black x red spruce hybrid family population is not different from red spruce, yet the uptake of calcium by a pure black spruce population is significantly greater than that of red in all but one population.

Serbian spruce (P. omorika), in its native sites in Europe, grows on limestone benches in the Dinaric Alps. In this Picetum, like red spruce, it is not taking up much calcium. This species may have a method of controlling calcium uptake or it may simply reflect the low calcium availability of this landtype. Calcium uptake in Norway spruce (P. abies) is a little greater but not essentially different from that of red. Blue spruce (P. pungens) and Brewer's spruce (P. breweriana) are at the same general level as that for red and Serbian. None of the populations of these species are taking up very much calcium, either demonstrating an ability to exclude it or the fact that it isn't available in the first place.

However, when the uptakes of Sitka, white and Engelmann spruces are considered, calcium availability does not appear to be limiting. There are two families of white spruce, one of them clearly taking up substantial amounts of calcium, even though lime supply in this landtype is not high. This is true for Engelmann spruce, and Sitka is not far behind. A second population of white spruce has lower uptake, about the same as for black spruce, but still in general greater than that of red, Serbian, blue and Brewer's spruces. Differences in uptake also are apparent for other elements not shown here (Gordon, unpubl.) demonstrating marked species differences in tolerances and uptake. This accounts to some degree for the exclusivity of some species growing on certain kinds of sites, and the more universal edaphic distribution of other species and populations within those species.

Nienstaedt and Teich (1972) have provided an excellent review of the genetic status of white spruce. Essentially, where white spruce comes in contact with Sitka spruce on the Kenai Peninsula of Alaska, and in the Skeena River Valley of B.C.; and where it comes in contact with Engelmann spruce in British Columbia, Alberta and Montana, there are extensive areas of introgressed populations of these species. Accounts of possible introgressive hybridization or even casual hybridization between white spruce and black spruce (Larsen 1965; Roche 1969) are unfounded, and are in sharp contrast to all artificial crossing information. A crossing table modified from Nienstaedt and Teich (1972) follows.

Table 4 sets down five categories of cross compatibility of white spruce with other North American and Eurasian spruce species. Introgression between Engelmann and Sitka spruce has already been mentioned. Crossing is relatively easy with Yeddo spruce (P. jezoensis), a Japanese species of two varieties. This species is somewhat similar to Sitka, but it differs from it in a number of characteristics and does not have the growth

Table 4. Cross compatibility of Picea glauca and other Picea species

Easy	Moderate	Difficult	Very Difficult	Failure
[1]P. engelmannii+	[4]P. pungens	[8]P. likiangensis	[11]P. mariana ⟷	P. mariana
[2]P. sitchensis +	[5]P. schrenkiana	[9]P. mexicana	[12]P. rubens	P. chihuahuana*
[3]P. jezoensis	[6]P. smithiana	[10]P. maximowiczii	P. koyamai ?	P. purpurea
	[7]P. omorika		P. koraiensis?	P. balfouriana
			P. bicolor ?	
			P. wilsonii ?	
			P. orientalis?	
			P. glehnii ?	
			P. abies ?	
			P. asperata ?	
			P. meyeri ?	
			P. montigena ?	
			P. retroflexa?	

+Also introgression

*Consistent failure

?Hybrid reported by one worker, but attempts by all other workers have consistently failed (hybrid still unverified)

First successful crosses are indicated: 1. Larsen 1948; 2. Eklundh 1943; 3. Rehder 1967; 4. Wright (in: Santamour 1967); 5. Fowler 1966; 6. Fowler et al. 1976; 7. Oksbjerg 1953; 8. Jeffers 1971; 9. Gordon 1980; 10. Jeffers 1971; 11. Gordon 1980; 12. Bongarten and Hanover 1982.

characteristics of Sitka.

The second category, moderate, has four species in it. These are species with which successful crosses are possible but not with all clones, and in which there are some barriers. If they are open-pollinated, side by side, crossing is very infrequent, but may be accomplished artificially with some effort.

The third group, classed as difficult, are species which can be occasionally crossed with some clones, but there have been many attempts at artificial crossing which have not been successful.

The fourth, or very difficult, category are those species which have been crossed very rarely with white spruce. Only one or two workers have been able to cross white spruce with red. Other species in this list are very uncertain. Hybrids have been reported but there has never been any verification of any of them. In general, white spruce does not cross with Norway spruce, or its close relatives, P. asperata, P. meyeri, P. montigena and P. retroflexa. There has possibly been one artificial cross made between black spruce and white spruce, and there is one individual occurring in nature called the Rosendahl spruce (P. glauca x mariana) which is so far considered to be the only possibly legitimate example of a putative natural hybrid. Most consistently, failures have been endless in attempting to cross white spruce with the four species listed in the last column. However, several of those in the very difficult category could probably be legitimately moved over to the last column.

The information generated from work on hybridization is being used in studies elucidating incompatibility, embryo inviability, hybrid inviability, crossability, homo and heterozygote phenomena, backcrossing phenomena, crossing frequency, ecological barriers, homeostasis, introgression, gene flow, genetic behaviour of sympatric and allopatric populations, genetic drift, genetic distance, heritability, quantitative population and ecological genetics, and many phases of tree improvement, wood quality, genotype x environment interaction, selection, propagation, etc.

Stand Dynamics of the Spruce-fir Forest and the Budworm (Choristoneura fumiferana)

The following stand structure and dynamics data (Figs. 32-38) illustrate and compare typical white spruce-fir stands in the boreal forest and typical red spruce-fir in the north temperate forest and show how the perpetuity of the spruce component in such stands is related to budworm events. The white spruce-fir example is in north-central Ontario, latitude 48°00', longitude 82°30', elevation 366 m; the red spruce-fir example in southcentral Ontario, latitude 45°00', longitude 77°18', elevation 335 m. The data are based on a series of plots in areas that have had the customary historical budworm events of most eastern spruce-fir forests.

Figure 32 presents primary stand structure of the white spruce-fir forest. At this stage of development, there are typically low numbers of very large white spruce trees. There are moderate numbers (20 per hectare) of immature trees in each centimetre class between 10-20 cm, and fairly good numbers (200-50 per hectare) in the 5-8 centimetre classes, respectively. Fir, in contrast, have no trees greater than 15 cm. However, in the 5-8

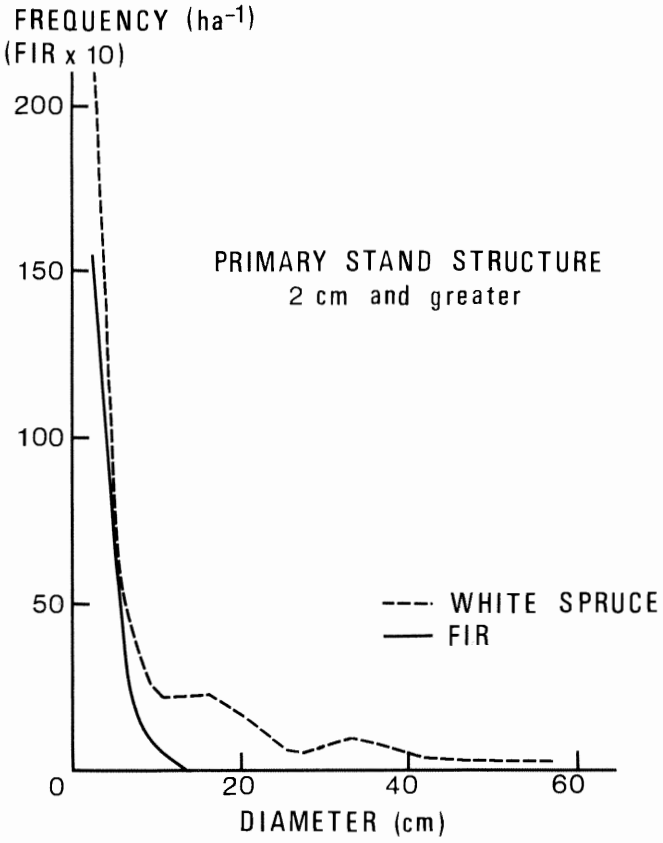

Figure 32. Primary stand structure, white spruce-fir.

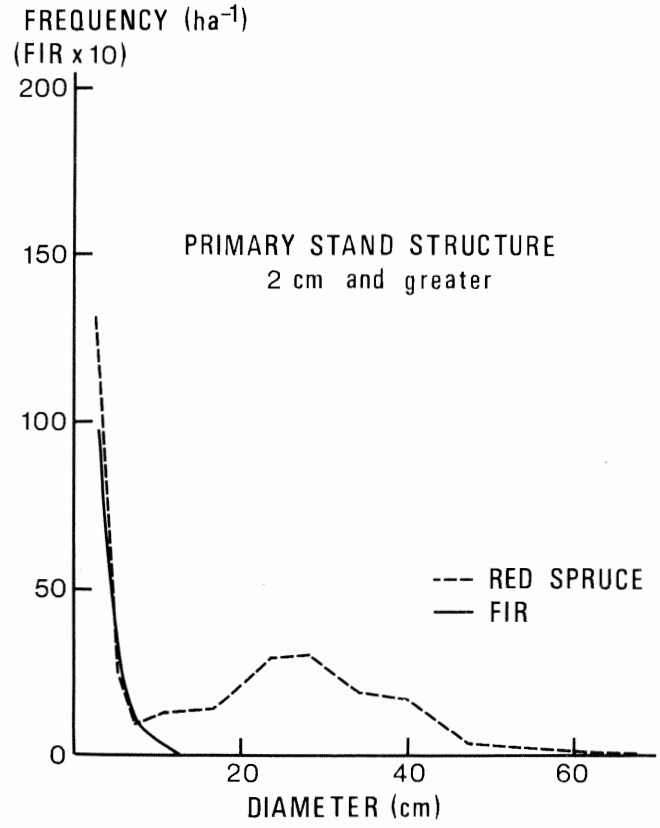

Figure 33. Primary stand structure, red spruce-fir.

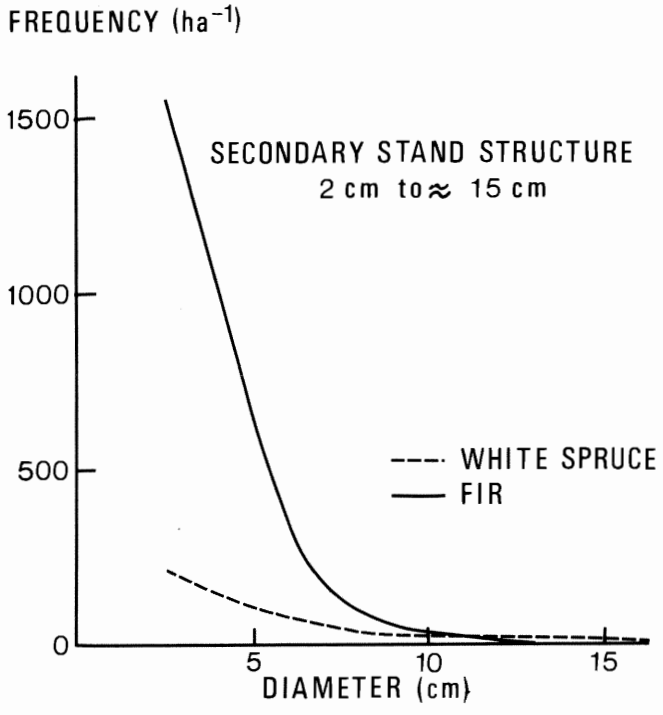

Figure 34. Secondary stand (rising understory) structure, white spruce-fir.

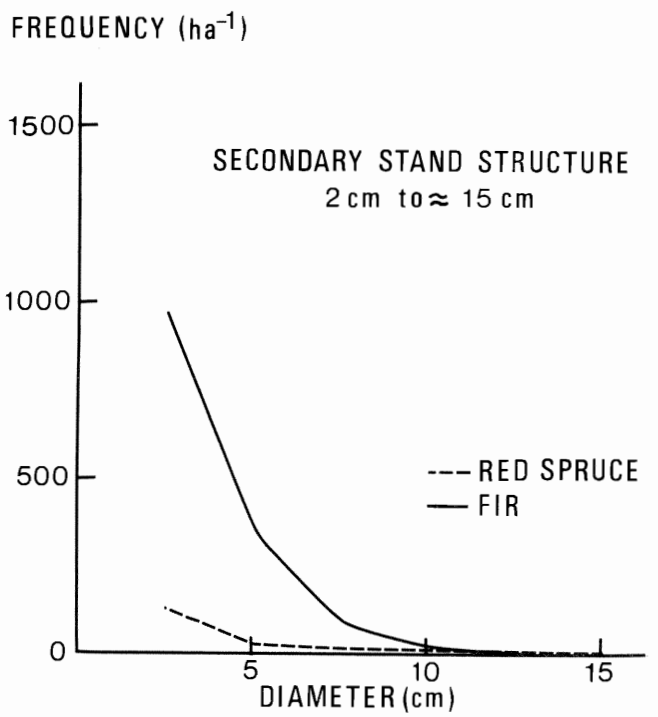

Figure 35. Secondary stand (rising understory) structure, red spruce-fir.

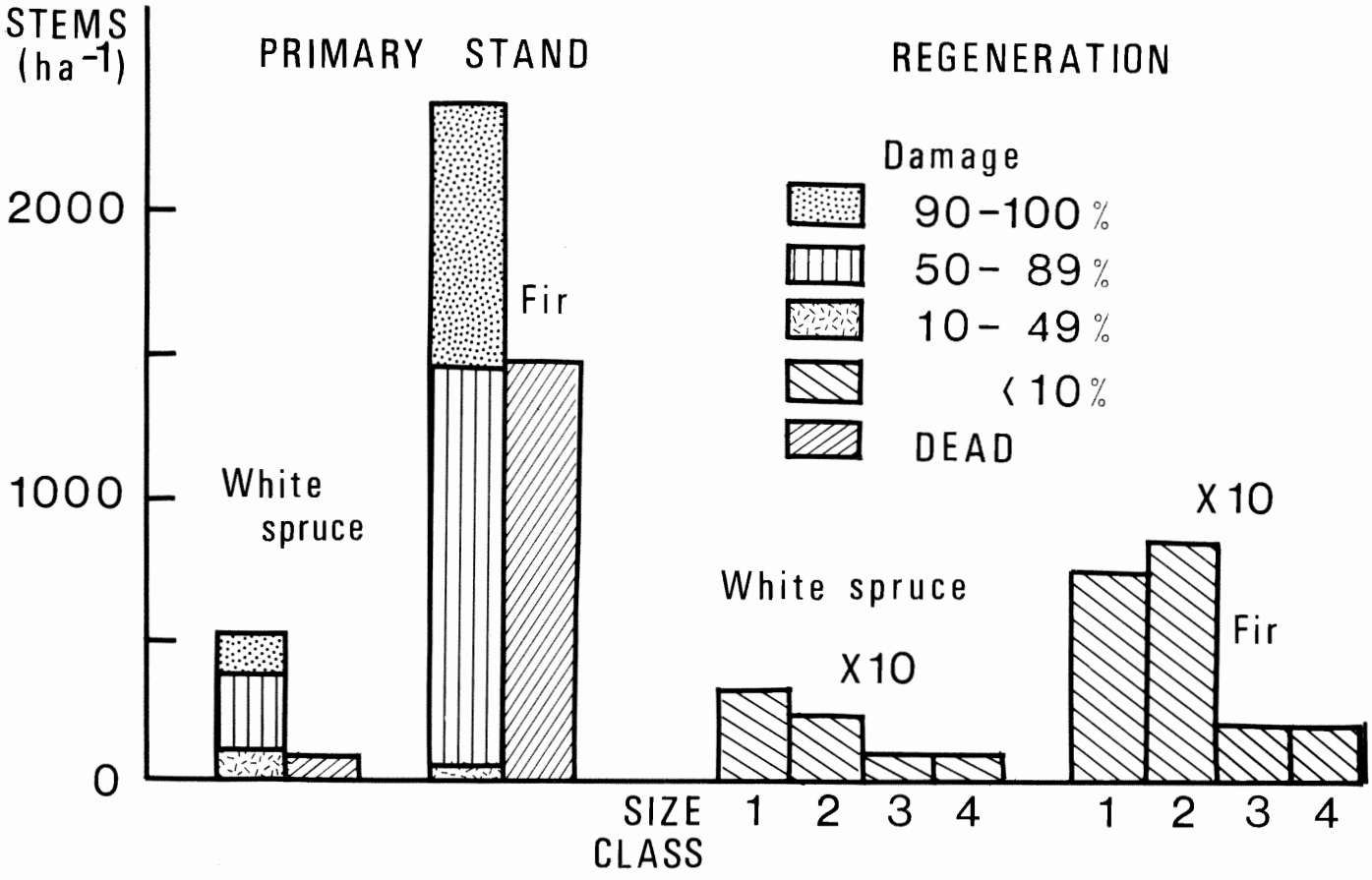

Figure 36. White spruce-fir stand structure (1979) following budworm attack. Primary stand includes standing dead, residual overstory, dead and damaged secondary understory.

centimetre classes, there are 1500 to 500 per hectare, respectively. This is a ratio of about 7:1 fir to spruce in the younger part of the stand. Such ratios commonly occur up to 10 or 12:1. The young fir are growing aggressively and, as expected, as this regeneration wave rises in the stand, the numbers of the small spruce will drop still further through competition from the fir.

Figure 33 illustrates the primary stand structure of the red spruce-fir forest. As in the preceding example, there are only small numbers of trees in the 45-65 centimetre diameter classes, and like the white spruce-fir stand, there are almost 20 trees per hectare in each of the centimetre classes between 10 and 20 in the red spruce-fir stand. Unlike the preceding stand, however, the red spruce-fir carry more individuals in the classes between 20 and 40 cm. This is compensated for by the slightly lower frequency in the 10-20 centimetre classes. Stands are roughly in the same state of development, however, and the fir has reached the 15 cm size class. The ratio of the fir to spruce in the rising regeneration wave in the 5-8 centimetre classes is about 8:1 fir to spruce. It is clear from this that as the small trees rise, the great preponderance of fir will be sustained and there will be some losses in the numbers of small spruce, again through competition with fir. In both of the cases illustrated, it is clear that the ensuing stands will be very much dominated by fir.

Figures 34 and 35 permit closer examination of the secondary stand between 2 and 15 centimetre diameter classes. Ratios of fir to spruce remain relatively constant by diameter class as indicated in the foregoing.

Figure 36 illustrates the relationship between the primary stand and the residual regeneration developing under it in white spruce-fir. The primary stand here contains the residuals destroyed and damaged by the budworm and also the rising secondary stand trees comprising the large numbers of fir and the much smaller numbers of spruce in the ratio of 7:1 in the very small diameter classes (2-15 cm). It is these trees which it is expected will form the next stand.

However, the structure of the regeneration which has formed underneath the primary stand is of interest. Regeneration has been divided into four size classes from 3 cm in height to 2 cm dbh. Here again, fir dominate, but it is imperative to scrutinize the relationship apparent in the 3rd and 4th regeneration classes from 45 cm in height to about 2 cm dbh. The ratio of fir to spruce is markedly different. In these critical size classes,

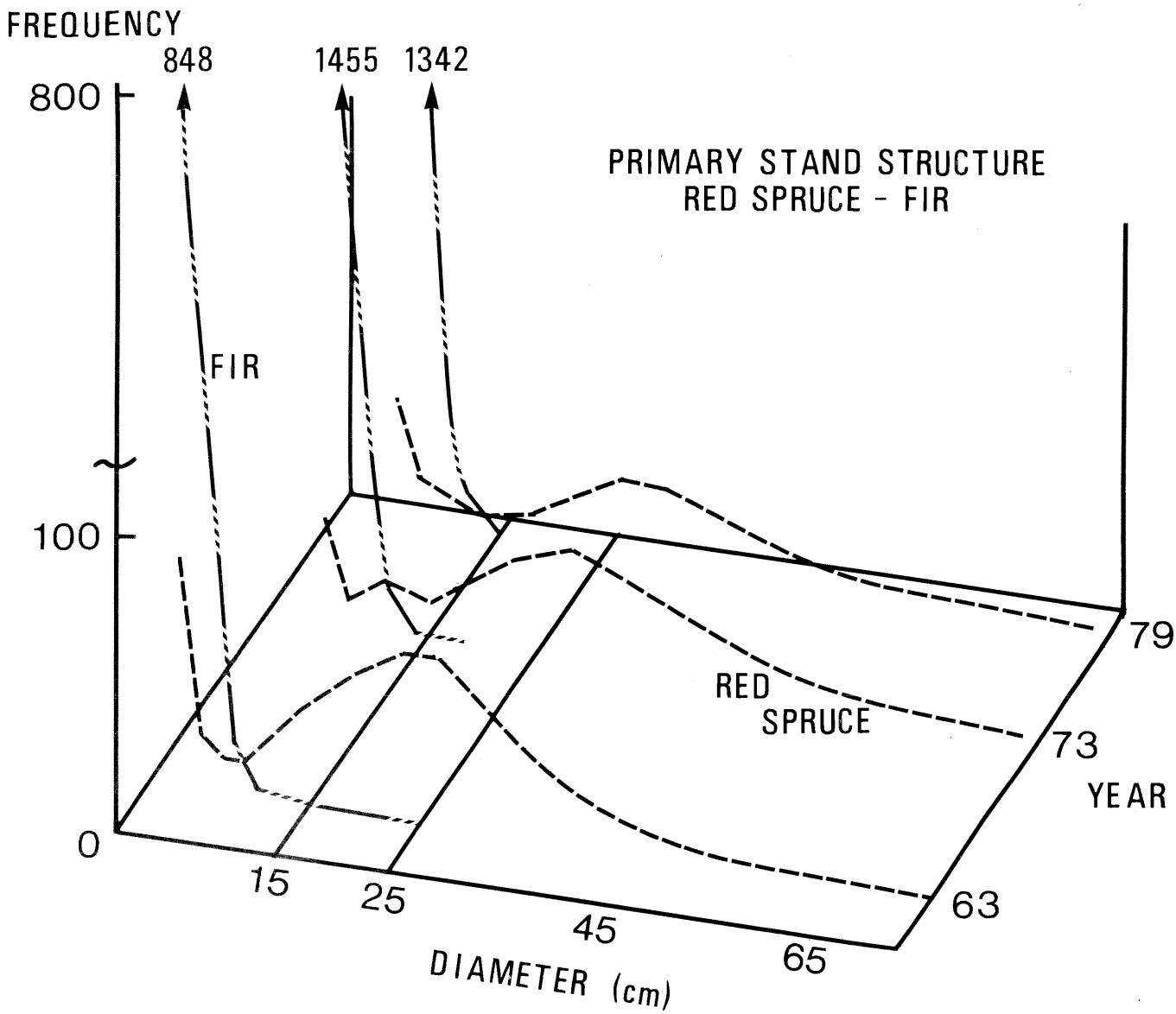

Figure 37. Red spruce-fir stand dynamics following the course of a budworm event.

the ratio is now 2:1 fir to spruce.

If the present overstory, including the rising secondary stand wave, were now wiped out, the stand would have a much more favourable composition of spruce relative to fir. The explanation for the shift in ratios in the regeneration is that despite the better seedling establishment characteristics of fir as compared to spruce, numbers of fir in the seed-bearing size in the original overstory have been totally eliminated by the massive preceding budworm event. This condition will prevail for many years, until such time as the rising wave of the secondary stand develops to a size which is consequent for flowering.

We have been privileged in being able to establish, monitor and work with data sets of long-term plots in spruce and fir. The great value of such long-term studies is clearly demonstrated as time goes on. These plots were initially established in 1959 and 1960 and are yielding very interesting data, some of which follows.

Figure 37 provides a model of the red spruce-fir forest showing stand dynamics through 16 years. It may be seen that for spruce the modal portion of the stand advances in this time period from 15-25 cm. There have also been some losses in numbers of individuals in spruce in the modal portion of the stand.

In the secondary portion of the stand, from 2-15 cm dbh, there were some initial losses in spruce, but their numbers have been holding and recently increasing slightly. Changes respecting fir are interesting. In the modal portion of the stand, fir reached 25 cm in 1963, but with ensuing remeasurements in 1973 and 1979, while the numbers had increased somewhat, fir became restricted to

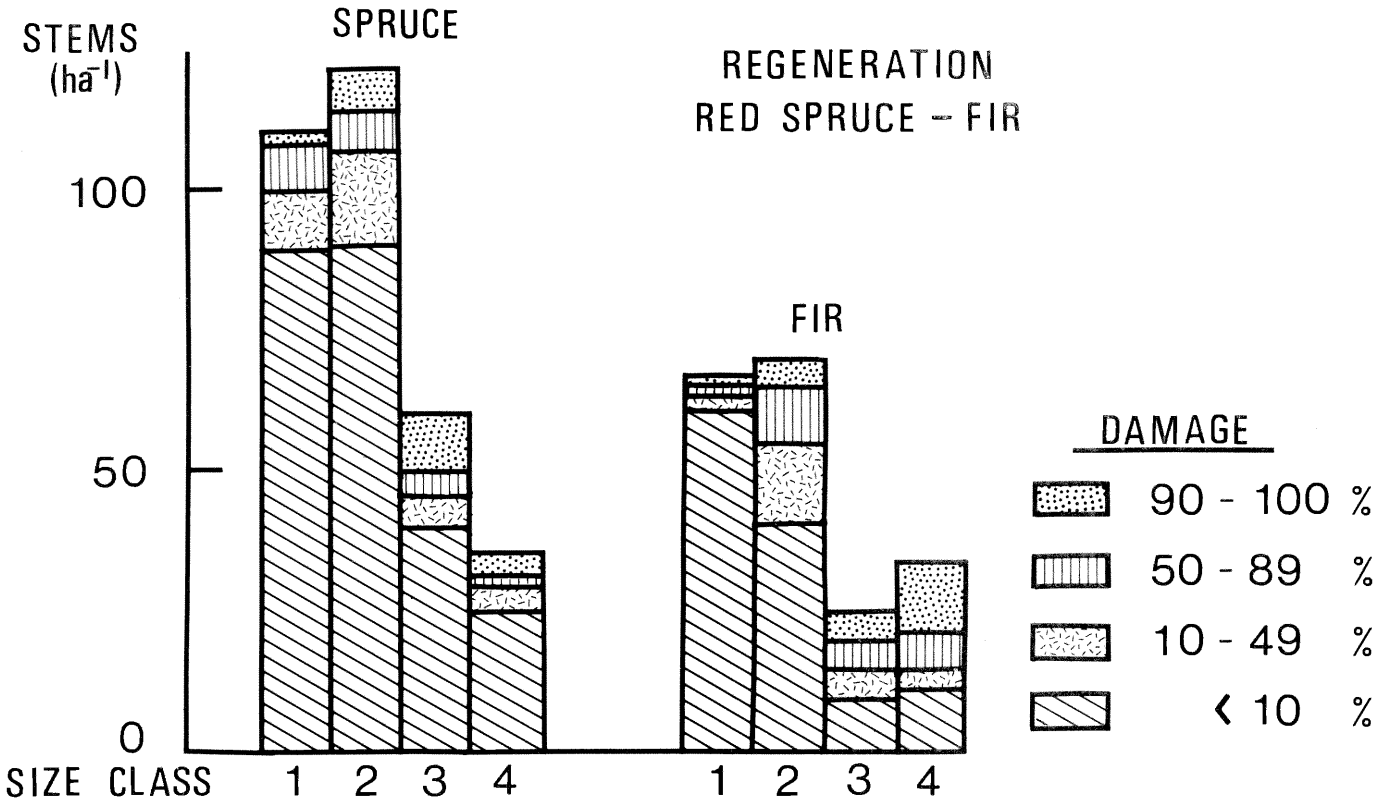

Figure 38. Red spruce and fir regeneration (1980) following a budworm event.

the classes below 15 cm, in fact, as we have seen from Figure 35, almost entirely to dbh size classes from 3-12 or 13 cm. The event which strongly influenced this stand development was a budworm buildup which initiated in 1971 and continued as a major outbreak through 1979.

Figure 38 presents data on the regeneration of the red spruce-fir forest. The regeneration is divided into size classes as above: the 3rd and 4th classes comprise seedlings from 45 cm to a metre in height, and one metre in height to 2 cm dbh. These are the most important in that they will be the size classes which, in most likelihood, will constitute the next stand. Damage categories are indicated, and what should be noticed are the differences in proportion of the budworm damaged to undamaged seedlings between spruce and fir. It may be seen that severely-damaged seedlings in the damage categories of 50% or greater, which will probably be eliminated as recruitment candidates for the future stand, constitute less than a quarter of both the 3rd and 4th size classes in the red spruce regeneration.

On the other hand, in the fir regeneration, more than a third in size class 3 and more than a half in size class 4 have been severely damaged and eliminated as recruitment candidates. The damage on the fir regeneration is twice as great as that on spruce in the last two size classes (3 and 4 combined) which, it will be recalled, are the trees now expected to enter the future stand. The higher numbers of spruce over fir in all regeneration classes is then an actual consequence of the budworm outbreak initiating in 1971.

It was noted in Figure 37 that fir was entirely eliminated between 1963 and 1979 from the 25 cm down to the 15 cm class, and most of it to lesser classes than that. Budworm not only reduced the fir in the stand largely down to size classes below flowering size, but also they would have interfered directly with flowering in those that were large enough to have flowers.

Since this data was collected, the process has continued to be played out. Current data coming in indicate that the secondary understory stand has indeed been heavily affected by budworm and large numbers of the fir have been totally eliminated. On the other hand, the spruce in that segment of the stand have to a large extent survived, and are still intact and growing. It will be seen that it is not, then, as was originally expected, the rising trees of the secondary understory stand (2-15 cm dbh) which will form or will even be desirable to form the next stand.

Figure 39 illustrates the red spruce stand overstory in 1959 with some old fir chicos still collapsing, and the rising secondary stand underneath consisting of almost pure balsam fir. The intensity of the outbreak in the secondary stand understory is shown in Figure 40 taken 20 years later in 1979. There are still surviving red spruce overstory trees, some of them damaged, some scarcely so, but balsam fir has almost entirely been eliminated.

Figure 39. Detail of red spruce-fir stand (1959). Overstory of red spruce, rising understory of pure balsam fir.

Figure 41 shows the interior of the red spruce-fir stand in 1979. The entire rising secondary or understory stand of small balsam fir is here seen to be totally stripped. There are hardly, if any, alive.

Figure 42 illustrates detail of a secondary understory stand in 1979, largely balsam fir, very heavily damaged or dead. A few still have some green foliage. A small red spruce about 1.5 metres high, and a single balsam fir about a metre are to

Figure 41. Interior of red spruce-fir stand. Rising secondary fir stand all stripped and dead.

be seen in the foreground in the rising regeneration class with very little damage and long well-developed leaders. The overstory red spruce are still fairly well intact. The red spruce in the secondary understory stand, about 5-8 metres in height, are alive and growing well.

In both the foregoing cases, the white spruce-fir and the red spruce-fir, a secondary budworm event has been substantially responsible for the maintenance of the spruce in the forest. Similar interpretations can be clearly deduced from the case history inventory data for the state of Maine

Figure 40. Red spruce-fir stand (1979). Red spruce overstory still surviving, balsam fir understory secondary stand all dead.

Figure 42. Detail of secondary understory red spruce-fir stand. Balsam fir all dead or dying; healthy red spruce regeneration dominating.

(Powell in press). I would propose that there are strong arguments for the co-evolution of the spruce budworm and the spruce-fir forest, and that where spruce and fir grow together, budworm are an essential factor in maintaining spruce in the stand through time.

Acknowledgements

I should like to acknowledge the unstinting support of my assistants, T. Norbert Lussier, Nancy Jondreau and Maria Famiglietti. I also wish to thank the many students of various disciplines who have assisted on our projects over the years, and my wife the late Jeanne Gordon who has supported and encouraged me in my work on spruce forests.

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STRESS AND DEATH OF TREES[1]

Alex L. Shigo[2]

Chief Scientist, USDA Forest Service,
Northeastern Forest Experiment Station,
P.O. Box 640, Durham, NH 03824

Abstract.--Trees survive after injury and infection so long as they set effective boundaries to resist spread of pathogens. Boundary-setting is beneficial so long as the volume of walled-off infected wood is small and the intervals between infection are long enough to allow enough new cells to be generated in new spatial positions that can hold enough energy reserves to maintain the tree. A tree may be able to trap solar energy, but when space for energy storage has decreased, all systems of the tree begin to diminish. Many secondary agents then attack. Fighting the secondary agents will not solve the basic problem of energy depletion, or stress, that may progress to irreversible strain and death. Answers to the basic problem of poor tree health will come only when tree management decisions are made on the basis of a much better understanding of the tree. Needed now is a new attitude about trees.

Introduction

Stress and death, and gloom and doom, are major current topics associated with forests worldwide: diebacks in Australia, exploitation of the tropical forests, large-scale dying of forests in Europe, dying of young planted forests in Korea, and, of course, all types of forest problems in the United States, and the list goes on and on. Is this recent attention to our world forests a media exaggeration, or do we really have some serious problems in our world forests? Are many forests of the world really in a state of stress and death?

During the last several years I have had opportunities to examine trees in several other countries. Some forests are very healthy; many were not.

A common thread that runs through many of the global tree problems is poor tree health. Insects and microorganisms are always present and are blamed for the problems, but I doubt that they are the causes or starting points of many of the tree problems. The organisms are often secondary agents. Too often we fight the secondary agents or the symptoms rather than the causes. And, even if we are successful in eliminating one group of secondary agents, another group will be ready to start.

A great advancement for humankind came about when the benefits of health were realized. It is better to concentrate on what keeps you healthy rather than on what makes you sick. Medical science advanced when bodies were systematically dissected. Then immunization treatments were used to make the body's own defense system function to keep disease at low levels. We must keep these points in mind as we discuss tree health problems. We should also concentrate on what keeps trees healthy rather than on what makes them sick. We should have a clear understanding of how trees are constructed and how they function. And we must help trees help themselves to use their defense systems more effectively.

There are some basic reasons why poor health is a major tree problem. Ignorance of tree basics is the major worldwide problem. We desperately need an attitude change about trees. Trees cannot sustain repeated abuse without serious injury. Trees do die! Decay is not a natural process beyond our limits of regulation. We can reduce the amount of rot. Many of the inaccuracies about trees that are being taught and are deeply entrenched in textbooks must be adjusted (Shigo 1980, 1982a, 1982b). We can start by learning about trees. This is not to say that anyone was or is wrong. It does mean that science advances as adjustments are made on the basis of systematic reexamination. Indeed, it is time to reexamine a tree: how it is built up, how it functions to stay built up, and how it eventually breaks down.

Some Tree Myths

Do you still believe that frost starts the long deep cracks that are called "frost cracks"? Do you still believe that wind starts the circumferential cracks called "wind shakes"? That trees heal wounds? That trees absorb minerals selectively from the soil to form mineral streaks? That heartwood is an unreactive tissue? That flush pruning is the best way to remove branches? The list goes on and on. My point is that if you believe these myths, and the many others that are in textbooks, it is no wonder that proper management schemes cannot be developed to produce high-quality trees that will produce high-quality products.

1/ Paper presented at SAF Region VI Technical Meeting: Forest Management and the Spruce Budworm. Burlington, Vermont, April 24-26, 1984.

2/ Portions of the research discussed here were supported by CANUSA.

It is far beyond the scope of this paper to discuss the many misconceptions about trees, treatments, and factors affecting defects. I shall discuss the role of energy reserves in the tree defense process. Excellent information on starch reserves in trees has been given by Wargo (1971, 1975, 1976, 1979).

Some Definitions

First it is absolutely necessary to define some terms. Voltaire said to define your terms and arguments will be less than a few minutes. These are my definitions, and it is doubtful that you will agree with them totally. They are terms that are used commonly by many people, but seldom defined. This is why there are so many arguments.

HEALTH is the ability--dynamic state--to resist strain. STRAIN is an injurious, irreversible condition caused by excessive stress. STRESS is a gradation of events resulting in a drain, blockage, disruption, or shunt of energy. ENERGY is fuel or the force that "runs things" or maintains vitality. VITALITY is the dynamic ability to grow and reproduce within the limits of vigor. VIGOR is the intrinsic genetically controlled capacity--potential--to survive after injury and infection. INFECTION is a process of energy transfer from host to pathogen. PATHOGEN is an agent that causes injury or strain to a host as a result of energy transfer. Organisms that decay trees are pathogens because pathogenesis is based on the entire organism and not on its parts. DISEASE is a process of energy transfer to pathogens from the host that results in a condition of strain to parts of the host or the entire host. HOST is the organism that has the stored energy and is interacting with a pathogen in energy transfer. ENERGY TRANSFER must consider the three laws of thermodynamics: (paraphrased here for emphasis) 1) you can never win, only break even, 2) you can only break even at absolute zero, and 3) you can never reach absolute zero.

Indeed, we cannot win them all, but we can surely win more than we are at this time.

How Do Trees Die

Trees, like other organisms, die three ways: dysfunction, infection, and mechanical disruption. There are many variations on these themes, and usually the variations overlap many times before death. Dysfunction occurs in many ways when tissues do not function properly. For example, this can occur when soil water is too high or too low for the tree, or when microelements or pH, or soil type, or any number of factors change or are changed. Trees can adapt to many conditions if they have the time. Any sudden change may make adaptation impossible or difficult. Tree problems associated with dysfunctions are least or poorest understood because they usually are not recognized until it is too late. We know so much about ends of processes, but so little about beginnings. Yet it seems that secondary agents can rapidly recognize the beginnings of the unhealthy condition when they attack. Tissue dysfunction affects not only growth and reproduction processes, but also the defense system. To be alive but defenseless is indeed the worst condition.

The real problem with dysfunction is that additional energy may not help the condition. Indeed, dysfunction is the malfunction of some vital tissue, organ, or process. Adding more energy or more fertilizers may not help a malfunctioning tissue or organ. In fact, some treatments, such as over fertilization, may actually make the malfunction worse. Disruption of sites by logging, mining, agriculture, and grazing will cause poor tree health: stress, strain, and death. Misunderstandings of tree problems also lead to planting the wrong tree in the wrong place (conifers on hardwood sites) --done repeatedly in Europe--and any number of disruptions that alter normal tree functions.

A major problem in understanding trees is that we have borrowed too many terms from other disciplines, especially human pathology. We then try to fit or force the terms onto the tree, and they often do not fit. A tree can have many large dead and dying branches, but also an equal number of very healthy branches. Is the tree half healthy or half dying and dead?

In a sense, trees are multiple plants, or communities of plants. The parts may die, and new parts are generated in new spatial positions. Or, the entire community may be in trouble. The dysfunction or infection may be affecting a part of the community, or the entire community of trees. We lack proper terminology to discuss clearly such an organism or "group of organisms."

Add to this the problems of mechanical disruption. The unique characteristic of a tree is its mechanical support system. Trees are still the biggest organisms ever to inhabit this planet. Trees have evolved unique ways to protect their mechanical support systems--they set boundaries to resist spread of pathogens. But, when a pathogen digests the support system, and the tree falls over, the tree is dead. This is why decay-causing organisms are pathogens.

In a sense, trees "attempt" to avoid some of the problems due to size by regulating generating with shedding. Trees by nature of the growth systems do get larger every growth period. But, trees regulate this somewhat by shedding twigs, branches, support roots, and absorbing roots that begin to age and die.

How a tree dies is not a simple matter. The more we know about how trees live, the more we can do to keep them from dying.

Energy

Energy is the fuel or force that maintains the biological machine. Trees get energy by trapping solar energy in a molecule of carbon dioxide and water. Of the 0.1% of solar energy trapped by all organisms on this planet, trees trap 50%. The energy is used as sugars and stored as starch, oils, and other materials. The energy maintains growth, reproduction, and a defense system. Insoluble energy reserves, mainly as starch and oils, are used to start the tree processes after dormancy. It takes a great amount of energy to maintain and operate a defense system. The other requirement is space for the needles and leaves to trap energy. Survival requires space and energy.

Energy and Boundary-Setting

To summarize to this point: Trees are highly compartmented, woody, perennial, shedding plants that are usually (but not always) large and single-stemmed. Trees generate new cells in new spatial positions and shed dying and dead parts. Trees do not restore injured and infected tissue. Trees do set boundaries to resist spread of pathogens--compartmentalization (Shigo and Marx 1977, Shigo 1979, Shortle 1979). A model of compartmentalization is called CODIT.

CODIT

To understand defects from the tree to the product it is absolutely essential to understand boundary-setting processes. To make this very complex subject clear, a model called CODIT was developed (Shigo and Marx 1977). CODIT is an acronym for Compartmentalization Of Decay In Trees. The model has two parts. Part I is in the tree at the time of injury and infection. Part I is represented in a model sense by three walls: walls 1 resist--not stop--vertical spread of the microorganisms, walls 2 resist inward spread, and walls 3 resist lateral spread. In a sense, the tree attempts to wall off the microorganisms to as small a volume as possible, while the microorganisms counter this attempt by spreading as far as possible, as rapidly as possible.

After injury and infection, the still-living cambium about the injury begins to form a new tissue called the barrier zone. The barrier zone is a very protective tissue, but a very weak structural tissue. The barrier zone is a weak conducting tissue. In the CODIT model this separating boundary is called Part II, or wall 4. Wall 4 is where ring shakes and radial splits begin. Wall 4 may form after wounds or the death of branches and roots.

Trees survive after injury and infection so long as they have the time, energy, and genetic capacity to recognize and compartmentalize injured and infected cells effectively, and then generate enough new cells in new positions to continue to maintain the tree. The new cells must be able to store sufficient energy to maintain growth, reproduction, and a defense system.

When energy is decreased, trees reduce growth and reproduction. When decreased energy reduces the defense budget, a high-risk situation begins. The risk is reduced when no further injuries are inflicted. But, when injuries are inflicted, the risk increases, especially when energy-drains caused by injuries and stresses repeat at shorter and shorter intervals.

The two important parts to energy reserves are: (1) the tree must have enough healthy needles or leaves in enough proper spaces to trap sufficient energy, and (2) the tree must have some place to store the energy reserves. This second requirement is often not considered. The second part also is counter to boundary-setting or compartmentalization.

Genetics of Boundary-Setting

The tree defense system is centered about boundary-setting. Trees that have the genetic program to resist spread of pathogens will limit the infected zones to small volumes (Garrett et al. 1979, Shigo et al. 1977, Lowert and Kellison 1981, Schmitt et al. 1978). Trees that have weak boundaries will have large volumes of infected wood. Compartmentalization is indeed an effective defense system when it functions to limit infected tissues to small volumes, and when the injuries and infections are not repeated within short periods. When more and more tissues that normally hold energy reserves are walled-off, the potential volume of wood for storage of reserves begins to decrease.

Starting Points for Infection

The three basic starting points for infections are: dying roots, dying branches, and mechanical injuries. It is impossible for a tree to grow in a forest without having some or all of the infection courts. Trees with strong genetic programs can wall off dying branches and roots effectively, and no volume of trunk wood is lost to the pathogens. When mechanical wounds are inflicted on the trunk, the tree responds to resist spread of the pathogen within the wood present at the time of injury, and then the tree forms a protective barrier zone that separates the infected wood from the new wood that continues to form.

As energy reserves decrease, the defense budget also decreases. The boundary-setting process is less effective. As new infections start, they spread faster and farther. When healthy wood is "trapped" between new infections and an older internal defect, the new infection will often spread rapidly into the "trapped" tissues.

The process of boundary-setting then begins to be a problem for the tree rather than the answer to survival.

Paradox of Boundary-Setting

One irony of the way natural systems operate is that a feature or characteristic of the system may be beneficial or destructive depending on the concentration of the feature, or characteristic--too little compartmentalization, too much compartmentalization--and timing--compartmentalization when energy reserves are high is beneficial, compartmentalization when energy reserves are low may be destructive.

The tree must produce new cells in new positions during the growing period or it ceases to be a tree. Energy is required for these functions. To compensate for lower energy reserves, the tree walls off more of its parts. But, when more and more branches are walled off, so are leaves and needles that trap energy. At this stage there is little hope for survival of the tree. Even if treatments could retain needles and leaves, and even if needles and leaves could trap an abundance of energy, there would not be enough space within the tree to store energy.

Long before a tree exhausts its energy supply, many weakly parasitic or opportunistic organisms attack and drain the remaining energy reserves. So, it is unrealistic to think that a tree will die because it exhausts its energy supply.

Aging and Boundary-Setting

When trees are young, 100% of their volume can be used for energy storage. The living cells in the wood store the energy reserves. As branches and roots die, and as injuries are inflicted, and as living cells in the wood die, the ratio of stem volume to volume of wood capable of storing energy reserves begins to decrease.

The tree regulates crown size and root mass by setting boundaries between aging, dying, and dead parts, and still living, healthy parts. The boundaries are usually effective in resisting spread of the microorganisms from the dying root or branch into the healthy wood. It seems that boundary-setting at the branch bases and root bases is under genetic control. When the microorganisms are aggressive, they may spread beyond the boundary and into the healthy wood. The tree usually responds by setting new boundaries deeper into the wood. The new boundaries may resist further spread and limit the microorganisms to small volumes of the joining stem or root. In other instances, the microorganisms may be even more aggressive and may breach the second boundary and spread into the trunk or the major root. The tree will still respond by resisting spread within the trunk or root, but also the tree does form a barrier zone that usually confines the infection to the trunk or root tissues present at the time the branch or root died.

How many boundaries are breached or broken may be a factor of aggressiveness of organisms, or it may be a factor of the tree. The tree may be a genetically weak tree that sets weak boundaries, or the tree may be an energy depleted tree that cannot set strong boundaries.

A young tree may be a genetically strong compartmentalizer, but as more and more branches and roots die, and as more and more injuries are inflicted, the boundary-setting capacity of the tree begins to decrease.

Once boundary-setting reduces the volume of wood that can hold sufficient energy to some yet unknown low point, the tree becomes strained. Once the tree is strained, the recovery is less and less likely.

Stress and Strain

A tree can have a great amount of stress without having strain. Stress includes all the dying branches, dying roots, and mechanical wounds. So long as the tree is able to collect and store sufficient energy, it will continue to grow and reproduce.

Stress also increases as dysfunction increases. Dysfunction of vital tree processes may be a genetic factor that becomes obvious very early in the life of the tree--usually leading to early death--or a factor associated with intrinsic genetically controlled aging processes. Dysfunction may also be associated with environmental factors such as discussed earlier, and also with some types of infections. Regardless, dysfunction results ultimately in an energy blockage, shunt, or drain, which is stress. And, when stress continues, strain may result.

Here are some important specifics about spruce and fir, based on my discussion on stress and strain.

Spruce, Fir, and CODIT

Fir has a very weak CODIT, Part I (Tippett and Shigo 1981, Tippett et al. 1982). What does this mean, especially for products? After branch death, root death, or mechanical wounds, the wood is rapidly invaded by microorganisms (Shortle and Ostrofsky 1983). But the tree produces very strong walls 4. In roots such a response permits the tree to remain alive with hollow roots, but the support function of the roots is greatly decreased. When such rot problems develop in large support roots that join at the tree base, a crack usually develops between the two joining roots. The vertical crack may extend far upward on the trunk. Cracks at the base of fir are reliable indicators of root rot, especially those caused by Armillaria mellea (Shigo and Tippett 1981).

As roots die in fir, and as microorganisms invade the wood within Part I, the wood may develop into wetwood, or either white rot or brown rot. Large columns of wetwood often develop upward into the trunk from dying roots (Schütt 1981).

New electrical methods have been developed to detect wetwood and decayed wood in fir and spruce (Davis et al. 1980, Blanchard et al. 1983). These methods make it possible to determine the width of sound wood, and to determine whether wetwood is present.

Spruce has a stronger Part I CODIT than fir. For this reason the columns of defect are usually smaller and end more abruptly in spruce than in fir. Ring shakes are common in spruce, but basal cracking is not as common in spruce as in fir. Spruce does not have as much wetwood. But spruce often has more problems with fungi associated with branch death. Fomes pini is common in spruce. Spruce seems to resist such infections very well until the number of infections becomes overwhelming, then the decay processes develop rapidly to form large central columns of defect.

What Can Be Done?

Excessive logging damage must be stopped now! Logging wounds--roots, trunks, branches--are major starting points for many types of defects including long cracks commonly called frost cracks. Frost does not start the cracks, wounds do (Butin and Shigo 1981).

Pruning practices must be adjusted now. Cuts behind the branch bark ridge and the injuries to the branch collar start many types of problems, including blue stains, ring shakes, vertical cracks, and cankers. Proper pruning (Shigo 1982a) does not mean leaving a stub, but the small branch collar must remain on the stem. If trees are pruned at an early age, this slight bulge will not reduce the width of clear wood for boards. But if the collars were removed, cracks and internal defects will form. Add to this the sawing of boards which contain the pith, and the splits will break outward, or the wet pockets associated with the branches will make drying difficult.

A logging wound reduction program must be started. Operators of machinery must be made aware of the damage that can result from wounds on the roots, trunks, and branches. Excessive logging damage must not be tolerated.

Decide whether the site will support high-quality trees. Measurements of cambial electrical resistance may help in making this decision.

Highly defective trees should be removed. Trees with basal cracks, especially balsam fir, should be first. If many cracked trees are growing on one site, it may be a root rot site, and the likelihood of growing quality trees there would be remote.

Know what you have on inventory plots. Use the Shigometer to determine internal condition of select trees. Use the Shigometer to help determine vitality of the trees.

Such a program involving removal of defective trees, thinning, proper pruning, and reduction of logging wounds on sites that will support high-quality trees, and the use of the Shigometer could result in a great increase in tree quality in a relatively short time.

Defective trees in our forests are primarily the result of long periods of high grading, taking the best and leaving the worst. In many of our forests, only the worst trees remain. It can be argued whether these trees are really genetically weak or tough trees, and that if given a reasonable change, whether they would grow into high-quality trees. I doubt this.

In an experiment involving deep drill bit wounds in sugar maples, paper birch, and yellow birch, selected as superior for growth rate and form, only a few of the trees were designated as strong compartmentalizers based on the volume of defect associated with the experimentally inflicted wounds.

At the same time we know from these studies and from other studies by our cooperators and other researchers that some individuals of a species are very strong compartmentalizers; they do limit defects to very small volumes. Studies on several species show that resistance to spread of decay is under moderate to strong genetic control (Shigo et al. 1977, Garrett et al. 1979, Schmitt et al. 1978, Lowerts and Kellison 1981). Genetic control is the key to future high-quality forests. We must increase our programs to select strong-compartmentalizing trees, and also to find faster and more accurate ways of identifying tough trees.

Biochemical enzyme markers may be a way to do this. Wounding studies are being done now on many species of conifers and hardwoods. Studies are also being done on very young trees to determine whether tough trees can be selected very early.

Conclusions and Warning

The worldwide pattern of poor tree health leading to many types of forest problems must be reversed before it is too late. Scientists must turn their attention to starting points of the problems rather than to the symptoms, secondary agents, and ends of the destructive processes. We cannot change decades, or even centuries, of mistreatment of our forests in a few years. We all share an education responsibility. We must make certain that decisions on our forests come from properly conducted experiments with controls. Learn what a tree is and learn how it functions to survive. Then let us help the tree help itself to survive in a healthy state. If we do not follow such a course, the fight against symptoms and secondary agents will continue, while more of our world forests die.

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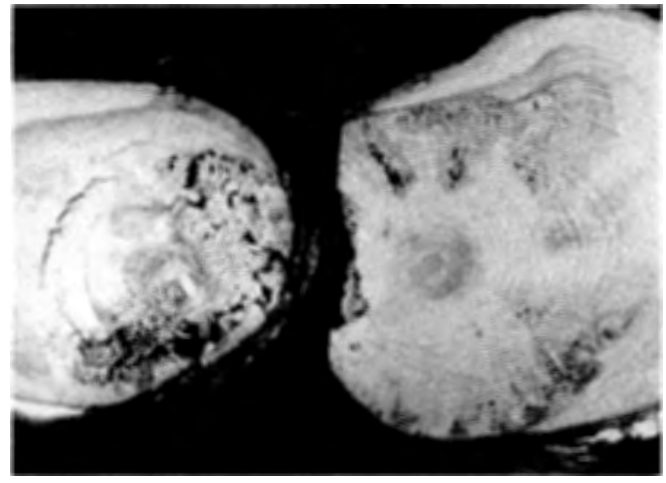
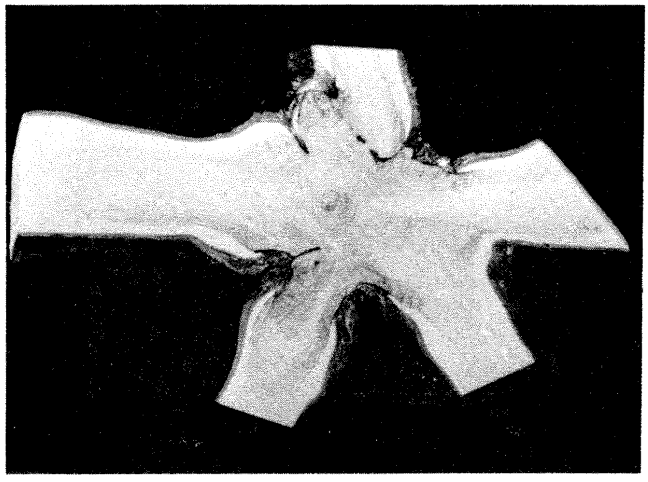
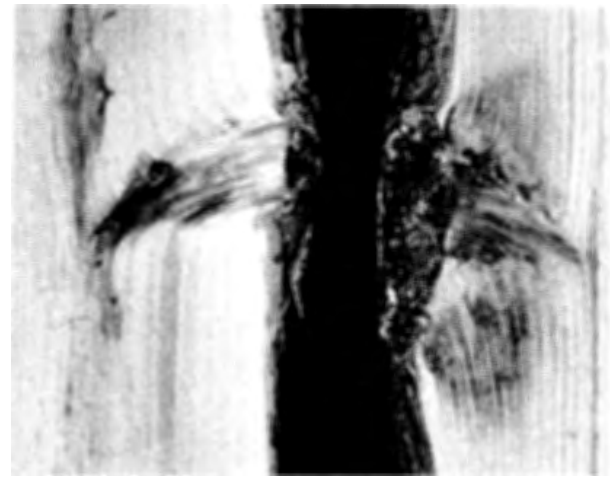
Armillaria mellea is a major cause of root rot in spruce and fir.



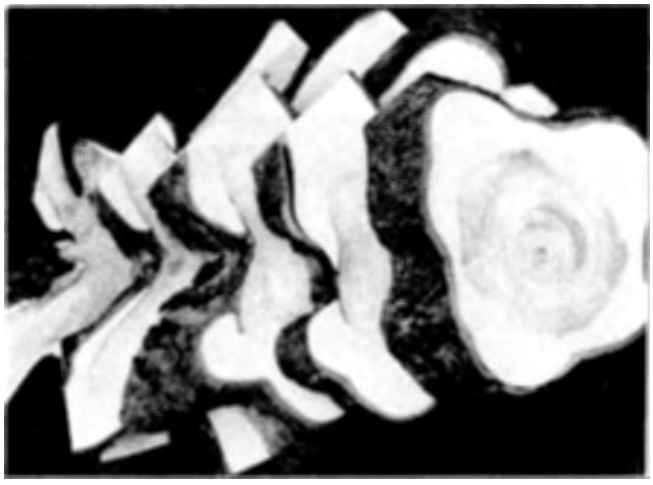
Two patterns of basal rot associated with A. mellea; left, center sound, right, decay advanced into the center.



Base of fir showing advanced decay associated with A. mellea between the roots.

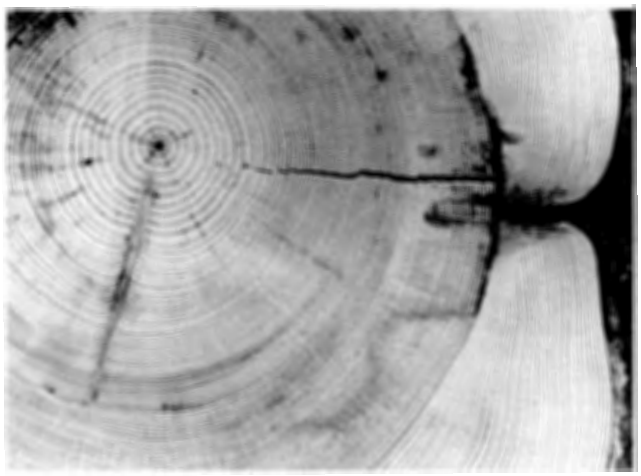


A proper pruning cut, left, and an improper flush cut, right, on a red pine after 2 years. Cuts should not be made behind the swollen collar at the branch base.



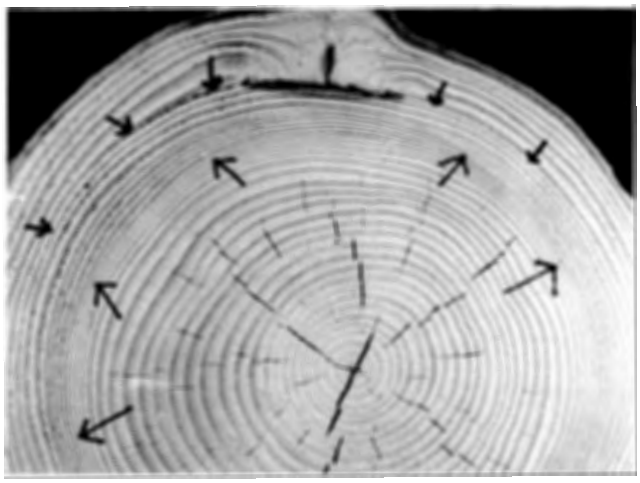
Basal sections from a fir show wetwood associated with root rot.

Dwarf mistletoe on red spruce can cause brooming, swollen trunks, and general decline of trees.

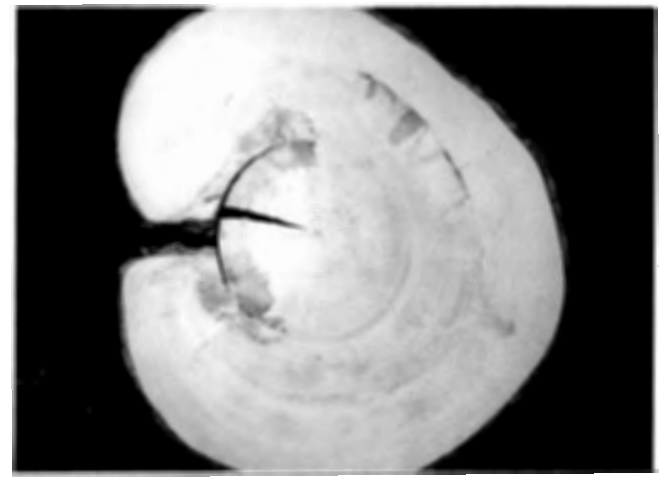


Wound on red spruce. Logging wounds are major causes of defects.

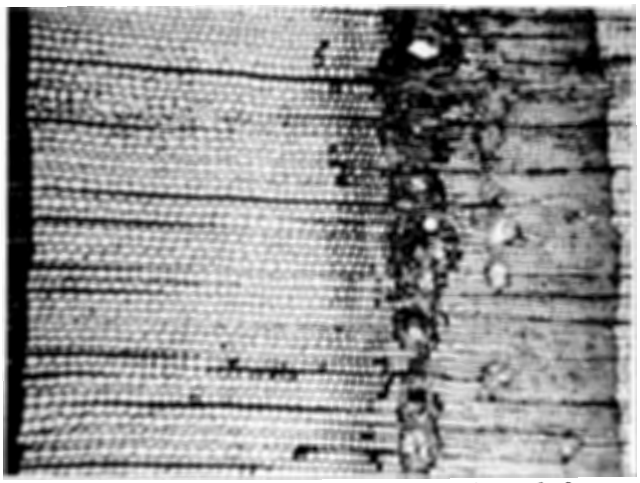
Ring shake in red spruce. Barrier zones associated with wounds and dead branches often start the shakes.



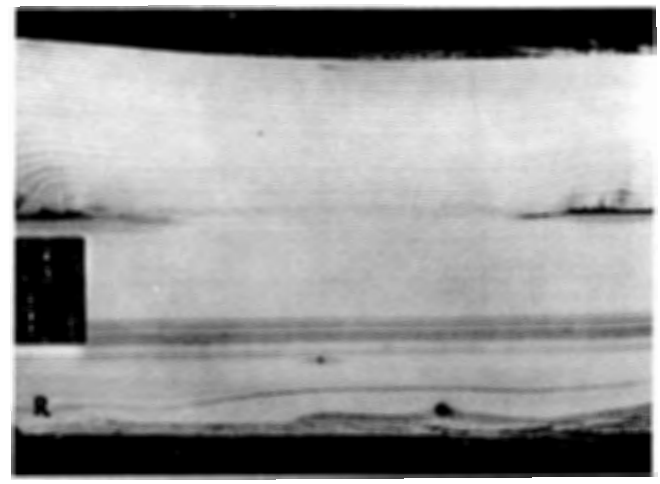
Small wound on Norway spruce. Small arrows show that barrier zone that formed after wounding. Large arrows show inward limit of resin ducts. Note lack of resin ducts behind wound.



Two major wounds in this red spruce limit its use for quality timber.



Microscopic view of the barrier zone 2 cm left of wound shown above. The barrier zone is the starting point for most of the shakes in trees.



The 2 small wounds in the red spruce sample are the starting points for ring shake.

DYNAMICS OF THE FOREST AND EASTERN SPRUCE BUDWORM OUTBREAKS

D. Gordon Mott

The temporal and spatial characteristics of the Eastern Spruce Budworm outbreaks since 1900 are evaluated qualitatively. Hypotheses concerning the role in epidemic dynamics of forest character, coupled with climate, density dependent populational processes, aerial forest spraying, and dispersal are offered. Speculation about future events and the roles of forest management and protection is indulged.

ASSESSING SPRUCE BUDWORM DAMAGE IN MICHIGAN'S UPPER PENINSULA, 1978-1983: A CASE STUDY

John A. Witter[1], Ann M. Lynch[1], Thomas P. Mog[2], and Bruce A. Montgomery[1]

[1]Associate Professor, Research Assistant, and Coordinator of the Lake States Spruce Budworm Technology Transfer Program, respectively. The University of Michigan, School of Natural Resources, Ann Arbor, MI 48109-1115.

[2]Pest Management Specialist, The Davey Tree Expert Company, Kent, OH 44240.

Three topics are discussed: our research and development program, the Michigan Impact Plot System (MIPS), and technology transfer. We describe the MIPS and our techniques for quantifying impact of the spruce budworm in the Hiawatha and Ottawa National Forests. We summarize percent mortality, total dead volume, live basal area per acre, dead basal area per acre, and defoliation rankings from sampled spruce-fir stands. Recommendations are made for future studies on forest damage assessment.

Introduction

The spruce budworm, Choristoneura fumiferana (Clemens), was not considered a major problem in the Lake States until recent years. More intensive forestry practices and greater market demand for spruce and fir have been partially responsible for the increased interest in techniques to measure and reduce impact of the spruce budworm in spruce-fir stands. Lake States land managers have been seeking additional information on the spruce budworm since the mid-1970s.

Over 2.5 million acres of commercial forest in Michigan are classified as spruce-fir (Montgomery et al. 1983c). The most recent spruce budworm outbreak was reported in the eastern part of Michigan's Upper Peninsula in the late 1960s, with mortality first observed in 1971. Heavy defoliation and considerable tree mortality occurred during the 1970s (Witter et al. 1984). The spruce budworm population dropped to fairly low levels during 1981 throughout most of the Upper Peninsula. Tree mortality occurred in 1982 and 1983 in stands that were heavily defoliated during 1978 to 1980 because mortality continues for one or two additional years following the end of an outbreak. Very low population levels were noted in 1981 and 1982, but in 1983 budworm populations increased in many areas. Noticeable defoliation occurred in the central Upper Peninsula during 1983.

There was very little information available in 1977 on the impact of the spruce budworm on spruce-fir stands in Michigan. With this in mind, a seven-year study was designed. Entomologists, foresters, biometricians, remote sensing specialists, computer specialists, economists, and technology transfer specialists were involved in this research. This paper will focus on three topics: our research and development program, the Michigan Impact Plot System, and technology transfer.

Research And Development Study Design

Studies to assess widespread damage to forests (by insects, diseases, and other agents) are very expensive and time consuming. We economized by concentrating our efforts on four major objectives that interacted and could be worked on simultaneously. Our objectives were to quantify the impact of the spruce budworm on spruce-fir stands in the Ottawa and Hiawatha National Forests, to develop techniques for measuring impact, to develop hazard-rating systems for spruce-fir stands in Michigan's Upper Peninsula, and to provide forest managers with pest management information, especially related to impact.

The study proceeded through the following steps:

1. Review existing literature and discuss proposed research ideas with other researchers and land managers (1977, 1978).
2. Determine long-term research objectives (1977-84).
   a. Quantify impact (1978-84).
   b. Develop techniques for sampling impact (1978-84).
   c. Develop hazard-rating systems (1978-84).
3. Develop study plans (1977, 1978) and submit grant proposals (1978-83).
4. Establish (1978, 1979) and evaluate (1978-84) the Michigan Impact Plot System.
5. Develop (1978-81) storage capabilities, computer programs, and mapping routines for the impact data collected during 1978-84.
6. Design and implement additional research studies to meet the objectives of this project (1979-83).
   a. Sampling size (1979).
   b. Remote sensing (1979-81).
   c. Regeneration (1980).
   d. Site classification (1982).
   e. Economics (1983).
7. Analyze data and develop final products (1979-84).
8. Determine new priorities and finalize studies for the next field session (winter prior to each field season).
9. Participate in user group meetings (1978-84).
10. Publish techniques and results from research studies (1979-84).
11. Develop and implement a technology transfer program (1981-85).
    a. Needs assessment survey.
    b. Manuals and handbooks.
    c. Remote sensing workshops.
    d. Evaluation of processes and products.

Michigan Impact Plot System

Methods

The Michigan Impact Plot System (MIPS) was established in the Hiawatha and Ottawa National Forests (Fig. 1) during 1978 and 1979. The sampling units used in the MIPS were: strata - Ottawa National Forest, Hiawatha National Forest, primary sampling unit (PSU) - forest compartment, secondary sampling unit (SSU) - a spruce-fir stand, and tertiary sampling unit (TSU) - circular plots (Mog et al. 1982, Mog 1981, Mog and Witter 1979). The PSU's and SSU's were weighted according to spruce-fir acreage and then selected at random for each national forest. Each SSU was divided into two approximately equal parts, and TSU's were randomly located within each half of the stand. A TSU was one of three circular plots of ca 0.05, 0.10 and 0.20 acres which were established around the plot center. Composite ground sampling unit refers to the three concentric circular plots nested around a single fixed plot center. The number of composite ground sampling units in the MIPS was 136 in 1979, but decreased slightly in succeeding years because a few of the sampled stands were harvested. The ground sampling units were measured each year from 1978 through 1984.

Results

Spruce budworm impact data for the years 1978 through 1983 is presented and discussed by national forest and selected districts for the following parameters: percent mortality, total dead volume, live basal area per acre, dead basal area per acre, and defoliation ranking. We chose three districts from each national forest to illustrate the variability of budworm impact within a national forest. Detailed impact information on the stands in the MIPS have been published (Lynch et al. 1982a-d, Mog et al. 1982).

Percent mortality. On a percent basis, approximately twice as much mortality occurred on balsam fir than on white or black spruce in the Hiawatha and Ottawa National Forests (Fig. 2).

Percent balsam fir mortality in the Hiawatha National Forest was extremely variable (Fig. 3). In the eastern districts, where the outbreak first started, balsam fir tree mortality was very high (e.g., 99% in the Sault Ste. Marie District, 74% in the St. Ignace District). The outbreak was present almost as long in the three western districts. However, average percent fir mortality was under 25% in each of the three western districts (Munising, Rapid River, and Manistique). The extreme differences in percent mortality between the eastern and western districts of the Hiawatha National Forest were probably due to the good markets for spruce and fir pulp in the western districts. There was little opportunity to harvest fir timber in the eastern districts due to lack of markets.

Percent balsam fir mortality in the Ottawa National Forest ranged from 19 to 54% through 1983, with the highest mortality (30 to 54%) occurring in the most western and northern districts (Bessemer, Watersmeet, Ontonagon, Bergland) where the outbreak originated in the western Upper Peninsula. Average percent fir mortality increased considerably between 1980 and 1983 in the eastern districts of the Ottawa National Forest (Fig. 3). By 1983 fir mortality reached 19 and 30% in the Iron River and Kenton Districts, respectively.

Total dead volume. Balsam fir has suffered a much greater loss of growing stock volume than white or black spruce. In the Hiawatha and Ottawa National Forests, approximately 90 and 84% of the total fir volume died. Through 1983, the estimated total dead volume of balsam fir had reached over 17 and 20 million ft^3 in the Hiawatha and Ottawa National Forests, respectively (Fig. 4). Total dead volume of balsam fir has tripled since 1978.

White spruce total dead volume showed a ten-fold and four-fold increase in the Hiawatha and Ottawa National Forests since 1978 (Fig. 4). Black spruce total dead volume doubled to tripled in both national forests during the last five years. At the end of 1983, total dead volume of white spruce was 1.4 and 2.4 million ft^3 in the Hiawatha and Ottawa National Forests, respectively. The total dead volume of black spruce was 0.4 and 1.4 million ft^3 in the Hiawatha and Ottawa National Forests, respectively. The relatively large volume of dead black spruce in the Ottawa National Forest may in part be attributed to site conditions and not completely due to budworm feeding (Mog et al. 1982).

Live and dead basal area. We present data for the amount of balsam fir basal area per acre only because the majority of live and dead basal area of susceptible host trees within the stands was balsam fir. A 36 and 30% reduction in live basal area of balsam fir was found in the Hiawatha and Ottawa National Forests, respectively, during the last five years (Fig. 5). A three- and four-fold increase in the amount of balsam fir dead basal area per acre has been observed since 1978. Estimated balsam fir dead basal area by 1983 for the Hiawatha National Forest was about 1.5 times that of the Ottawa National Forest. The balsam fir live basal area per acre remaining in 1983 was a little higher in the Hiawatha National Forest (27 ± 7 to 24 ± 3 ft^3/ac).

Changes also have been noticed in the amount of total live basal area per acre of white and black spruce. The average annual change in the live volume of white spruce was -0.40 and 0.0 ft^2/ac in the Hiawatha and Ottawa National Forests, respectively. The average annual change in the live volume of black spruce was +0.20 and 0.0 ft^2/ac, in the Hiawatha and Ottawa National Forests, respectively.

Considerable variation in the amount of live and dead basal area of balsam fir has

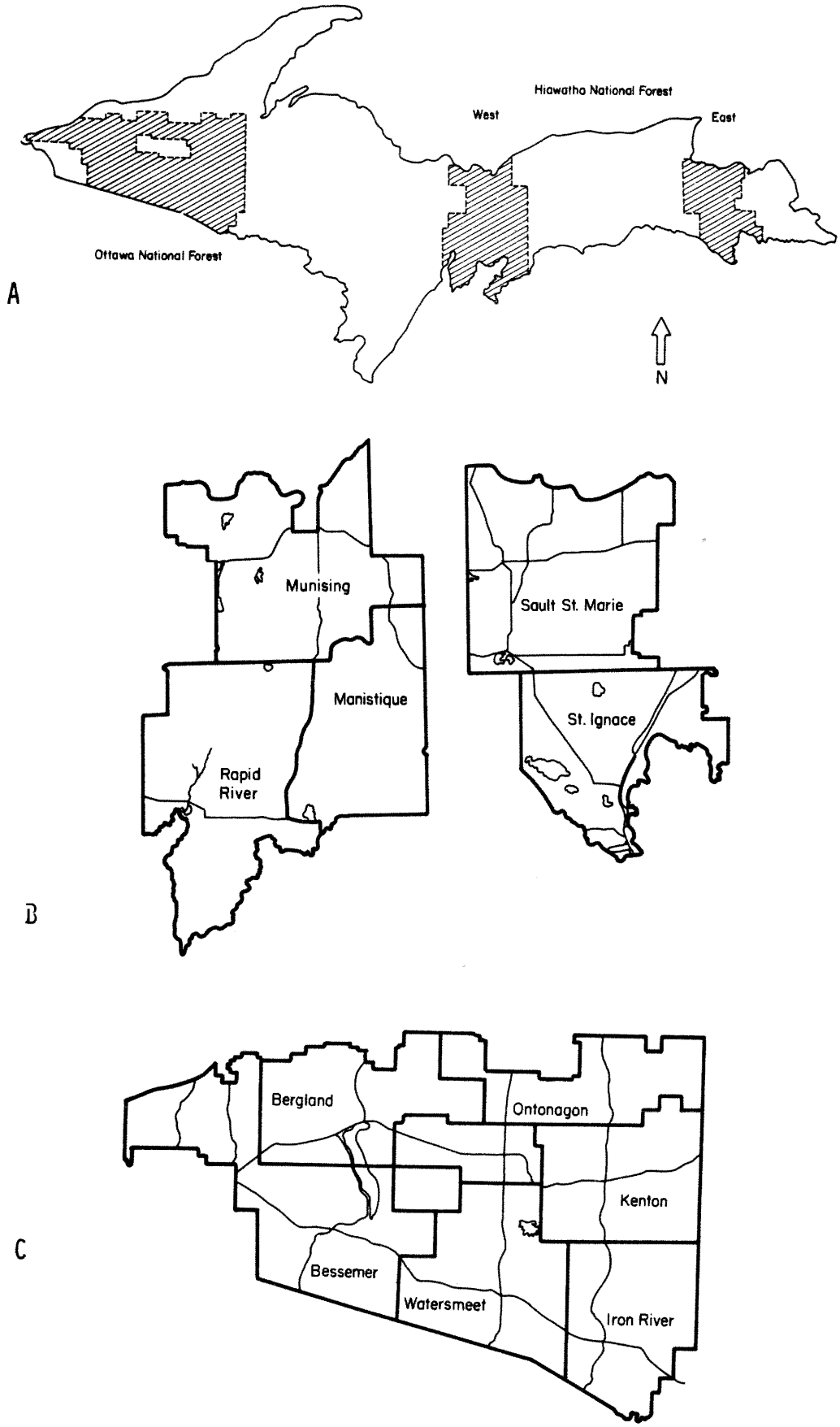


Fig. 1. Location of the: (A) Ottawa and Hiawatha National Forests, (B) districts in the Hiawatha National Forest, (C) districts in the Ottawa National Forest.

occurred in the various districts during the last five years (Fig. 6). In the Hiawatha National Forest, live balsam fir basal area/acre increased slightly in the Munising District, stayed about the same in the Manistique District, decreased about 20% in the Rapid River District, and decreased over 75% in the St. Ignace and Sault Ste. Marie Districts. Total dead balsam fir basal area/acre has increased three-fold in the Munising and Manistique Districts, but still was under 9 ft^2/ac; increased ten-fold in the Rapid River District (equaled 20 ft^2/ac in 1983); has reached over 40 ft^2/ac in the St. Ignace and Sault Ste. Marie Districts.

In the Ottawa National Forest districts, live balsam fir basal area per acre has decreased 10 to 55% during the last five years. Total live balsam fir basal area varies from 14 ft^2/ac in the Watersmeet District to 44 ft^2/ac in the Kenton District. A two- to eight-fold increase in dead balsam fir basal area/ac has occurred in the western Upper Peninsula since 1978. By 1983, total dead balsam fir basal area/ac was 11 to 12 ft^2/ac in the Bergland and Iron River Districts, 20 ft^2/ac in the Bessemer District, and 25 ft^2/ac in the Watersmeet, Ontonagon, and Kenton Districts.

Some of the factors responsible for these variations in the live and dead basal area of balsam fir are: (1) quantity of balsam fir present in stand prior to outbreak, (2) stand species composition, (3) site factors, particularly those indicative of soil moisture availability, and (4) length of time outbreak has been in progress (Lynch et al. 1984a).

Defoliation ranking. The average defoliation rankings for balsam fir, white spruce, and black spruce were similar in both national forests (Fig. 7). The defoliation ranking for balsam fir increased considerably between 1978 and 1980 and then stayed the same or decreased. There were small differences in the average defoliation ranking for white spruce and black spruce. The defoliation ranking by year for balsam fir was consistently higher than the corresponding defoliation ranking for spruce. For example, in 1980, the defoliation rank was 2.7 and 1.9 for balsam fir and spruce, respectively. This correlates with the pattern of greater mortality and growth loss exhibited by balsam fir over white and black spruce.

DISCUSSION

We briefly discuss the: (1) scientific and management implications of the MIPS, (2) number and size of plots within the MIPS, (3) variability within the MIPS, and (4) suggestions for reducing cost when sampling impact.

A thorough understanding of the interactions between the budworm, site conditions, and stands is necessary if we are going to manage the forest in an ecologically sound and financially rewarding manner. We have made considerable progress during the last seven years in developing a knowledge base (from the MIPS and other studies) on the spruce budworm in the Lake States. Using the MIPS as the initial data base, short-term and long-term rating systems, which predict the amount of future damage to spruce-fir stands from budworm feeding, have been developed for the Lake States land manager (Olson et al. 1982, Lynch et al. 1984b). These systems provide land managers with additional decision-making tools (Witter and Lynch 1984). Further long-term studies on fir-budworm interactions (i.e., budworm-stand-site relationships, budworm population monitoring) are still necessary to improve our knowledge base and decision-making abilities.

Karpinski and Witter (1982) determined the number of plots (2-5) and plot size (0.05, 0.10, 0.20, 1.0 ac) required to quantify various impact parameters at a given allowable error. In general, the coefficient of variation decreased more rapidly by increasing the number of plots than by increasing plot size. The greatest reduction in the coefficient of variation occurred between 2 and 3 plots. We found that our sample scheme for the MIPS was adequate, but we recommend three 0.10 ac plots for future studies. Three 0.10 ac plots were used in our validation studies for the hazard-rating system.

It is difficult to make comprehensive statements concerning the percent allowable error of various parameters within the MIPS at the national forest, district, compartment, and stand levels. The coefficient of variation (percent allowable error) is generally much lower at the national forest level, sometimes quite variable at the district level, and usually reasonably good at the compartment or stand level. Lynch and Witter (1983a-d) compared the estimates for live trees (number/ac), percent tree mortality, live basal area, and dead basal area for additional plots sampled in each district in 1981 with the 1981 estimates from the MIPS. Comparisons were reasonably good for most estimates in districts with more MIPS plots, but some relatively large differences occurred in some districts with relatively few plots in the MIPS or where the MIPS sampled stands in that district may not have been very representative of the stands in that district. For example, tree mortality in the Sault Ste. Marie and St. Ignace Districts, based on the 1981 MIPS data was 99 and 71%, respectively. Supplementary data collected in 1981 indicated that fir mortality in these two districts may be only as high as 76 and 46%, respectively (Lynch and Witter 1983c).

Analysis of data from the MIPS indicated that the amount of variation within the data set was exceedingly large. For example, individual stands vary from little defoliation and no tree mortality to 100% fir mortality. We could have obtained more homogenous data within MIPS by: (1) sampling in just a few districts, (2) choosing only stands with a high percentage of fir, or (3) traveling the main roads and selecting stands within easy walking distance, thereby sampling relatively more stands with better drainage and fewer stands on very wet sites. Fowler and Witter (1982) reported that a

set of more homogenous stands, as just described, would probably yield less variable estimates than the estimates from the MIPS. However, the bias associated with such estimates of impact parameters for the entire spruce-fir forest could be very large. The accuracy of such estimates may be very low and the distortion of the probability statements due to bias very high. Therefore, estimates from the MIPS are probably not as precise as those based on a more homogenous set of stands. Nevertheless, they are more representative and more accurate with distinctly smaller biases. Fowler and Witter (1982) provide a detailed discussion on the accuracy and precision of impact parameters.

Hopefully, some of the extreme variation will be explained by current studies on the budworm-stand-site interactions. Intensive multiple-factor methods of site classification have been employed with success for over 50 years in Europe. Similar, but more extensive methods are widely used in Canada (Barnes et al. 1982). During 1982 and 1983, a classification system for spruce-fir stands was developed for the Ottawa National Forest. Twenty-one dryland and four wetland site units were distinguished on the basis of topographic features, soil factors of drainage and texture, and ground cover vegetation (Hix et al. 1983). Damage to balsam fir was proportionally greater by 10 to 25% on organic soils and on dryland ecosystems with somewhat poorly drained soils (Hix et al. 1984). The shallow rooting habit of balsam fir on these kinds of soils lowers the trees' ability to withstand defoliation and drought injury.

Collecting impact information is important, but very time consuming and expensive. We expect that more of the parameters required for measuring impact will be available from routine compartment inventories as forest management in the Lake States becomes more intensive. Also, a series of permanent plots which utilize pheromone traps for measuring budworm populations will be operational in Michigan's Upper Peninsula by 1985 or 1986. These changes in inventory methods for forest stands and pest populations may help considerably in reducing the cost of collecting impact data. We may further reduce the costs of gathering certain impact data by using data obtained from aerial photographs of permanent plots. Olson et al. (1982) and McCarthy et al. (1983) described the techniques that can be used to obtain impact data from 35 mm or 70 mm photography. Hopefully, comparable cost data of sampling impact from ground plot sampling and aerial photographs will be available shortly.

Technology Transfer

Technology transfer plans should precede research projects and then technology transfer actions should accompany each project (Allen et al. 1982). This helps ensure that the research is needed and that the results reach the user community in an appropriate and timely manner. Meetings with Lake States forest managers in 1977 and 1978 revealed a need for operational techniques to monitor spruce budworm damage. The Michigan Impact Plot System was established to assess budworm damage and to relate it to easily measured stand variables. Close contact was maintained between the land managers and the researchers. The University of Michigan and Michigan State University, with funding support from the CANUSA Program, became involved in 1981 in a technology transfer program for the Lake States Region (Montgomery et al. 1984b).

Needs-assessment surveys of forest managers and pest management specialists indicated that the technology transfer team should produce information packages on spruce budworm biology, insecticides, silviculture, remote sensing, and impact (Rogan et al. 1982a, b). A manual (Montgomery et al. 1983c), technical reports (Lynch et al. 1982a-d), handbooks (Flexner et al. 1983, Montgomery et al. 1982), leaflets (Lynch et al. 1984b, Montgomery et al. 1983a, b), and video tapes (Montgomery et al. 1984a) have been developed.

Specifically relating to the research work discussion under the MIPS, eight technical reports summarizing the amount of spruce budworm damage were distributed to the area's forest managers. News releases, popular articles, handbooks, and leaflets also were written to alert forest managers and landowners about the current status of the infestation and the use of short- and long-term rating systems.

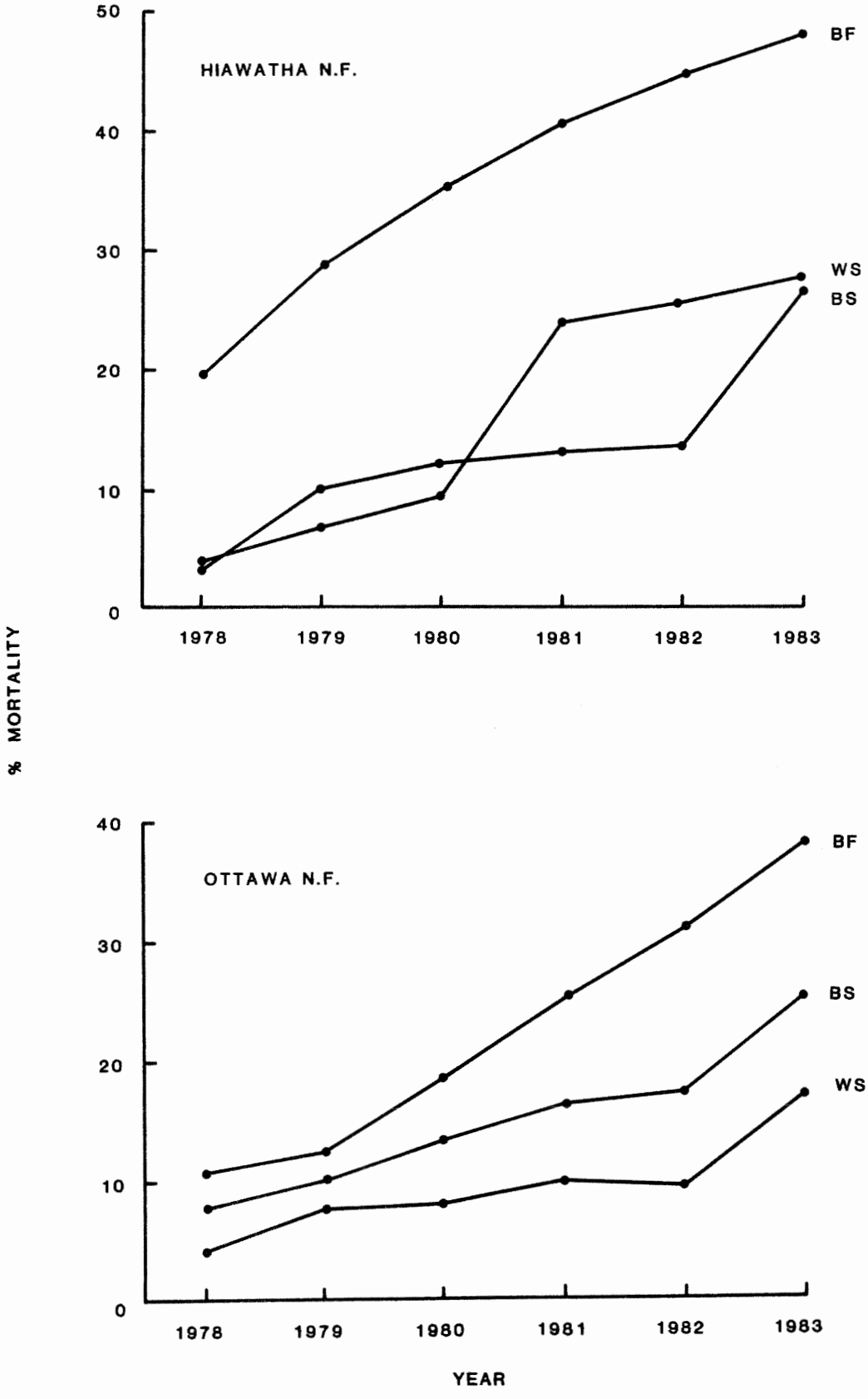


Fig. 2. Average percent mortality of balsam fir, white spruce, and black spruce on the two national forests, 1978-1983.

To test this hypothesis, decay tests were done in 1983 to determine the decay rate of wood from balsam fir with an IER of > 250 kΩ (Type A, Figure 2), and with an IER < 100 kΩ (Type B, C, D, Figure 2). Type B wood looked the same as A, but had become wet and ionized within the living tree, type C wood was ionized the same as B but visibly discolored, and type D wood was decayed by whiterot fungi in the living tree. When these four types of non-sapwood tissues from balsam fir were put in decay chambers with Haematostereum sanguinolentum, a decay pathogen of balsam fir, type B wood decayed faster than A and equivalent to C, and decay was most rapid in already decayed wood (Figure 3).

In a preliminary study done during the 1982 growing season, the IER at a depth of 4.5 cm was measured in 10 canopy trees on sites classified for growth potential by CER. Sites were classified as having a low decay potential if the IER of most trees was > 250 kΩ, or classified as high if most were < 100 kΩ. All spruce sites measured were rated as low, fir sites as half low, half high. Spruce from low decay potential sites had mostly type A non-sapwood in the butt section, fir some type A and type B, but little C and D. Fir sites rated as having a high decay potential had mostly type B, C, and D wood in the butt section. If these sites also had a low growth potential, mean CER > 12, this makes such sites a very high risk to produce fir wood because internal decay is increasing as periodic growth is decreasing.

Each combination of growth potential determined by CER, and decay potential determined by IER, will have its own risks, problems, and remedies. The measurements are rapid, simple, and quantitative. The interpretation of the measurements are not simple, and require a thorough understanding of the complex growth and decay processes operating in trees. However, progress has been made toward developing an electronic monitoring system for periodic site evaluation over time to help forest managers see declining growth and increasing internal defect when there is still time to take effective action to minimize loss.

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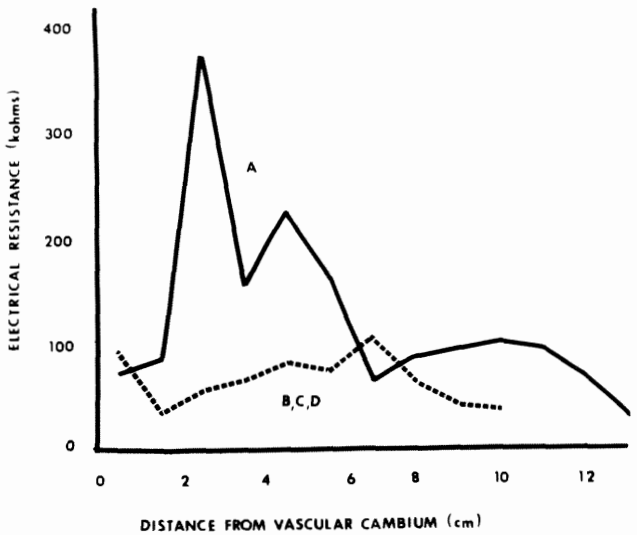

Fig. 2. Internal electrical resistance (IER) at 140 cm above ground with increasing depth from the vascular cambium. Solid line = tree from site of low decay potential with some type A wood (IER > 250 kΩ); broken line = tree with mostly type B, C, D wood (IER < 100 kΩ).

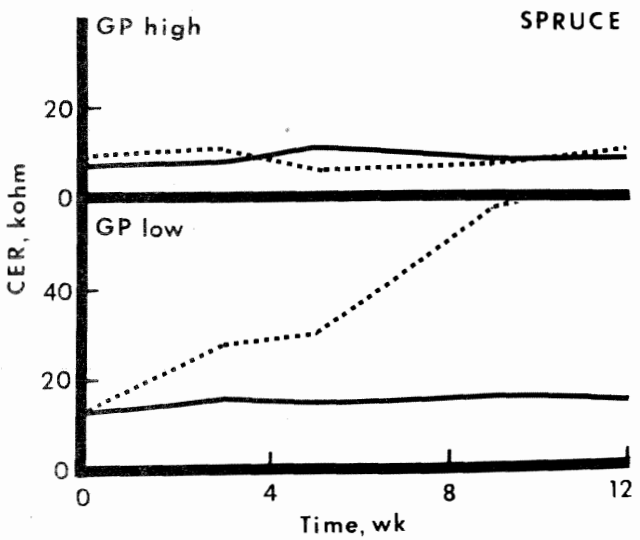

Fig. 1. Change in cambial electrical resistance during first 12 weeks after girdling of spruce trees of high growth potential (GP), CER < 10 kΩ, or low growth potential CER > 12 kΩ. Broken line = girdled trees; solid line nongirdled controls.

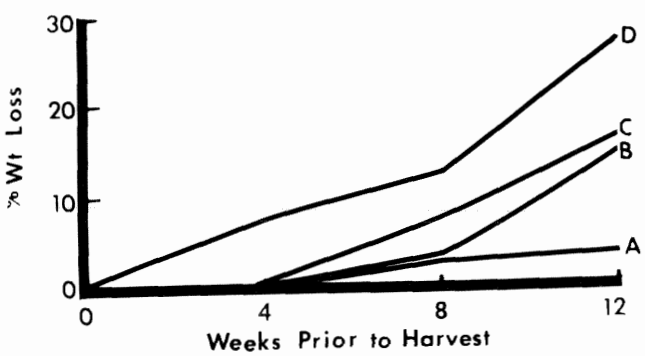

Fig. 3. Weight loss due to decay by Haematostereum sanguinolentum. A = nonsapwood with IER > 250 kΩ; B = nonsapwood with IER < 100 kΩ that looks like A; C = wood like B but visibly discolored; D = wood like B but visibly decayed by a whiterot fungus.

GROWTH RESPONSES OF BALSAM FIR DEFOLIATED BY SPRUCE BUDWORM

DALE S. SOLOMON

Principal Mensurationist
NEFES, USFS
Orono, Maine 04469

The annual defoliation of balsam fir trees by the spruce budworm produces different patterns of defoliation in different stands. These different histories produce different growth responses in the radial increment along the bole. As the reduced amount of current foliage remains on the tree to become the 1- and 2-year-old foliage, the volume growth in the upper portion of the bole is reduced. When the reduced foliage remains on the tree to become the foliage in the third or fourth age class, the volume increment in the lower bole is reduced. The results of three levels of protection and the resulting growth response are discussed. The effect of a single year of protection can be detected in increased growth response in the upper bole several years after application. Moderate protection, after defoliation, of nearly mature codominant balsam fir indicates that protection 3 out of 7 years can sustain the present level of bole volume growth without continued decline. Intensive protection after defoliation of younger dominant trees indicates that the volume growth along the whole bole can be brought back to earlier non-defoliated levels. The overall growth responses of balsam fir trees are related to the pattern of the defoliation history and the amount of foliage in the different age classes.

A major concern of forest managers is the growth response of trees in stands that are under stress. One of the most frequent stresses placed upon the spruce-fir forest in the Northeast is defoliation by the spruce budworm Choristoneura fumiferana (Clemens). Balsam fir, (Abies balsamea (L.) Mill), one of the major species in the spruce-fir forest, may retain its needles for 8 to 10 years. The budworm usually feeds on the current year's foliage, but occasionally feeds on the older foliage. Continued defoliation of the current foliage will have an influence on tree bole growth, and if severe enough may kill the tree.

A method of expressing bole growth at different locations along the bole has been presented by Duff and Nolan (1953). The radial increment at different locations along the bole, plotted over the age of cambium, has been widely used to show changes in bole growth of balsam fir caused by defoliation by the budworm (Mott et al. 1957) and also for western species (Williams 1967). These investigations have shown the growth response over the bole declines as the tree is defoliated by a single defoliation pattern. Work on Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) has shown how defoliated trees decline in growth and their radial increment responds when the spruce budworm epidemic declines (Thomson and Van Sickle 1980).

The decline in volume increment due to defoliation by the spruce budworm has been calculated for balsam fir stands (Kleinschmidt et al. 1980b) and for individual trees and stands in the East (Solomon 1983). The decline in growth response of trees with a known defoliation history may not be applicable to trees with different defoliation histories. Also, the growth response over the bole when trees within stands are protected has not been determined. Therefore, to provide the forest manager with estimates of tree growth response, dominant and codominant balsam fir trees with different defoliation and protection histories were compared.

Methods

In 1978, sixteen even-aged 0.01 hectare plots were selected on well-drained sites in northwestern Maine (Kleinschmidt et al. 1980b). The plots, located in predominantly fir stands, had diverse defoliation histories between 1973 and 1978. In 1980 and again in 1982, additional plots were located in similar areas in order to extend the range of defoliation histories, species composition, and ages of the sample plots. Each plot was selected in a portion of the stand with minimal mortality and no other disturbances. Preliminary annual defoliation estimates were made, using reports from the Maine State Forest Service and visual examination of branch samples.

On each plot the species, diameter at breast height (dbh), and crown diameter were measured and recorded. Each tree was felled and cross-section discs taken above the butt swell, at breast height, at 1.5 m intervals along the bole to the base of the crown, and then at 1.0 m intervals. Disc height and total height were measured. Along an average radius on each disc the bark thickness and annual radial increment were measured or remeasured with a MEASU-CHRON Digital Micrometer to 0.01 mm.[1]

An average branch was sampled from the third, sixth, seventh, and eighth or eleventh whorl from the top of each tree, depending upon the plot. The age at which the whorl formed was determined by sectioning and aging the bole on either side of the whorl. Foliage was removed by age class of needles for each branch; those older than 6 years were combined into one age class. The foliage was then oven dried (105°C) and weighed. The amount of defoliation was estimated

[1] The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U.S. Department of Agriculture or the Forest Service of any product or service to the exclusion of others that may be suitable.

by comparing the actual weight of each age class of foliage remaining on the sampled branch to the predicted nondefoliated weight of comparable foliage (Kleinschmidt et al. 1980a). Kleinschmidt's equations were used to predict the foliage weight for age classes 1 through 5 on each sample branch in the top half of the crown of each tree. After each age class was weighed, the predicted and measured foliage weights were summed over the sample branches for each tree. The proportion of foliage remaining was estimated by dividing the actual weight by the predicted weight, and the percent defoliation for each tree was determined. The plot defoliation was estimated as the average defoliation of the trees on the plot used in the analysis.

The annual volume increment for the past 20 years and total volume inside bark were calculated for each tree. An algorithm was used to predict volume increment and the predicted was compared to the actual volume increment for each tree. The annual volume increment, both predicted and actual, was added to the total inside-bark volume. The individual tree's growth reduction was estimated from the difference between these volumes. An average was then determined for either dominant or codominant trees in each of the different defoliation and protection histories.

Results and Discussion

The bole volume growth of balsam fir declines as the severity of the defoliation history increases (Kleinschmidt et al. 1980b). Since balsam fir can retain its foliage for 8 to 10 years, different amounts of annual defoliation result in less current foliage being produced and eventually reduce the amount of foliage available for tree growth. A model was developed to predict the amount of current foliage produced and the amount remaining in each age class (Hayslett and Solomon 1983). The reduction in the amount of foliage in the older age classes reduces bole volume growth (Solomon In Press). These results for balsam fir seem to relate different age classes of foliage to the growth of different sections of the tree.

Forest managers have sought to reduce the loss in volume growth caused by defoliation and to keep trees alive by protecting them. Protecting trees reduces budworm populations and provides for more current foliage to be passed on to successive age classes as the tree ages.

One-Time Protection

To show the growth response of trees to a single year of protection, four dominant fir trees were cut from one plot in 1978, after 5 years of defoliation with protection in 1976. The trees were 52 years old and had an average dbh of 19.4 cm. The average annual amount of foliage available for tree growth is predicted for each age class (Table 1). As the amount of defoliation caused by budworm continued to increase annually, the amount of current foliage retained each year decreased.

The reduction in foliage eventually causes a reduction in radial growth along the bole of the tree. (Figure 1). In 1974, 2 years after the start of defoliation, there is a slight decline in growth rate with a greater reduction in the upper boles. In 1976, 3 years after the start of defoliation, a more substantial reduction occurs in the lower bole near breast height. As can be seen in Table 1, 1976 is the year that the

Table 1. Predicted average annual total foliage weight in kg by classes for four dominant defoliated balsam fir trees protected one time.

Year	Average Defoliation (%)	Age Classes							
		Current	1	2	3	4	5	6+	Total[a]
1972	--	4.65	4.02	3.45	2.78	2.20	1.55	0.78	14.78
1973	57	2.10	4.50	3.85	3.12	2.30	1.60	0.92	16.30
1974	59	1.75	2.02	4.30	3.50	2.60	1.68	0.98	15.08
1975	97	0.10	1.70	1.95	3.92	2.90	1.88	1.00	13.35
1976	25[b]	3.45	0.10	1.62	1.78	3.25	2.10	1.12	9.97
1977	40	3.02	3.32	0.10	1.48	1.48	2.35	1.25	9.98
1978(Predicted)	--	----	2.91	3.20	0.10	1.22	1.06	1.40	9.89
1978(Actual)[c]	--	----	3.82	2.94	0.06	0.45	0.66	0.96	8.89

[a] Total includes 1 to 6+ age-classes

[b] Protected

[c] Estimated actual foliage weight by age classes using branch samples

Figure 1--Annual radial increment in mm at standardized heights above ground for dominant defoliated and nondefoliated balsam fir trees protected one time.

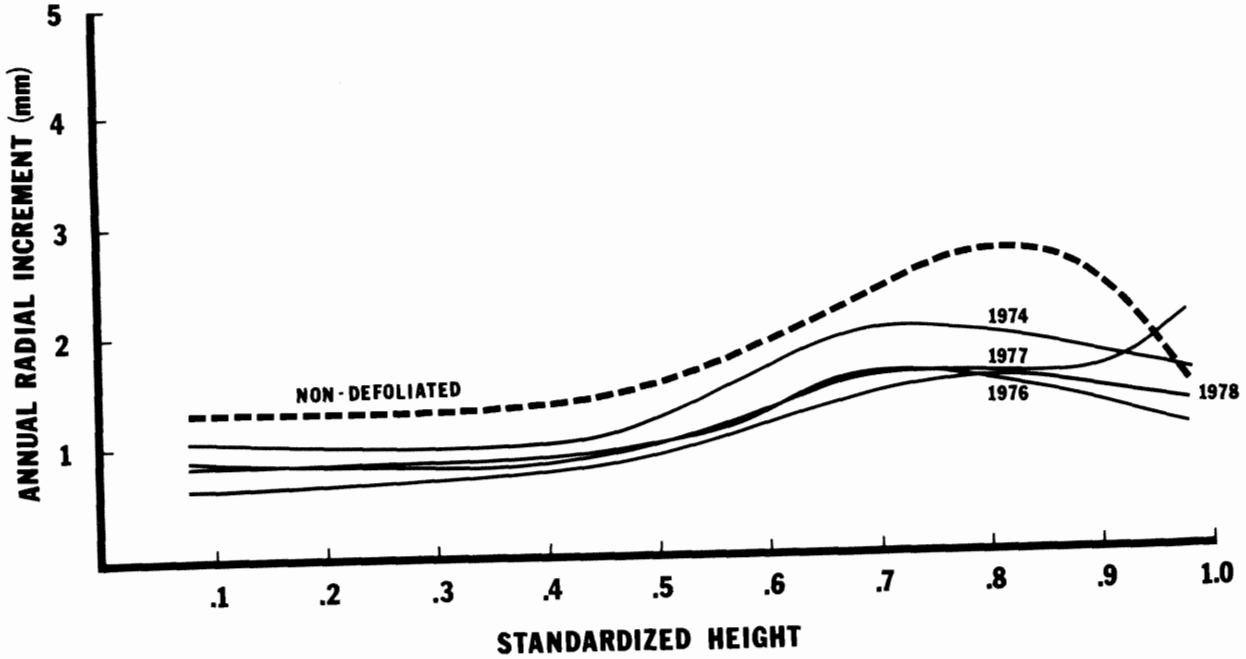

Table 2. Actual and predicted average annual volume increment and total volume for trees with different defoliation histories and protection intensitites, in thousands of cubic centimeters.

	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982
PROTECTED ONE TIME											
Defoliation (%)	--	57	59	77	25[a]	40	--				
Annual											
Actual	8483	8531	8400	8709	6762	7337	6344				
Predicted	12889	13382	13854	14291	14716	15126	15515				
Loss (%)	--	36.25	39.37	39.06	54.05	51.49	59.11				
Total											
Actual	205784	214315	222714	231423	238184	245522	251865				
Predicted	220326	233708	247562	261853	276569	291695	307210				
Loss (%)	--	8.30	10.04	11.62	13.88	15.83	18.02				
MODERATELY PROTECTED											
Defoliation (%)	--	60	80	69	53[a]	39[a]	48	81[a]	--		
Annual											
Actual	6179	6658	6680	6564	5289	4161	4474	4264	3447		
Predicted	5104	5258	5424	5599	5780	5968	6152	6347	6553		
Loss (%)	--	-26.62	-23.16	-17.24	8.49	30.27	27.28	32.83	47.39		
Total											
Actual	129968	136626	143306	149869	155158	159320	163793	168057	171504		
Predicted	123437	128695	134119	139718	145498	151466	157618	163965	170518		
Loss (%)	--	-6.16	-6.85	-7.27	-6.64	-5.19	-3.92	-2.50	-0.58		
INTENSIVELY PROTECTED											
Defoliation (%)	--	15	70	90[a]	70	86[a]	71[a]	77[a]	45[a]	27[a]	--
Annual											
Actual	6826	7055	8038	7775	6467	4417	3592	6356	10246	9043	7346
Predicted	6963	8075	9266	10494	11676	12763	13664	14300	14608	14578	14245
Loss (%)	--	12.63	13.26	25.91	44.61	65.39	73.71	55.55	29.86	37.97	48.34
Total											
Actual	66404	73459	81496	89271	95738	100155	103747	110103	120349	129392	136750
Predicted	61124	69199	78465	88959	100635	113399	127063	141363	155971	170550	184795
Loss (%)	--	-6.16	-3.86	-0.35	4.87	11.68	18.35	22.11	22.84	24.13	26.00

[a] Protected

reduced foliage from 1973 enters the 3-year-old age class. The trees were protected in 1976, but the volume increment over the whole bole continued to decline through 1976 to 54 percent (Table 2). The growth in the upper bole increased slightly in 1977 as the protected 1976 foliage entered the 1-year-old age class. The annual volume growth in 1978 declined below the 1976 level (Table 2).

The average cumulative total volume growth for the dominant trees declined 18 percent below that predicted from a continuous function based on an average of the 5 years before defoliation (Table 2). This method produced results similar to those published previously for the average of all trees on the plot (Kleinschmidt et al. 1980b).

Moderate Protection

A plot cut in 1980 was analyzed after 7 years of defoliation with protection in 1976, 1977, and 1979. The foliage on three codominant trees was modeled by age class from the beginning of defoliation in 1973 (Table 3). The trees were 52 years old and had an average dbh of 17.3 cm. The annual foliage production declined for the first 3 years and then increased in 1976 after protection. The radial growth in the lower bole for the same corresponding time was not different from the average annual radial growth during 5 nondefoliated years (Figure 2). The growth decline can be seen first in the upper bole in 1975, 2 years after the start of defoliation. In 1976, the fourth year of defoliation and the first year of protection, the growth decline was substantial over the entire bole of the tree, causing a decline in the lower bole at breast height. The annual volume increment increased considerably in 1976 and 1977 (Table 2).

After 2 consecutive years of protection in 1976 and 1977, the current and 1-year-old foliage increased. However, there was less 3- and 4-year-old foliage because of the defoliation in 1973 and 1974. Thus, in 1977, the radial increment increased in the upper bole but continued to decline in the lower bole (Figure 2). The improvement in volume growth can be seen in the years of 1978 and 1979, when the annual growth loss is less (Table 2). Although the annual volume increment increased with protection, the negative percent growth loss for the total bole continued, because of the insensitivity of the model to codominant trees. Thus the total actual volume remained larger than that predicted, starting in 1976.

In the three years from 1978 to 1980, the stand was protected once. The current foliage did not increase in 1978, but a major foliage increase occurred in the 2-, 3-, and 4-year-age classes successively. These increases correspond to the radial increment (Figure 2) and volume increment (Table 2) remaining about the same for the same period of time. This seems to indicate that the 2 years of protection kept the volume growth from declining. And protecting the current foliage in 1976 reduced the growth loss as that increase in foliage reached each succeeding age-class of needles in 1978, 1979, and 1980.

Table 3. Predicted average annual total foliage weight in kg by age classes for three codominant defoliated balsam fir trees with moderage protection.

Year	Average Defoliation (%)	Age Classes							
		Current	1	2	3	4	5	6+	Total[a]
1972	--	3.04	2.63	2.24	1.82	1.42	1.01	0.50	9.62
1973	60	1.35	2.94	2.52	2.04	1.50	1.04	0.59	10.63
1974	80	0.63	1.30	2.82	2.92	1.68	1.09	0.63	9.81
1975	69	0.60	0.61	1.25	2.56	1.90	1.22	0.66	8.20
1976	53[b]	1.01	0.58	0.59	1.14	2.12	1.37	0.73	6.53
1977	39[b]	1.76	0.97	0.56	0.53	0.94	1.54	0.82	5.36
1978	48	1.50	1.70	0.93	0.51	0.44	0.68	0.92	5.18
1979	81[b]	0.55	1.45	1.63	0.85	0.42	0.32	0.52	5.19
1980(Predicted)	--	----	0.53	1.39	1.48	0.70	0.31	0.52	4.67
1980(Actual)[c]	--	----	0.79	1.49	2.02	0.61	0.39	0.70	6.00

[a] Total includes 1 to 6+ age-classes

[b] Protected

[c] Estimated actual foliage weight by age classes using branch samples

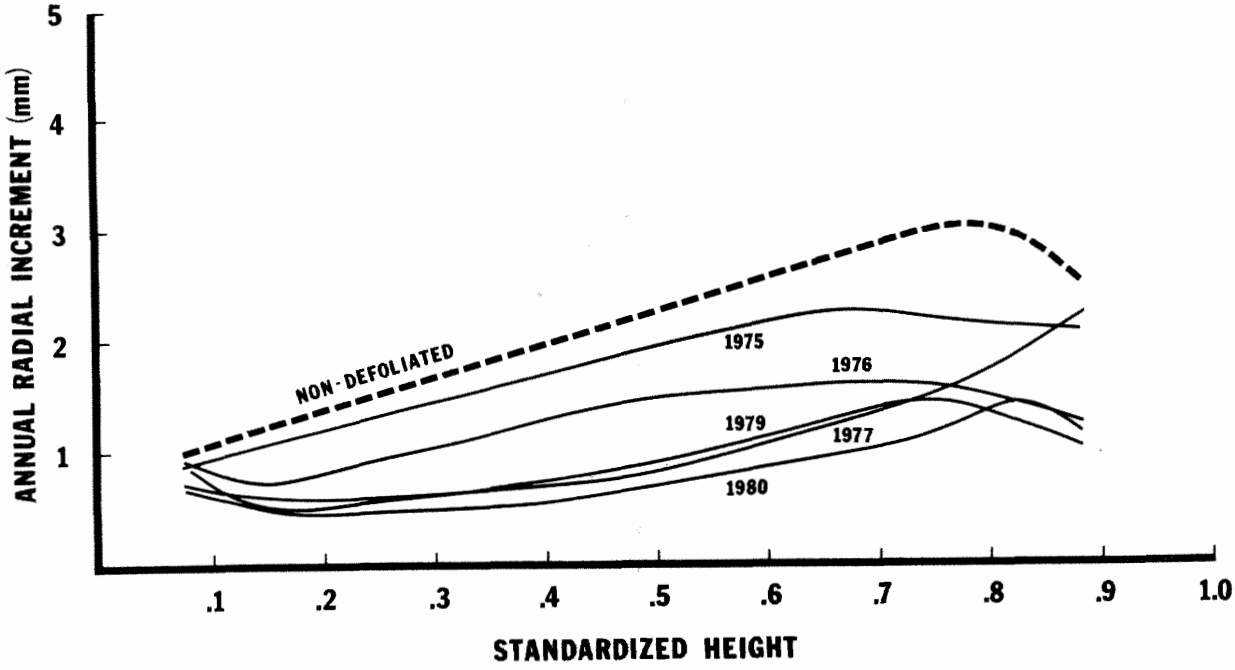

Figure 2--Annual radial increment in mm at standardized heights above ground for codominant defoliated and nondefoliated balsam fir trees moderately protected.

Intensive Protection

A plot cut in 1982 was protected for 6 years during 9 years of defoliation. The trees were 36 years old with an average dbh of 15.6 cm. The average foliage on two dominant trees is predicted by age classes starting in 1973 (Table 4). The defoliation of the current foliage in 1973 and 1974 caused a reduction in the amount of foliage that remained on the tree to become the foliage in the third- and fourth-year age class 4 years later.

The decline in current foliage 4 years after the start of defoliation is similar to that in the previous categories of protection. For these years the levels of defoliation are moderate, and as the defoliation continues the resulting growth response declines, first in the upper bole and then in the lower bole (Figure 3). In younger trees the crown covers most of the bole and a growth response over the whole bole would be noticed (Piene 1981). Similarly, in older trees the growth decline occurs in the crown but does not become distinguishable until several years later. The apparent relationship between percent defoliation and increment (Alfaro et al. 1982) may not be accurate, depending on how and where it is measured.

In 1976, the radial increment is almost constant along the entire bole. The radial growth at breast height is about the same for 4 years after the start of defoliation because defoliation is low in the first year and a sizeable amount of foliage remains to become the third age class of foliage in 1976 (Table 4).

The decline in radial increment at breast height occurred in 1977, 4 years after the start of defoliation. The first protection in 1975 had minimal influence on tree growth (Severe defoliation can occur within a protection zone because of wind drift, timing, weather, etc.). The increased foliage in 1976, when defoliation was less, resulted in an increase in radial growth in the upper bole in 1977 and 1978. The average annual volume increment suffered considerable loss through 1978 because radial growth in the lower bole continued to decline (Table 2).

Continuous protection started in 1977, but the defoliation remained high (Table 4). The slight increase in foliage in the 1- and 2-year-old age classes produced an increase in radial increment (Figure 3). By 1978, after 2 years of continuous protection, the growth in the upper bole had increased and the radial increment in the lower bole continued to decline. In 1979, the lower bole growth increased after remaining current foliage increased in 1976, and survived to become the needles in the third age class. Protection during 1979-81 increased the amount of current foliage, which resulted in an increase in foliage remaining in the third and fourth age classes in 1980 and 1981 (Table 4). The corresponding annual increment continued to increase in the upper bole as well as the lower bole when more foliage remained to occupy older age classes.

Table 4. Predicted average annual total foliage weight in kg by age classes for two dominant defoliated balsam fir trees with intensive protection.

Year	Average Defoliation (%)	Age Classes							
		Current	1	2	3	4	5	6+	Total[a]
1972	--	1.12	0.95	0.79	0.63	0.46	0.33	0.32	3.48
1973	15	1.07	1.08	0.91	0.72	0.52	0.34	0.39	3.96
1974	70	0.41	1.03	1.03	0.82	0.60	0.38	0.41	4.27
1975	90[b]	0.14	0.41	0.99	0.94	0.68	0.43	0.45	3.89
1976	70	0.37	0.13	0.38	0.90	0.78	0.50	0.51	3.20
1977	86[b]	0.14	0.36	0.13	0.34	0.74	0.56	0.59	2.72
1978	71[b]	0.32	0.14	0.35	0.12	0.28	0.54	0.67	2.10
1979	77[b]	0.24	0.31	0.13	0.31	0.10	0.21	0.66	1.72
1980	45[b]	0.60	0.23	0.30	0.12	0.26	0.07	0.34	1.32
1981	27[b]	0.68	0.58	0.22	0.27	0.10	0.19	0.14	1.50
1982(Predicted)	--	----	0.66	0.56	0.20	0.22	0.07	0.07	1.78
1982(Actual)[c]	--	----	2.61	1.53	0.56	0.37	0.12	0.03	5.22

[a] Total includes 1 to 6+ age-classes

[b] Protected

[c] Estimated actual foliage weight by age classes using branch samples

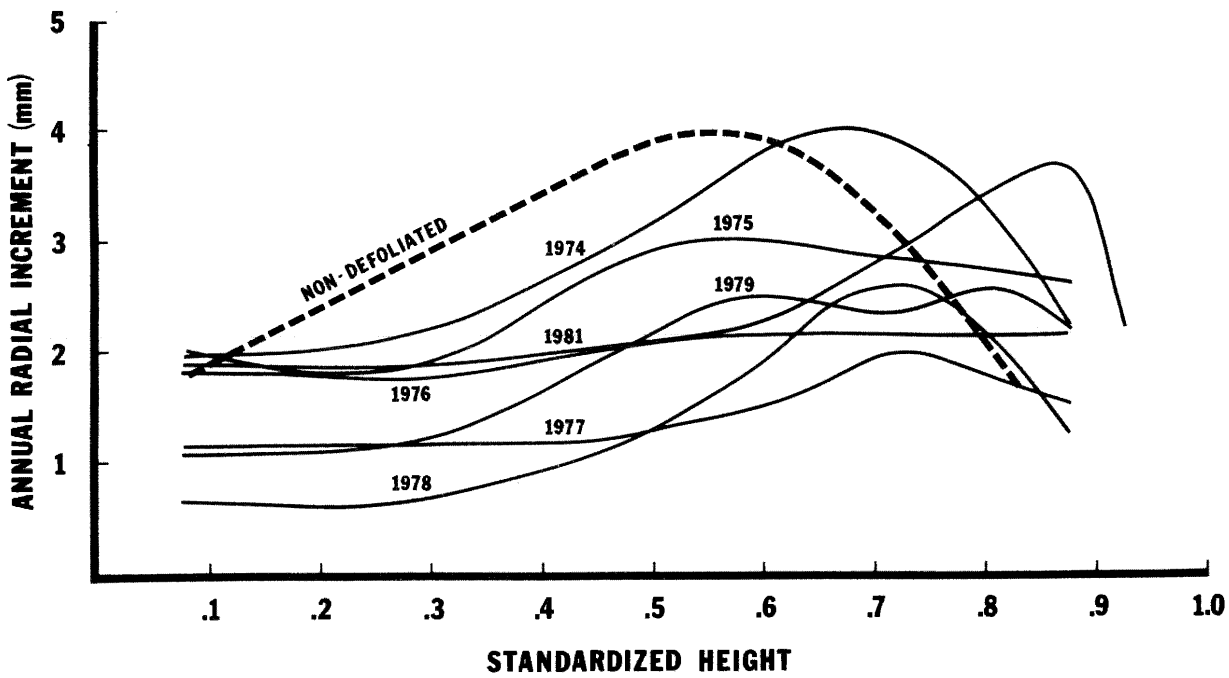

Figure 3--Annual radial increment in mm at standardized heights above ground for dominant defoliated and nondefoliated balsam fir trees intensively protected.

The annual volume increment continued to decline as the result of defoliation up to 1978; then the increase in foliage in the older age-classes caused an increase in growth (Table 2). The total volume increment remained about the same, reflecting the loss that had occurred previously. However, this increase in volume increment prevented a continued loss of total bole volume growth. Even after 4 more years of defoliation, the total bole volume loss reached 26 percent with protection.

Conclusion

The bole growth of balsam fir trees is related to the amount of foliage available. Since balsam fir can retain its foliage for 8 to 10 years, defoliation of the current foliage usually does not have a significant effect on tree growth that year or the next. In fact, reduced growth in the upper bole is only apparent 2 to 3 years after defoliation, when the reduced foliage has entered the 1- or 2-year-old age classes. Similarly, the radial increment in the lower bole is reduced when the reduced foliage reaches the third and fourth age classes.

One-time protection of full-grown, dominant balsam fir increases the radial increment in the upper bole, but has small effect on the growth decline at breast height. The use of moderate protection on full-grown codominant trees indicates that the decline in bole volume growth can be reduced and the level of growth maintained. Intensive protection of half-grown dominant balsam fir trees indicates that not only can the decline in bole volume growth be reduced, it can even be reversed and growth restored to previous levels. The growth response to continued protection happens first in the upper bole and then in the lower bole as the increased foliage survives enter the older age classes.

As the annual defoliation of balsam fir trees continues, the reduced amounts of current foliage become the foliage in each successive age class. When this reduction reaches the younger (1- and 2-year-old) age classes, the bole volume growth in the upper bole is reduced; when the same foliage enters the 3- and 4-year-old age classes, the volume growth in the lower bole is reduced. Maintaining a level growth rate or restoring a previous growth rate can be accomplished by planned regulation of protection. The protection of current foliage increases the amount of current foliage that is passed along to each succeeding age class.

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PREDICTING THE RISK OF SPRUCE BUDWORM DAMAGE USING HAZARD AND VULNERABILITY RATING SYSTEMS

David A. MacLean

Research Scientist, Canadian Forestry Service, Maritimes Forest Research Centre, P.O. Box 4000, Fredericton, N.B., Canada

Seventeen hazard and vulnerability rating systems available for predicting the risk of spruce budworm damage in eastern Canada and the United States are reviewed and discussed. Hazard rating is short-term (often annual) mortality risk assessment that has been used extensively in planning annual spray operations. Vulnerability rating is a longer-term assessment of the risk of damage based on characteristics of stands, that is used primarily in priorizing stands for harvesting. With the increasing usage of computer-based forest inventory mapping systems (often termed Geographic Information Systems), rating the vulnerability of individual stands as a function of stand characteristics becomes relatively easy for large forest areas.

Management of a forest during a spruce budworm (Choristoneura fumiferana Clem.) outbreak must involve judgements of the relative vulnerability (or risk of mortality) of different stands within the region. Stands vary with respect to species composition, age structure, site, etc., and all of these factors influence the degree of growth losses and tree mortality caused by budworm defoliation. Effective management should include directing harvesting operations to the most vulnerable stands to limit losses, concentrating protection (insecticide application) activities on the most vulnerable stands, and the use of silvicultural techniques to reduce damage. First, however, one must be able to determine the relative vulnerability of stands.

In general terms, there are some clear differences in vulnerability to budworm damage due to species and age-class of stands (MacLean 1980). Balsam fir (Abies balsamea (L.) Mill.) trees and stands are more vulnerable than spruce (Picea sp.) trees and stands. White spruce (Picea glauca (Moench) Voss) and red spruce (P. rubens Sarg.) are more vulnerable than black spruce (P. mariana (Mill.) B.S.P.). Mature and overmature stands are more vulnerable than immature stands. To give an idea of the damage to be expected in different types of stands, MacLean (1980) found average tree mortality levels of 85% in mature fir stands, 42% in immature fir stands, 36% in mature spruce stands, and 13% in immature spruce stands, based on plots from a number of studies. In essence, this information could be considered a very simple vulnerability rating system, which could be used to select stands for treatment; more sophisticated, quantitative vulnerability rating systems are available, however.

In this paper, I will review the hazard and vulnerability rating systems that have been developed for use in eastern Canada and the United States.

Hazard Rating versus Vulnerability Rating - Is There a Difference?

Although the terms hazard rating and vulnerability rating have been used interchangeably and synonymously with "risk rating" in some studies, I am reserving a specific usage for each term in this paper, based on the commonly accepted usage in eastern Canada and Maine.

Hazard rating systems are used on an annual basis to predict severe budworm damage and probable tree mortality, primarily as a guide in formulating spray operations. These systems include estimates of budworm population level for specific areas, usually in terms of egg-mass density. Most hazard rating systems are based on methodology originated by Webb et al. (1956).

In contrast, vulnerability rating systems are used to rate the relative vulnerability to spruce budworm damage of different areas of forest, primarily for priorizing stands for harvesting or management planning. In other words, vulnerability rating indicates the relative level of tree mortality which can be expected from a spruce budworm outbreak, as a function of stand characteristics. Vulnerability rating systems are based entirely on characteristics of the forest; they do not include an estimate of annual budworm population level, but implicitly assume a general outbreak scenario. Vulnerability rating systems date from those of Westveld (1945) and Balch (1946). In this paper, I have further divided vulnerability rating systems into two types: (1) empirical systems based on intuitive observations which produce relative ratings of stands, and (2) quantitative systems which predict the amount of mortality as a function of stand characteristics, through the use of regression or multiple regression equations.

Hazard Rating Systems

Hazard rating systems have been used extensively in Maine, the Maritime Provinces, Newfoundland, Quebec, and Ontario as an aid in planning spruce budworm spray operations. The various hazard ratings used in different jurisdictions have been described by Dorais and Kettela (1982). Most are based on the methodology of Webb et al. (1956), and differ only in detail. The one exception to this is the system used in Quebec, where hazard maps are constructed by overlapping a 4-yr sequence of defoliation maps and the current egg-mass infestation map (Hardy and Dorais 1976).

Calculation of hazard rating is shown in Table 1. Hazard values are based on data collected annually from aerial surveys and ground sampling points. Each value represents a composite estimate of current defoliation, previous defoliation, tree vigor, and budworm egg-mass density. The summed values of the various combinations of possible hazard conditions range from 0 to 20, and are rated as low (1-7), moderate (8-10), high (11-14), and extreme (>15) (Webb et al. 1956). Protection was originally applied in New Brunswick under conditions of high hazard (Webb 1955), but this has evolved into the current policy of protection under moderate or higher hazard (Dorais and Kettela 1982).

Table 1. Hazard rating systems are designed to predict severe budworm damage and probable tree mortality, as a guide in formulating spray operations (Webb et al. 1956, Dorais and Kettela 1982). Hazard is computed by summing values for estimates of current defoliation, previous defoliation, tree vigor, and number of budworm egg masses

	Tally code	%	Hazard rating
(1)	Current defoliation		
	0	0	0
	T-2	1-25	+1
	3-6	26-65	+2
	7-10a	66-100	+3
	10b	100+	+4
(2)	Previous damage or loss of old needles		
	0	0	0
	L (light)	1-25	+3
	M (moderate)	26-65	+6
	S (severe)	66-100	+9
(3)	Tree vigor		
	P (poor)		+2
	F (fair)		0
	G (good)		-2
(4)	Egg masses per 10 m² of foliage		
	0		0
	1-108		+1
	109-260		+2
	261-434		+3
	435-1086		+4
	1086+		+5

Sum of hazard rating values	Hazard
0-6	Low
7-10	Moderate
11-14	High
15+	Very high

Note: Hazard rating systems used in the Maritime Provinces, Newfoundland, Ontario, and Maine are all based on Webb et al. (1956), but vary in detail. The above system is that used in the Maritime Provinces (Dorais and Kettela 1982).

Empirical Vulnerability Rating Systems

Empirical vulnerability rating systems are summarized in Table 2. Eight systems have been developed for rating the vulnerability of stands or regional areas of forest, while two individual tree rating systems have been developed for classifying trees in selective cutting.

The 8 stand or regional vulnerability rating systems are generally quite similar, and provide an estimate of vulnerability in from three to five relative classes (Table 2). All systems are primarily based on the relative amount of balsam fir and (or) the maturity of fir, the most vulnerable species. Other factors, which have been included in specific rating systems, include the proportion of fir in the stand, the relative crown position of fir and hardwoods, the volume of spruce, tree vigor, stand density (or crown closure), stand size and isolation, topography, and climate. Calculation of vulnerability generally involves using tables or formulae to assign numerical values to the various factors, summing the rating, and translating the numerical value into a specific vulnerability class. Although the rating systems are described in general terms in Table 2, it will be necessary in many cases for a user to refer to the original reference in applying a specific rating system to an actual area of forest.

To provide a better idea of the use of these systems, the most recently developed "vulnerability index" (Blais and Archambault 1982, MacLean 1982) is described in detail in Table 3. This rating scheme was developed by Canadian Forestry Service scientists from Ontario, Quebec, the Maritimes, and Newfoundland. It was designed to use presently available forest inventory data, and was meant to be used at a regional, or forest management unit, level. Calculation of the vulnerability index is based on the combined volume of fir and white spruce per unit area, the maturity of fir, the volume of black spruce and red spruce, and a climatic rating based on temperature and precipitation (Table 3). Four vulnerability classes (low, moderate, high, and very high) were defined following testing of the vulnerability index on forest units in several regions (Blais and Archambault 1982, MacLean 1982). Results of applying the vulnerability index to the province of New Brunswick, divided into a grid of 80 units, are shown in Figure 1. Testing of the index showed that the numerical ratings were in agreement with the actual fir mortality in over 90% of the management units in Quebec (Blais and Archambault 1982), and that the results in New Brunswick and Nova Scotia compared well with current knowledge of vulnerability in the region (MacLean 1982). The vulnerability index shows considerable potential as a management tool, although some forest managers have expressed the need for a comparable system for use at the level of individual forest stands. One recent attempt to design such a system is described in a later section of this paper.

Table 2. Summary of empirical vulnerability rating systems for predicting the risk of spruce budworm damage in eastern Canada and the United States. Vulnerability rating systems which predict the amount of mortality for different stands are presented in Table 4

Region	Reference	Description of vulnerability rating system
Stand or regional rating systems - United States		
Northeastern U.S.	Westveld (1945)	Vulnerability = volume bF (cords/ac) x BA average bF (in^2). Vulnerability was classed as low (20-99), medium (100-249), and high (>250).
Maine	McLintock (1949)	Vulnerability rated as low, medium, or high on the basis of fir volume per acre and maturity. High vulnerability was $\geq$ 4.0 cords/ac of mature fir.
Michigan, Minnesota	Graham (1956)	Vulnerability rated in 5 classes based on maturity of fir and relative crown position of fir and hardwoods.
Lake States	Bean and Batzer (1956)	Vulnerability rated in 5 classes based on age and volume of spruce-fir, proportion of fir, size of stand, and vigor.
Stand or regional rating systems - Canada		
New Brunswick	Balch (1946)	Vulnerability rated as low, moderate, or high, with highly vulnerable stands containing > 8 cords/ac, over half of which was fir.
New Brunswick	Morris and Bishop (1951)	Vulnerability rated in 4 classes as a function of stand density (crown closure), species composition (% fir), and maturity (height of softwood).
New Brunswick	van Raalte (1972)	Vulnerability rated on the basis of species composition, stand age - height, stand density, isolation, and topography.
Eastern Canada	Blais and Archambault (1982) MacLean (1982)	A numerical vulnerability index was calculated based on volume of fir and white spruce, maturity of fir, volume of red spruce and black spruce, and climate (see Table 3).
Individual tree rating systems		
Northeastern U.S.	McLintock (1948)	Rating of relative risk of damage for trees on a specific site, as expressed by growth rate. Individual trees are rated for crown class, crown ratio, and vigor.
Northeastern U.S.	Westveld (1954)	Individual tree "vigor-resistance" rating based on maturity, dominance, and crown class. Designed to be used in classifying trees for selective cutting.

The individual tree vulnerability rating systems of McLintock (1948) and Westveld (1954) originated in the northeastern United States, and were designed to rate the relative risk of damage for trees on a specific site. Both systems are based on factors associated with tree growth rate, including crown class (or dominance), crown ratio, vigor, and maturity (Table 2). This type of system, which acts as a guide for selecting trees to cut or retain in individual stands, should be used in managing uneven-aged woodlots or stands. Westveld (1954) in particular advocated selective cutting techniques to make spruce-fir stands more resistant to spruce budworm outbreaks.

Table 3. Calculation of the vulnerability index (Blais and Archambault 1982, MacLean 1982) involves assigning numerical ratings to four components, and then determining a composite index, as shown below

(1) Combined volume of fir and white spruce (m^3/ha)

	Rating
1-6	1
7-13	2
14-20	3
21-27	4
28-34	5
35-41	6
42-48	7
49-55	8
56-62	9
63+	10

(2) Percentage of mature fir (>60 years old)

	Rating
1-20	1
21-40	2
41+	3

(3) Combined volume of black spruce and red spruce, using the same numerical rating scale as for fir and white spruce (above). This factor is included only if the fir-white spruce volume is $\geq$ 27 m^3/ha.

(4)

Climate	Rating
warm-dry	8
warm-wet	4
cool-dry	4
cool-wet	0

where
warm = mean annual temperature of 2.5°C or more
cool = mean annual temperature below 2.5°C
dry = precipitation of 900 mm/yr or less
wet = more than 900 mm/yr

Vulnerability Index = (Volume rating bF-wS x Maturity rating bF) + Volume rating rS-bS + Climate rating

Vulnerability Index	Vulnerability Class
0-7	Low
8-15	Moderate
16-24	High
25+	Very high

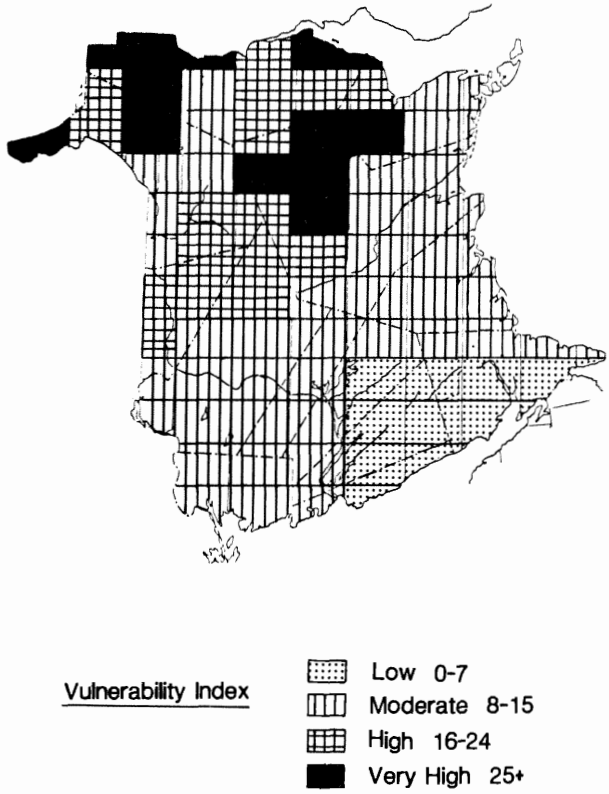

Figure 1. An example of application of the vulnerability index (described in Table 3) to 1:50,000 map sheet areas of New Brunswick (from MacLean 1982).

Quantitative Vulnerability Rating Systems

Quantitative vulnerability rating systems, which relate the amount of mortality caused by spruce budworm damage in different types of stands to stand characteristics, are summarized in Table 4. Batzer (1969) developed the first system of this type, based on data from 23 stands in Minnesota, which predicted percent dead fir basal area as a function of percent spruce basal area, percent nonhost basal area, and fir basal area (ft^2/ac). This equation explained 56% of the variability in mortality among stands. Batzer and Hastings (1981) derived a similar equation based on an additional 35 stands in Minnesota, which predicted dead fir basal area from fir basal area and percent nonhost basal area, and explained 87% of the variability in mortality. Lynch *et al.* (1984) carried out analyses of mortality data from 24 and 41 stands in the eastern and western Upper Peninsula of Michigan. The equation for the eastern stands was similar to that of Batzer and Hastings (1981), except that "aspen" (*Populus* spp.) was substituted for "nonhost species", but the regression for the western Michigan stands predicted dead fir as a function of fir basal area, percent fir in stand (based on number of stems), and an index of the stand position on an east-west gradient (Lynch *et al.* 1984).

MacLean (1980) carried out a similar analysis, based on the combined data from a large number of previously published studies. Multiple regression analyses relating percent fir and spruce mortality to up to four independent variables failed to show strong relationships (R^2 or total explained variance < 50%), however, MacLean (1980) derived relationships between mortality in terms of basal area and the initial basal area of host species present. Four equations were

constructed, for mortality in mature fir stands with < 20% hardwoods, mature fir stands with > 20% hardwoods, immature fir stands, and mature spruce stands (Table 4). This analysis indicated that mature fir stands suffer consistently heavy mortality that often approaches 100%, a hardwood component in mature fir stands reduces the fir mortality slightly, and immature fir and mature spruce stands suffer lower, more variable mortality than mature fir stands (MacLean 1980). Data available from a recent study of spruce mortality in New Brunswick (MacLean et al. 1984) corroborate results of MacLean (1980), and indicate that typically one-quarter to one-half of the basal area or volume in spruce stands can be expected to die during an uncontrolled budworm outbreak. It would seem that our best model of tree mortality caused by spruce budworm, at least in a general forest management sense, is that of a constant proportion of the host basal area or volume (i.e., a linear relationship). This follows for both balsam fir and spruce, but the proportion of a stand that can be expected to die during an outbreak varies considerably between these two species types.

In addition to the quantitative vulnerability rating systems in Table 4, a useful method for assessing current levels of spruce budworm damage from small-format aerial photographs (35-mm color positives) has been developed by McCarthy et al. (1983). A damage severity rating (four classes from low to severe) is obtained for individual stands based on photo-interpreted estimates of defoliation of living spruce and fir, and proportion of tree mortality in the stand. A test of the method showed that photo interpretation of forest damage condition matched ground inspection in seven out of eight stands surveyed (McCarthy et al. 1983). A self-instruction manual (Olson et al. 1982) is available as a training tool for those interested in spruce budworm damage assessment from small-format aerial photos.

Table 4. Summary of quantitative vulnerability rating systems that predict the amount of mortality caused by budworm damage in different types of stands

Region	Reference	Equation	R^2	n
Minnesota	Batzer (1969)	% Dead bF BA[a] = 70.144 + 0.529 (% spruce BA) - 0.636 (% nonhost BA) - 0.272 (bF BA in ft^2/ac)	0.56	23
Minnesota	Batzer and Hastings (1981)	Dead bF BA in ft^2/ac = 0.97 (bF BA in ft^2/ac) - 0.42 (% nonhost BA) - 4.1	0.87	35
Michigan[b]	Lynch et al. (1984)	(1) Dead bF BA in m^2/ha = 1.009 + 0.868 (bF BA in m^2/ha) - 0.081 (% aspen BA)	0.90	24
		(2) Dead bF BA in m^2/ha = 0.255 (bF BA in m^2/ha) - 0.154 (% bF in no. stems) + 0.270 (stand position on east-west gradient)	0.58	41
Eastern Canada[c]	MacLean (1980)	(1) Dead bF BA in m^2/ha = 1.00 (bF BA in m^2/ha) - 1.21	0.98	26
		(2) Dead bF BA in m^2/ha = 0.76 (bF BA in m^2/ha) + 0.47	0.93	11
		(3) Dead bF BA in m^2/ha = 0.59 (bF BA in m^2/ha) - 1.88	0.62	21
		(4) Dead spruce BA in m^2/ha = 0.31 (spruce BA in m^2/ha) + 0.89	0.54	13

[a]Percent balsam fir (bF) basal area (BA) in dead trees (arc sine transformation).

[b]Equations (1) and (2) from Lynch et al. (1984) are for stands on mineral soils in the eastern and western Upper Peninsula of Michigan, respectively.

[c]Equations from MacLean (1980) are linear regression relationships of fir and spruce mortality (in terms of basal area) versus fir or spruce basal area, that were derived from a summary and reanalysis of data in the literature. Equations (1) to (4), respectively, represent mature fir stands with < 20% hardwoods, mature fir stands with > 20% hardwoods, immature fir stands, and mature spruce stands.

Vulnerability Rating and Harvest Scheduling Based on Stand Yield Projection

When the vulnerability index concept (MacLean 1982) was presented to forest managers in New Brunswick, it became apparent that while the index might have use as a general tool, there was a strong need for a system to rate the vulnerability of individual stands, and schedule the harvest progression of stands based on both vulnerability and their natural rate of decline due to overmaturity. A harvest scheduling/vulnerability rating system has subsequently been developed in New Brunswick (Erdle et al., in preparation), which quantifies stand vulnerability in terms of expected volume losses during a spruce budworm outbreak. This system calculates two future yield projections for each stand in a management area, which represent protected (budworm spraying) and uncontrolled budworm outbreak (growth loss and mortality) situations. These two yield projections are then compared, and vulnerability is calculated as the difference in yield (cubic metres per hectare) between the protected and budworm-influenced stand projections at a given point in time. A harvest schedule for stands in the management area is determined as a function of both losses of yield due to stand overmaturity, and vulnerability. The method couples the New Brunswick Department of Natural Resources Geographic Information System, a wood supply model, and a simple stand development model to derive and produce a harvest schedule map that is compatible with a chosen harvest level (based on sustainable yield). The computing power of the Geographic Information System enables application of the technique to forest holdings of 100 000 ha or more (Erdle et al., in preparation).

The procedure for establishing vulnerability to budworm is as follows. First, forest structure and stand yield data are compiled for the area of interest. This includes determining the spruce and fir proportions and age structure of each stand in the management area (e.g., proportions of immature, mature, and overmature spruce and fir). Secondly, the development of each stand is then projected for a 30-year period, assuming a continued protection program (control conditions), based on user-specified yield curves for different stand types and different spruce-fir components. Thirdly, the development of each stand is projected assuming a budworm outbreak and no protection, based on explicitly defined levels of growth loss and mortality for specified budworm outbreaks or defoliation conditions. These projections use the methodology outlined in MacLean and Erdle (1984); differing growth loss and mortality levels are applied to balsam fir and spruce in immature and mature stands. Fourth, the vulnerability to budworm is calculated for each stand as the difference between the yields of the control stand projection and the budworm yield projection. Note that in this system, vulnerability of a specific stand is not constant but varies with stand development and the level of budworm damage. Lastly, all stands in the management area are ranked with respect to (1) the level of vulnerability, and (2) the rate of natural deterioration due to overmaturity, or 5-year volume losses (cubic metres per hectare) under control conditions. These rankings are then used to derive the harvest schedule for individual stands, i.e., which stands should be harvested in the 0-5 year period, 5-10 year period, etc.

The approach of using stand yield projections to rate vulnerability of individual stands appears to have considerable potential as a management tool. This method will allow managers to combine harvest scheduling, vulnerability rating, and protection (spray) planning into an integrated forest management system (Erdle et al., in preparation). Protection can then be directed to where it is most needed and not wasted on stands scheduled for harvest in the near future. Similarly, stands that are most vulnerable or most severely damaged can be identified and harvested first to limit losses and to obviate protection measures. Perhaps most importantly, both vulnerability to budworm and results of protection activities can be evaluated in terms of expected stand yields and timber supply.

Summary and Conclusions

Seventeen hazard and vulnerability rating systems are available for estimating the risk of tree mortality and spruce budworm damage in areas ranging from Newfoundland to Minnesota and Michigan. In general, hazard rating may be thought of as a short-term, mortality risk assessment that is used primarily in planning annual spray operations, whereas vulnerability rating is a longer-term comparison of the risk of damage based on characteristics of stands. Hazard rating has been used extensively in eastern Canada and Maine. Vulnerability rating has been used to a certain extent in some areas, but appears to have much more potential use in forest management, particularly with the increased usage of computer-based forest inventory mapping systems. Calculation of the vulnerability of all individual stands in large management areas (100 000 ha or more) of forest can be accomplished easily using computer-based inventory systems.

Whereas hazard rating combines annual estimates of budworm population level, current and previous damage, and tree condition to forecast future damage, vulnerability rating is based solely on measureable characteristics of stands. Vulnerability rating therefore implicitly assumes that a general, "average" budworm outbreak occurs in all stands. It is important to realize that vulnerability rating can only produce a general, "average" estimate of tree mortality and budworm damage for stands. To the extent that budworm defoliation in an actual stand varies from that of the "average", assumed outbreak, mortality or vulnerability will also vary. That is, if the budworm outbreak is less severe in one of two otherwise identical stands, the level of tree mortality in that stand will also be less, but

vulnerability would be predicted to be similar. This caveat applies to both empirical and quantitative vulnerability rating systems; these systems should be used to provide a comparative rating of the risk of damage in different stands or management units of forest, rather than an absolute estimate of expected tree mortality for specific stands.

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DROPLET DEPOSIT FROM AERIAL APPLICATIONS OF DIFFERENT PESTICIDE FORMULATIONS

A. Sundaram, K.M.S. Sundaram, B.L. Cadogan

Research Scientists
Forest Pest Management Institute
Canadian Forestry Service
Environment Canada
1219, Queen Street East
Sault Ste. Marie, Ontario
P6A 5M7

Abstract

Spray deposit was measured on conifer foliage and Kromekote® card/glass plate units following aerial applications of nine pesticide formulations under different conditions. With the oil-based mixtures, the non-volatile medium had a higher viscosity and provided a greater deposit. Results with the water-based mixtures were variable because of the presence of different ingredients and application conditions.

Introduction

In aircraft application of pesticides for spruce budworm control, formulation properties and meteorological conditions influence the behaviour of the sprayed material from the point of emission to the target level and its deposition on the target surface (Smith and Burt 1970; Ware *et al.* 1970; Butler *et al.* 1969; Burt and Smith 1974; Barry *et al.* 1977).

Spray droplets of formulations containing volatile ingredients undergo in-flight evaporation resulting in decreased droplet sizes and deposit of the sprayed material (Seymour 1969; Joyce and Beaumont 1978). Viscosity and surface tension are known to affect the droplet size spectrum of a liquid during atomization (Yates and Akesson 1973). The efficiency of spray deposition in forest tree canopies would therefore depend indirectly on formulation properties, if the spray delivery conditions, crop canopy and meteorological factors were to remain the same in different applications. The influence of chemical structure has also been demonstrated on increased target deposition and decreased off-target deposit of sprays (Kaupke 1965; Reimer *et al.* 1966). The present paper provides deposit data obtained from aerial spray trials of four aminocarb and two fenitrothion formulations, one blank formulation and two *Bacillus thuringiensis (B.t.)* formulations. The objective is to understand the role of formulation properties, application conditions and meteorological factors on spray droplet spectra, droplet density (droplets/cm^2) and spray volume deposits per unit area of crown foliage and ground sampling units.

Materials and Methods

Details on spray formulations, experimental blocks, sample trees, spray application conditions and meteorological factors are given in Tables 1, 2 and 3.

The ground sampling units used were the Kromekote® card/glass plate system developed by Randall (1980). These were placed in the clearing of about 5 to 6 m radius made around each sample tree. The trees were chosen to be of nearly uniform canopy size, height (∿12 to 14 m) and DBH (∿15 to 18 cm). For the June experiments, foliage of the previous year's growth was sampled randomly from the mid-crown at 1 h after spraying. For the August experiment however, mature foliage of the same year was sampled. The ground sampling units were also collected at 1 h after spraying. All samples were transported immediately to the mobile laboratory in the field where the foliage was frozen at -20°C. The glass plates were eluted with a suitable solvent and the eluates were stored in bottles away from heat and sunlight.

At the end of the field trials, the samples were transported to the FPMI laboratory, and the glass-plate extracts were analyzed by spectrofluorometry for obtaining the spray volume deposit per unit area (Tables 2 and 3). The Kromekote® cards were examined by microscopy to evaluate droplet stain sizes and droplet density. Spread factor was determined for the spray mixes to convert the stain sizes into the corresponding aerodynamic droplet sizes before evaluating the size spectrum, number and volume median diameters (NMD and VMD) and maximum diameter (Dmax) (Tables 2 and 3). Foliage samples were homogenized with a suitable solvent, subjected to a column cleanup procedure and concentrated for the determination of the AI by GLC according to the procedures (Sundaram 1974; Szeto and Sundaram 1980). For SPA-3409, *B.t.I* and *B.t.II*, the GLC method could not be used since they contained no chemical insecticide, and therefore, spectrofluorometry was used to measure the fluorescent dye present in foliar deposits. Deposit concentrations were measured in *ppb (ng* AI per *g* foliage or *ng* dye per *g* foliage). (Tables 2 and 3.)

For determining the physical properties of formulations, viscosity, surface tension and droplet evaporation rates were measured at the temperatures encountered in the field (Tables 2 and 3). Viscosity was measured using Ostwald's viscometer. Surface tension was determined using the capillary rise method (Maron and Prutton 1965). To measure the rates of evaporation, droplets of defined sizes were produced in the laboratory using the rotary device designed by Rayner and Haliburton (1955), and were captured on glass fibre of known thickness and the droplet diameters were measured by microscopy at various time intervals at the temperatures encountered in the field, under almost still air conditions. The evaporation characteristics of formulations were expressed as the residual percentage of droplet volume remaining after the evaporation of the volatile components (Tables 2 and 3).

Table 1. Spray Formulations, Dosage and Application Rates

Formulation Abbreviation	Composition (v/v%)	Dosage (AI/ha)	Application Rate (L/ha)	Treatment Time and Location
AA-3409	Matacil® 180F 25.93; Atlox®3409F 1.27 Water 72.27; Rhodamine B 0.53	70g[a]	1.5[a]	June 1981; New Brunswick
AID-585	Matacil® 180F 25.93; ID585®72.07 Automate B Red 2.00	70g[a]	1.5[a]	June 1981; New Brunswick
AS-6N	Matacil® 180D 25.93; Sunspray® 6N 72.07 Automate B Red 2.00	70g[a]	1.5[a]	June 1981; New Brunswick
SPA-3409	Sunflower oil 7.00; Atlox®3409F 1.50 Water + 7g polymer 90.50; Rhodamine B 1.00	-	3.0[b]	August 1981; Ontario
AT-100	Matacil® 180F 25.93; Triton® X-100 10.7 Water 70.07; Rhodamine dye 1.00	70g[a]	1.5[a]	June 1982; New Brunswick
FCT-100	Fenitrothion tech. 10.90; Triton® X-100 10.7 Cyclosol® 63 24.00; Water 61.10 Rhodamine dye 1.00	210g[c]	1.5[c]	June 1982; New Brunswick
FT-100	Fenitrothion tech. 10.9; Triton® X-100 10.7 Water 77.40; Rhodamine dye 1.00	210g[c]	1.5[c]	June 1982; New Brunswick
B.t.I	Thuricide® 48B 25.00; Water 74.70 Chevron sticker 0.10; Erio Acid Red 0.20	30 BIU[d]	9.45[d]	June 1982; Ontario
B.t.II	Thuricide® 48B 25.00; Water + 2.73g polymer 39.80 Water + 2.19g sticker 35.00; Erio Acid Red 0.20	30 BIU[d]	9.45[d]	June 1982; Ontario

[a] Formulation was applied twice at 5 day interval, each at 70g/1.5L/ha to provide a total of 140g/3.0L/ha.
[b] Formulation was applied twice at the same time, each at 1.5L/ha to provide a total of 3.0 L/ha.
[c] Formulation was applied twice at 5 day interval, each at 210/1.5L/ha to provide a total of 420g/3.0L/ha.
[d] Formulation was applied twice at the same time, each at 15 BIU/4.725L/ha to provide a total of 30 BIU/9.45L/ha.

Results and Discussion

Droplet density values are presented in Tables 2 and 3 as the Mean ± SD for each formulation. In the 1981 trials, the two oil-based mixes, AID-585 and AS-6N, provided higher droplet densities and larger droplet sizes than the Atlox®-based emulsion. This is probably due to the 80% relative humidity (RH) at which AA-3409 was sprayed. Water-based mixtures are known to undergo in-flight evaporation at RH values 80% and below (Matthews 1979), resulting in smaller droplet size spectrum. Since the two oil-based mixtures have evaporation characteristics independent of RH values of the ambient air, they produced droplet spectrum dependent upon temperature only. Between the two oil-based mixes, the non-volatile Sunspray® oil-based AS-6N provided a higher value and this is attributable to the physical properties such as higher viscosity and lower evaporation characteristics. In the case of the blank formulation SPA-3409, the low RH of 80% is expected to cause lower droplet density and smaller droplet sizes, but the presence of a polymer (Table 1) had caused the largest droplet spectrum observed (Table 3), and because of this the droplet density was the lowest and so was the coverage. However deposits on foliage and glass plates was the highest. This is because of the large droplet sizes which contributed to a large droplet volume and mass deposit.

Table 2. Spray Application Details, Weather Factors, Formulation Properties and Spray Deposit Data for Aminocarb Formulations

Formulation	AA-3409[a]	AID-585[a]	AS-6N[a]	AT-100[b]
Spray Block Size (ha)	50	50	50	50
Aircraft Type	Cessna 188	Cessna 188	Cessna 188	Cessna 188
Aircraft Speed (km/h)	160	160	160	160
Atomizer Units	4 x AU3000	4 x AU3000	4 x AU3000	4 x AU3000
Spray Height Above Canopy (m)	30	30	30	30
Emission Rate (L/min)	24.5	24.5	24.5	23.7
Wind Speed (km/h) (at 10m above ground)	0.25	0	0	5 ± 3
Temperature (°C) (average of 10m and 1m values)	13.0	10.0	16.5	11.1
Relative Humidity (%)	80	96	73	81
Sample Trees (No.)	12[c]	12[c]	12[c]	7[c]
Ground Sampling Units (No.)	36	36	36	28
Droplet Density	6 ± 6	13 ± 6	15 ± 6	4.3 ± 4
NMD (μm)	28	35	45	20
VMD (μm)	36	39	68	32
Dmax (μm)	73	85	105	94
Foliar Deposit (ppb)	2300[d]	2500[d]	2800[d]	700[d]
Deposit on Glass Plate (ml/ha)	52.5[e]	165[e]	210[e]	47.5[e]
Viscosity (cp)	2.42	4.24	35.4	3.59
Surface Tension (dyne/cm)	31.0	29.2	31.3	31.5
Droplet Evaporation Characteristics (Limiting Residual Vol. %)	28.0	38.0	100.0	34.0

[a] Data are from 1st application.
[b] Data are from 2nd application.
[c] Balsam fir *[Abies balsamea* (L.) Mill.].
[d] *ng/g* of AI from GLC measurements.
[e] Values are from spectrofluorometric measurements.

Table 3. Spray Application Details, Weather Factors, Formulation Properties and Spray Deposit Data for Fenitrothion, Blank and *B.t.* Formulations

Formulation	FCT-100[a]	FT-100[a]	SPA-3409[b]	*B.t.I* [b]	*B.t.II* [b]
Spray Block Size (ha)	50	50	3.0	50	50
Aircraft Type	Cessna 188	Cessna 188	Cessna 185	Cessna 185	Cessna 185
Aircraft Speed (km/h)	160	160	160	160	160
Atomizer Units	4 x AU3000	4 x AU3000	4 x AU3000	4 x AU3000	4 x AU3000
Spray Height Above Canopy (m)	30	30	6.0	30	30
Emission Rate (L/min)	23.7	23.7	12.0	38.0	38.0
Wind Speed (km/h) (at 10m above ground)	3 ± 1	3 ± 1	0 ± 0.5	9 ± 3	14 ± 3
Temperature (°C) (average of 10m and 1m values)	11.1	11.7	23.5	13 ± 1	17 ± 1
Relative Humidity (%)	75	87	80	75	75
Sample Trees (No.)	7[c]	7[c]	25[d]	30[c]	30[c]
Ground Sampling Units (No.)	28	28	100	120	120
Droplet Density	5.3 ± 1.1	19.1 ± 7	3.3 ± 1.3	27 ± 9	21 ± 10
NMD (μm)	34	24	75	8	12
VMD (μm)	99	31	144	58	40
Dmax (μm)	138	130	380	143	155
Foliar Deposit (ppb)	800[e]	1700[e]	150[f]	125[f]	86[f]
Deposit on Glass Plate (ml/ha)	55.0[g]	74.0[g]	468[g]	456[g]	360[g]
Viscosity (cp)	7.22	12.0	41.2	2.04	3.65
Surface Tension (dyne/cm)	33.3	32.1	38.0	25.5	38.9
Droplet Evaporation Characteristics (Limiting Residual Vol. %)	27.0	38.0	30.0	5.5	8.7

[a] Data are from 2nd application.
[b] Data are from both applications since the two applications were made at the same time.
[c] Balsam fir *[Abies balsamea* (L.) Mill.].
[d] White spruce *[Picea glauca* (Moench) Voss].
[e] *ng/g* of AI from GLC measurements.
[f] *ng/g* of dye from spectrofluorometric measurements.
[g] Values are from spectrofluorometric measurements.

In the 1982 trials, the three emulsion formulations behaved somewhat similar to the AA-3409 emulsion in 1981, in producing a lower deposit on glass plates than those of the two oil-based formulations AID-585 and AS-6N. FCT-100 had significantly higher viscosity than AA-3409 and AT-100, but this did not seem to influence the deposit pattern to a great extent (Tables 2 and 3). However, FT-100 had the highest viscosity among the four mixes, AA-3409, AT-100, FCT-100 and FT-100, and this appears to cause the highest droplet density and deposits on foliage and ground sampling units. However, this could also be due to the high RH of 87% (Table 3). No direct inverserelationship is evident between viscosities and evaporation characteristics of these four emulsions. Between the two *B.t.* formulations, *B.t.II* had a higher viscosity and lower evaporation, but it provided a lower droplet density and volume deposit, because of the larger droplet spectrum observed. Once again, the presence of polymeric components appears to cause larger droplet sizes.

It is worth noting that the two *B.t.* formulations, in spite of the favourable higher wind speed conditions (Table 3), failed to provide higher foliar deposits although they provided higher deposits on the ground sampling units (Table 3). This is probably because of the larger volume rates of application, which are known to provide a wider droplet spectrum (Joyce and Beaumont 1978). While the evaporation of water from smaller droplets increased the proportion of fine droplets in the spray cloud which are too inefficient to impact on foliage, the presence of larger droplets, having a high sedimentation rate, resulted in greater ground deposits. This indicated the need to optimize the volume rates for every formulation and spray application systems.

In conclusion, the following are indicated in the paper:

1. An inverse relationship appears to exist between the viscosity and evaporation characteristics of oil-based spray mixes, i.e. the higher the viscosity, the lower the evaporation. Such a trend was not observed with water-based formulations.

2. With the oil-based spray mixes, the higher viscosity caused a larger droplet spectrum and higher deposits on foliage and on glass plates.

3. Surface tension values of all spray mixes did not vary to a great extent and consequently any influence on droplet size spectrum can be expected to be similar with all mixes.

4. The suitability of polymeric components should be judiciously evaluated for each formulation and spray application systems and for the target types. Otherwise polymers can only bring disadvantages, such as an undesirably large droplet spectrum.

5. It is essential to determine the optimum volume rates of emission for each formulation and spray delivery systems. Otherwise, volume rates greater than the optimum level, would only increase ground deposition of sprays leading to ground contamination and wastage of pesticide materials.

Acknowledgements

The authors gratefully acknowledge the financial support of the Eastern Component of the CANUSA for the field trials of three out of the nine formulations studied. The authors also express their sincere appreciation to the scientists and support staff of the two projects in FPMI, *viz.*, Insect Growth Regulators and Bacterial Pathogens.

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BT STRAIN AND FORMULATION RESEARCH AT THE CENTER FOR BIOLOGICAL CONTROL

FOR "SAF REGION VI TECHNICAL MEETING: FOREST MANAGEMENT AND THE SPRUCE BUDWORM"

F. B. Lewis and N. R. Dubois

Project Leader and Microbiologist, respectively, Center for Biological Control of Forest Insects and Diseases, Northeastern Forest Experiment Station, Hamden, CT 06514

Introduction

One of the major objectives of the CANUSA program has been to bring microbial control into functional use in spruce budworm management and control programs. Bacillus thuringiensis (Bt) is the microbial agent with the greatest potential to meet this objective, but until recently has performed erratically in field operations. There are many reasons for this erratic performance--two reasons addressed in this paper are: (1) The strain of Bt being used and (2), the formulation-application-deposit of the material.

Bt Strain Research

Several years ago (1974), Dr. Howard Dulmage, ARS, organized an international cooperative research effort on the spectrum of activity of Bt against major agricultural and forest pests, including spruce budworms. The purpose of this large interactive study was to calibrate known serotypes and isolates of Bt to the standard Bt (HD-1S-1971 until 1980, HD-1S-1980 from 1980 on) and compare activity of these isolates among the major pest insects. Over 600 isolates, uniformly prepared by Dr. Dulmage's laboratory, were distributed to the major research groups cooperating in this endeavor. Our laboratory was involved in the screening of these preparations against the gypsy moth and the eastern spruce budworm. In the course of these screenings against laboratory-produced spruce budworm (FPMI), one of us (NRD) isolated several new Bts that exhibited greater activity against the budworm than the commercially available strain (HD-1) and most of the standardly produced HD isolates examined in the screening. Morris and Moore (1983) reported on the comparative potencies of 50 HD isolates against laboratory-produced fifth-instar larvae. Data showed a 1200-fold difference from the most active to the least active strain. Similar data have been obtained in our laboratory.

Table 1 illustrates the wide range of activity of Bt isolates to spruce budworm larvae--prior to formulation for field use.

TABLE 1. RANGE OF ACTIVITY OF Bt LABORATORY BIOASSAYED AGAINST FOURTH INSTAR SPRUCE BUDWORMS.

Bt STRAIN	LC 50 (µg)	LT 50 (days)
NRD-12	1.68	2.66
NRD-10	1.32	2.75
HD-1S-1980 (Standard)	3.62	5.08
HD-53	1.45	5.20
HD-278	12.92	5.10

All laboratory bioassays are conducted with standard protocols using uniformly aged larvae reared on artificial diet in a temperature-controlled cabinet. Dose-response data are obtained from more than one assay. Coefficients of variation are about 40-45% with the standard HD-1S-1980 reflecting the variability of the response of spruce budworm larvae.

The significance of the differences in activity among all these Bt strains is that the most effective strain, in terms of percent larval kill or speed of larval kill, may not be in use against the spruce budworm. This will certainly have an impact on any suppression effort and will have a major impact on any economics of Bt use. Several isolates exhibit faster action, certainly desired, but no greater larval mortality, thus giving better foliage protection. Several strains exhibit equal activity against the insect at significantly lower dosages, certainly desired from an economic point of view.

These large differences in activity of Bt strains are further complicated by the formulation-application aspects of the problem--as discussed by Dr. **Sundaram--which** involve the chemistry and physics of the total formulation, its biological parameters, and the physics, meteorology, and aerodynamics of application.

Formulation Research

The formulation-application-deposit problem, particularly with microbials, has been identified by many researchers and in three major symposia as the most critical area needing resolution for regular utilization of these agents in pest management systems, including the spruce budworm.

At the Center for Biological Control of Forest Insects and Diseases, we have begun to develop a formulation-application facility consisting of an aerial spray simulator, a sunlight simulator, an automatic drop counter, and a bioassay room. These facilities are in place at our Ansonia field site and are in the process of being calibrated and standardized. These facilities are designed to simulate aerial sprays and to evaluate, primarily, the biological effects of drop size, and density, stickers, deleterious sunlight wavelengths, adjuvants, volume, additives, carriers, and timing of Bt, NPV, and other microbial agents used against major eastern defoliating insects. The principal reason for developing the facility is to bridge the gap between laboratory analyses and actual field trials which as you all know involve large expenditures and have many uncontrollable factors.

Figure 1.--a - external view of spray simulator

Aerial Spray Simulator

The heated spray simulator is 16x12x12 feet with a base turntable with rotation adjustable from 0-3 r.p.m. Four smaller turntables, geared 3 times the rotational speed of the main turntable, are mounted above the main turntable. Experimental microbial sprays are delivered 12 feet above the turntables by a model 250 Beecomist[1] nozzle with a digitized rpm meter controlled by rheostat. The experimental formulations are delivered to the nozzle by slight airpressure to simulate 0.5-4.0 gallons per acre A variable speed fan is mounted 3 feet above the nozzle to introduce down draft if desired.

Spray deposit is caught by plants, cards, petri dishes or other surfaces and then subject to simulated rain, sunlight, etc. for weathering testing, and the deposit is sized and counted in the droplet counter.

Droplet number and size is controlled by the formulation flow rate and amount, the nozzle speed, the turntable rotation, and the fan.

We are experiencing some difficulties with uniformity of deposit with low gallonages, and are presently modifying the flow system to the nozzle.

Figure 1, a, b, c, shows the spray simulator, and Figure 2 illustrates preliminary droplet distribution of 2 gallons per acre at different nozzle speeds.

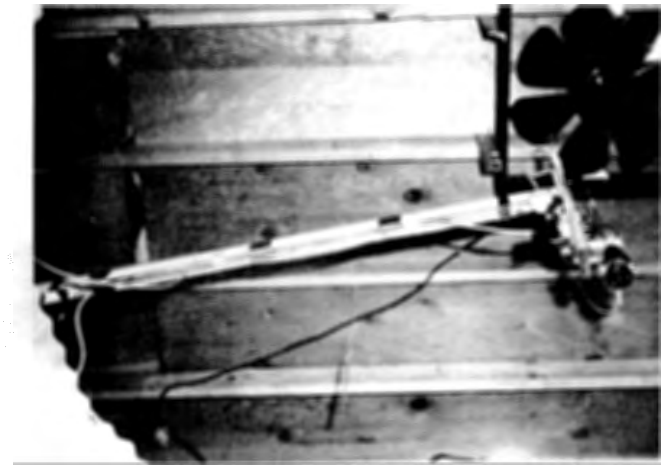

Figure 1.--b - nozzle and feed mechanism

Figure 1.--c - turnable

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[1]The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U.S. Department of Agriculture or the Forest Service of any product or service to the exclusion of others that may be suitable.

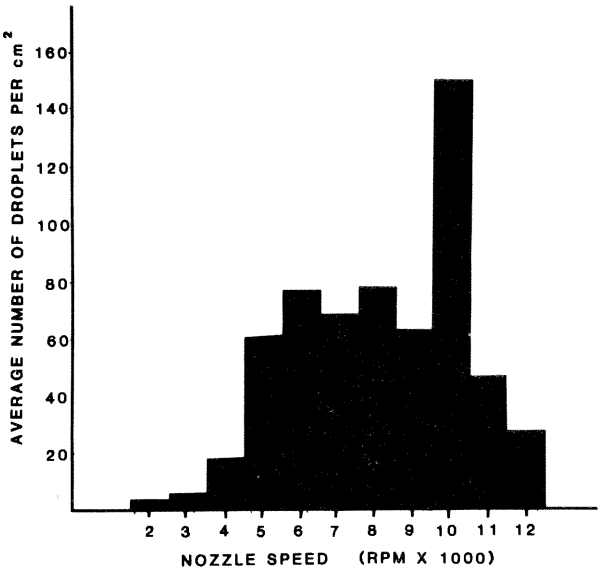

Figure 2.--Droplet spectrum at 2 gallons per acre 2 gallons per acre delivery volume.

Sunlight Simulator

The sunlight simulator, designed by Dr. Conrad Mason, U.Mich., under a CANUSA grant, simulates the total flux of the sun at New Haven latitude in mid June (Figure 3). The simulator is 2x4 feet, has eight dual fluorescent fixtures each containing a sunlight and a black light of 40 watts each. The table and the fixtures are height-adjustable. The table was intended to give U-V exposures approximating those outdoors, but recent calibrations have shown that more UV-B and UV-C are being generated than reaches the earth's surface at the New Haven latitude.

Preliminary results with tests indicate that the table will provide good information on U-V degradation of microbial formulations, but that modifications, by light filtration or rheostating will be required to simulate actual sunlight fluxes.

Figure 3.--Sunlight simulator with treated plants in position.

Droplet Counter

A Quantimet® Image Analyzer model 720 was acquired from the Pacific Northwest Forest and Range Experiment Station (Figure 4). This device automatically counts and sizes droplets in pre-determined bin-size ranges. A deposit surface can be sized, counted, and hard-copied in less than 30 seconds.

All experimental formulations tested in the spray tower can be sized and counted the same day as simulated application. Light-colored spray formulations do have to be dyed to provide contrast to the deposit surface.

Figure 4.--Droplet counter with Kromecote card in position.

Future Direction of Formulation-Application Research

Optimal use of microbial agents in pest suppression or pest management systems, such as the spruce budworm Integrated Pest Management, will only come about by optimizing the formulation of the agent and delivering this formulation to the target pest most efficiently and effectively. Concurrently the most effective strain of the organism for the target pest must be properly selected.

Microbial insecticides are different from conventional insecticides. The active ingredient is a living entity, subject to biological enhancement or degredation. They are easily inactivated by physical phenomena. They are particulate, presenting quite different problems from soluble materials, and they are usually applied in a water-based formulation, thus increasing the evaporation-deposition problem.

Our plans revolve around the biological problems of droplet content, distribution of the active ingredient in the drop, the effect of drop size on biological content, the synergistic or antagonistic biological effects of U-V screens, stickers, stains and dyes, and anti-evaporation agents. The physical attributes of different delivery systems have biological effects on these agents. We hope to concentrate in these areas from the biological point of view rather than the conventional physical formulation-application research.

We hope to incorporate new developments in laser technology for droplet analysis, new information on sunlight wavelength effects on microbials, other than U-V, and new designs and improvements in application hardware and technology.

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CHEMICAL INSECTICIDES FOR SPRUCE BUDWORM

B.V. Helson

Research Scientist, Forest Pest Management Institute, Canadian Forestry Service, Environment Canada, Sault Ste. Marie, Ontario, Canada P6A 5M7

The use of chemical insecticides for eastern spruce budworm control from 1945 to the present will be reviewed. In the past 4 years, over 12 million hectares have been sprayed in eastern Canada and Maine with 4 insecticides primarily, MATACIL, fenitrothion, Sevin and Orthene. Application rates, formulations and other characteristics of these insecticides will be presented. Recent research and development at the Forest Pest Management Institute with new formulations of MATACIL, fenitrothion and Sevin will be discussed as well as some new or recently resurrected insecticides such as Zectran, Larvin and permethrin.

Introduction

Chemical insecticides have been the most commonly used tools for spruce budworm control in Eastern Canada and Northeastern United States. There are a number of reasons for this. They are effective, easy to apply quickly to large areas at low volumes, and economical. Besides Bt, there are at present no other non-chemical options available which approach these attributes. Furthermore, extensive environmental impact studies have demonstrated that currently-used insecticides at registered rates and use patterns are relatively safe and do not result in unacceptable disturbances to environmental quality. Chemical insecticides have proven invaluable in protecting the forest resource from spruce budworm and we must ensure that they remain a viable control method so that forest managers will have a choice of options available to use in the future.

History of Insecticide Use

In Canada, 7 insecticides have been used over the past 40 years for the control of spruce budworm by aerial application to large areas (Nigam 1980). DDT was used extensively in operational control programs in several provinces at various times from 1945 to 1968. Aerial application of phosphamidon began in 1963 and this insecticide was used quite extensively until 1978. Zectran was used on a small scale between 1969 and 1974 while operations with trichlorfon started in 1970 but it has not been used extensively since 1977. Of the insecticides in current use, control operations started with fenitrothion in 1967, with MATACIL in 1970 and Orthene in 1974 on a very small scale. Unlike the US, Sevin has only been used occasionally and on a very small scale for spruce budworm control in Canada. During the period from 1965 to 1980, approximately 12.5 million kg or 27.5 million lb. of these insecticides have been used on about 50 million hectares or 125 million acres to control spruce budworm.

Over the past 4 years, the major users of chemical insecticides for spruce budworm control have been the state of Maine, and the provinces of New Brunswick, Quebec and Newfoundland. In Maine, Sevin has been the major insecticide used during this period except in 1983 when MATACIL was the primary insecticide. Orthene has also been regularly used to a lesser extent and some Zectran was applied in 1983. The redevelopment and use of Zectran for spruce budworm control will be discussed later in this paper. Approximately 1.5 million hectares have been sprayed in Maine over the past 4 years. In eastern Canada fenitrothion and MATACIL have been the insecticides used almost exclusively for spruce budworm control during the past 4 years. In New Brunswick, approximately 7 million hectares have been sprayed, primarily with fenitrothion. In Quebec, approximately 3.3 million hectares have been treated primarily with MATACIL and some fenitrothion while during the past 3 years about 354 thousand hectares have been treated in Newfoundland. In total, approximately 12 million hectares or 30 million acres have been sprayed with Sevin, fenitrothion, MATACIL or Orthene between 1980 and 1983[1/].

Characteristics of Currently Used Insecticides

All of these insecticides are carbamate or organophosphorous chemicals which inhibit acetylcholinesterase, the enzyme which breaks down acetylcholine. Acetylcholine is a chemical which regulates the transfer of nerve impulses across nerve junctions. If it is not broken down, the acetylcholine accumulates and nerve impulses continue to be transmitted.

1/ Above statistics compiled with permission from Forest Pest Control Forum Reports, Unpublished Reports or Personal Communications.

Under such continuous stimulation, the nervous system cannot function properly and the insect eventually dies.

Aminocarb

MATACIL or aminocarb is a carbamate insecticide formulated and marketed by Chemagro Ltd. in Canada and Mobay Chemical Corp. in the US. Its acute oral toxicity and dermal toxicity to rats are 30 and 275 mg/kg (LD50) respectively. It is the most toxic of the 4 insecticides to spruce budworm larvae and is used at the lowest dosages. It is registered for aerial application in Canada at 52-90 g AI/ha with 1 or 2 applications a season. In the US, it is registered at 2.4 oz AI/acre in one application or 1 oz AI/acre in each of 2 applications 5 to 6 days apart. Typically, this insecticide has been applied in 2 applications at either 52 or 70 g AI/ha for each application. MATACIL 180-D or 1.8D Oil Soluble Concentrate containing 180 g aminocarb/ℓ has been the formulation used previously. More recently, a new flowable formulation, MATACIL 180F or 1.8F containing the same concentration of aminocarb has been used operationally in some spray programs. It can be mixed straight with an oil carrier such as fuel oil or ID585, or with water with the addition of an emulsifier. This flowable formulation was developed to replace the previous formulation, MATACIL 1.8D which contained nonylphenol as the primary solvent. Concern had been expressed about the toxicity of nonylphenol to certain aquatic organisms which were more sensitive to this solvent than to aminocarb itself. The new formulation is much less toxic to fish than the previous formulation (Szeto and Holmes 1982).

This MATACIL 180F formulation was extensively tested at the Forest Pest Management Institute to determine its relative toxicity to spruce budworm in the laboratory, its spray characteristics, its efficacy in the field, as well as its environmental impact and fate in the forest ecosystem. The contact and residual toxicities of this flowable formulation were comparable to existing MATACIL formulations. In a double application at 70 g AI/ha in either ID585 or Atlox + H_2O it was as effective in controlling spruce budworm larvae and protecting balsam fir and spruce foliage as MATACIL 1.8D (Cadogan et al. 1984). Both MATACIL 180F mixes had very little observable impact on the forest songbird, benthic invertebrate, Atlantic salmon and brook trout populations monitored (Millikin 1982, Kreutzweiser 1982). Apart from relatively high concentrations in balsam fir needles, residues in air, stream water, stream sediment, aquatic moss, fish, soil and litter generally disappeared quite rapidly indicating that this formulation has low persistence at this application rate (Sundaram et al. 1983).

Fenitrothion

Fenitrothion is an organophosphorous insecticide with an acute oral and dermal toxicity to rats of 330-800 mg/kg and 890-1200 mg/kg respectively. It is marketed by several companies under different trade names including Sumithion by Sumitomo Chemical Co., Folithion by Chemagro Ltd., Novathion by Cheminova and Accothion by American Cyanamid. It is about 3 times less toxic than aminocarb to spruce budworm larvae and is typically used at a dosage of 210 g AI/ha in each of 2 applications. It is registered in Canada for either a single application at 280 g AI/ha or 2 applications 4-6 days apart at 140-210 g AI/ha for each. New Brunswick is the major user of fenitrothion. They obtain ca 95% technical material and formulate it with the emulsifier, Atlox 3409F and Dowanol TPM for application as a water based mix, or to a lesser extent with Cyclosol 63 and ID585 as an oil based mix.

A new formulation of fenitrothion, Sumithion 20% Flowable has recently been developed by Sumitomo Chemical Co. which can be mixed directly with water without the addition of an emulsifier. This formulation is presently being evaluated at FPMI. Its mixing, spraying and storage characteristics are good. This flowable formulation is as toxic to spruce budworm larvae as other aqueous based fenitrothion formulations, both when larvae are exposed directly to it or when untreated larvae are exposed to treated foliage. Its residual toxicity is also comparable to other fenitrothion formulations. The efficacy of this product in controlling spruce budworm and providing foliage protection will be field tested this spring in New Brunswick.

Carbaryl

Sevin or carbaryl is a carbamate insecticide with low mammalian toxicity. The acute oral LD50 to rats is 560 mg/kg while the dermal LD50 to rabbits is greater than 2000 mg/kg. It is produced and marketed by Union Carbide Corp. Its toxicity to spruce budworm larvae is lower than the other insecticides and correspondingly, it is sprayed at the highest rates of application. It has been used extensively by Maine for spruce budworm control, most recently at a dosage of 6 oz AI/acre in each of 2 applications. It is registered for this purpose at 1 lb AI/acre. Sevin-4-Oil,

the formulation used, is a dispersion of finely ground carbaryl in oil designed to be mixed only with an oil such as kerosene or fuel oil as a carrier. It contains 4 lb carbaryl/US gallon. Union Carbide recently introduced a new formulation of carbaryl, Sevin FR, a suspension of microfine carbaryl in a water medium which can be mixed with water as a carrier. This formulation has been field tested extensively in Maine. It was also tested in the initial stages of our insecticide evaluation program at the Forest Pest Management Institute. Its direct contact toxicity to spruce budworm larvae was similar to Sevin-4-Oil and another formulation, Sevin XLR. The toxicity of Sevin FR to untreated larvae on treated foliage appeared to be about 4 times better than its contact toxicity. The residual toxicity of the 3 Sevin formulations was also similar except that Sevin FR in Dowanol TPM was more persistent than the same formulation in PA-3, an additive supplied by Union Carbide. This product was ready for field efficacy trials but its development has not continued further.

Acephate

Finally, Orthene or acephate is an organophosphorous insecticide which has been used on a small scale for spruce budworm control, particularly in Maine. It has a low mammalian toxicity with oral LD50 values of 866-945 mg/kg to rats and a dermal LD50 of more than 2000 mg/kg to rabbits. It is marketed by Chevron Chemical Co. It is slightly more toxic than Sevin to spruce budworm larvae and is currently being used in Maine at the registered dosage of 8 oz AI/acre in a single application. The formulation used is a Forest Spray Concentrate containing 85% acephate as a powder which is soluble in water.

Recent Developments with Chemical Insecticides

As indicated above, new formulations of current insecticides have been or are being actively developed for spruce budworm control. There are various reasons for this but a common feature of these formulations is that they can be sprayed with water which reduces the cost of application by eliminating the need for an oil carrier.

There are few new insecticides on the horizon with potential for spruce budworm control. In the future forestry will be almost entirely dependent upon insecticides developed for use in agriculture. Only a small portion of those developed for agricultural uses will be suitable for forestry use. Furthermore, relatively few new insecticides are being introduced for any purpose because of the very high cost of development and because it is becoming increasingly more difficult to discover new compounds.

Having said this, there are some new or recently resurrected insecticides currently under development with potential for spruce budworm control. Zectran or mexacarbate is not a new insecticide but it has been recently reintroduced by Union Carbide Corp. who have purchased its rights from Dow Chemical. This insecticide had been tested and registered for spruce budworm control both in Canada and the US but it was not being marketed by Dow. It still has a registration for this use in the US but the registration has lapsed in Canada. Union Carbide is actively developing this insecticide again for forestry and other uses in the US and Canada. It was field tested for spruce budworm control in Maine last year.

Zectran is a carbamate insecticide which is structurally very similar to aminocarb. Its acute oral toxicity to various mammals ranges from an LD50 of 22 to 63 mg/kg while its dermal toxicity to rabbits is 500 mg/kg. New formulations are presently under development including a liquid formulation which is soluble in oil or which can be mixed with water to form an emulsion with the addition of a suitable emulsifier, and a water-based flowable formulation which can be mixed directly with water. These formulations are being extensively evaluated at FPMI. The contact toxicity of these new formulations to spruce budworm larvae is similar to the previous Dow formulation of Zectran and also to comparable formulations of aminocarb. Their toxicity to untreated larvae on treated foliage and Zectran's residual toxicity under natural weathering or greenhouse conditions are also comparable to aminocarb. Zectran will be field tested by FPMI this season for its efficacy against spruce budworm at 70 g AI/ha or 1 oz AI/acre in a double application.

Another carbamate insecticide, Larvin or thiodicarb from Union Carbide is in the initial stages of evaluation at FPMI. Its contact toxicity to spruce budworm larvae is intermediate to aminocarb and fenitrothion while its toxicity to untreated larvae on treated foliage is as good as aminocarb. Its residual toxicity in one test was excellent with no apparent decline in mortality over a 10-day period at a deposited dosage of 224 g AI/ha. This insecticide has also been tested extensively by the USDA Forest Service against western spruce budworm. Using an aerial spray simulator, Richmond

(1983) found that thiodicarb reduced larval populations by at least 90% at 105 and 160 g AI/ha and suggested that this insecticide should be tested in the range of 140-327 g AI/ha by aerial application.

Finally, I would like to discuss a relatively new group of insecticides, the pyrethroids and particularly one of them, permethrin. These pyrethroids are the most toxic insecticides to spruce budworm larvae ever tested at FPMI. Permethrin is about 3 times more toxic than aminocarb while deltamethrin is about 25 times more toxic than permethrin. Their residual toxicity against spruce budworm is also very good. Relative to their insect toxicity, the toxicity of these pyrethroids to mammals and birds is quite low. The acute oral toxicity of permethrin for example to various mammals is greater than 4000 mg/kg while the acute oral LD50 to several bird species ranges from 9900-38,000 mg/kg. However, these pyrethroids are highly toxic to fish and perhaps more importantly to aquatic invertebrates. The toxicity (48 hr TLM) of permethrin to several species of fish ranges from 1.8 to 38.5 micrograms per litre of water. At FPMI, permethrin was selected as a representative pyrethroid and intensively investigated to determine its effectiveness against spruce budworm by aerial application and its environmental impact, particularly in aquatic ecosystems. These studies have demonstrated that 2 aerial applications of permethrin at 17-18 g AI/ha can provide large scale spruce budworm control (DeBoo 1980, Zylstra and Obarymskyj 1981). No direct fish mortality in forest streams has been observed at this dosage or in fact at dosages of 70 g AI/ha or less suggesting that a safety factor to fish does exist with this insecticide (Kingsbury 1983). However, at 17.5 g AI/ha, permethrin causes severe disturbances to aquatic invertebrate communities in streams with likely secondary effects on fish populations including temporary growth rate reductions and movement of fish out of treated areas (Kingsbury 1983). For these reasons, Kingsbury (1983) has concluded that permethrin at 17.5 g AI/ha should only be considered appropriate for aerial use in situations where no such aquatic systems are present or where it can be demonstrated that they can be effectively buffered from the effects of treatment. Several scientists at FPMI are presently heavily involved in a research program designed to identify the size of buffer zones necessary to protect sensitive aquatic habitats from ground and aerial applications of permethrin for forestry use. Permethrin has recently received a commercial registration in Canada for the control of spruce budworm and other forest insect pests in woodlands by ground application only at 17.5-35 g AI/ha in one application per season.

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TIMING SPRAY APPLICATIONS AGAINST THE SPRUCE BUDWORM

John B. Dimond

Professor of Forest Entomology, University of Maine, Orono, ME 04469

Timing of spray applications for spruce budworm control requires consideration of an array of factors. The major ones are the stages of spring development of the insect and of its host trees. However, one should also consider densities of the insects and vigor of host trees, forest management and pest management goals, weather effects on insect activity, and associated insect pests.

Introduction

Effective control of spruce budworm with sprays depends on many factors, including choices of insecticides, dosages, spray volumes, swath widths, droplet size, etc., but proper timing of applications can be as important as any of the above. Sometimes, in large spray programs, decisions on when to spray are influenced by human pressures to get the work started, or finished, for financial reasons or to reduce morale problems due to prolonged inactivity of personnel. The sprays are not always applied at the best time with respect to larval vulnerability, host tree foliage development, and weather. In large spray projects, one cannot expect that ideal conditions will prevail at all times, but one should hope to exploit the good conditions often with the poorer ones avoided. As in statistics, we might consider two types of errors, Type I and Type II. In the Type I case, an over-cautious spray manager continually rejects spraying under conditions that are marginal on one basis or another; this may result in failure to complete the spray project by the time the insects have pupated or have already caused unacceptable damage. In the Type II case, an anxious spray manager may use all of the marginal spray time, finishing the spray project in a timely fashion, but a substantial proportion of the spray blocks may show poor protection. I suggest that, in practice, Type II errors are much more common than Type I errors.

Aerial sprays have been tried against spruce budworm moths in New Brunswick (Thomas et al. 1977) with little success. Greatest knockdown of female moths occurred among those which had already deposited their eggs (Thomas 1978).

All present spraying is directed against the larval or caterpillar stages while they are active and feeding, causing damage to the trees.

The timing of spray applications for reduction of insect numbers and their damage is determined by: (1) spring development of the insect and (2) bud and shoot development of the host tree species concerned. But, decisions based on these major factors may also be modified by consideration of insect densities and target tree vigor, forest management and pest management goals, weather, and the presence of associated insects.

Insect Development

First instar larvae hatch from eggs in mid summer, enter diapause without feeding, and overwinter as second instars in silken hibernacula on the host tree branches. There have been no serious attempts to control those early, inactive stages. Upon resuming activity in May of the following year, the second instars mine within old needles of the host trees (Atwood 1944, McGugan 1954), there being no new foliage flushed as yet. On balsam fir and white spruce, third instar larvae have access to swelling buds which are mined. Instars IV - VI feed and develop within expanding current shoots until pupation. Needle-mining and bud-mining stages of the insect are generally considered as being poor targets for spray, since the larvae are enclosed within plant tissues. The normal timing of a single spray application, therefore, would be once buds have flared and the insects are actively feeding on the expanding shoots. While this period involves larval instars IV - VI, treatment is generally applied during peak instar IV to avoid the heavy damage caused by the later stages. In a given location, there is a period of two weeks before late instars cause serious damage.

When *Bacillus thuringiensis* is used, it is often recommended to apply treatment at peak instar III or between instars III and IV. The rationale for this early timing is that B.t. works more slowly than most chemical insecticides, and therefore, insects must be exposed to the bacterial insecticide earlier to avoid unacceptable damage to the trees. The validity of this argument is questionable, but it certainly does not apply now with the improved efficacy of B.t. formulations and dosages. Fast and Dimond (1984) suggest that a later timing of B.t. is more effective. This protects foliage as well as a single application of chemical insecticide; B.t. is rarely used in double (split) applications.

Chemical insecticides are frequently used as two (occasionally three) successive applications of a reduced dosage. This is done either to deal with the special timing problems involved with treating spruce (see Host Species and Their Development), or when spruce budworm numbers are very high in relation to the foliage resource available (see Insect Densities).

Adequate timing for spraying must take into account two trends. As larvae grow in the spring, they become more exposed and active, and make contact more readily with insecticides (Miller and Kettela 1975, Miller and Fisher 1978). While more insecticide is required to kill larger larvae (Nigam 1975), the larger forms contact and ingest

more spray deposit. However, the longer one waits to spray, the more defoliation one must accept (Webb 1955). Miller (1977) showed that 87 percent of total food consumption by budworm caterpillars occurred during the VI (last) larval instar. Treatments should be completed by early in this instar. Damage caused by the earlier stages is usually acceptable unless populations are unusually abundant, as at the peak years of an outbreak.

These comments on timing apply to balsam fir for the most part, and the special problems in dealing with spruce are discussed later.

Spruce budworm development is determined by code among budworm workers. L3 signifies larval instar III. L6 and P signify larval instar VI and pupae, respectively. Hereafter, this code will be used. Similarly, a distribution of several instars is quantified into a single larval index (L.I.) (Hardy et al. 1977). In a budworm population containing 20 percent L2, 45 percent L3, and 35 percent L4, L.I. would be calculated as:

$$(2 \times 20) + (3 \times 45) + (4 \times 35)/100 =$$
$$(40 + 135 + 140)/100 =$$
$$315/100 = 3.15$$

L.I. of 3.15 is somewhat beyond peak L3; a value of 3.5 is mid-way between peak L3 and peak L4, etc.

Host Species and Their Development

The host species that are frequently damaged by the budworm are balsam fir, white spruce, and red spruce. Hemlock can also be severely damaged when mixed with fir or spruce. Black spruce is more resistant, but nevertheless, suffers severe damage and death in certain circumstances. Larch and pines are fed upon, but severe damage is not a problem.

Development of the spruce budworm in the spring seems best adapted to fir and white spruce. Swelling buds are normally available to the bud-mining third instars when they first need them. And, upon molting to L4, flushed buds and expanding shoots are available. Thus, at peak L4, budworms feeding on fir are feeding on expanding shoots, which also provide a target for the deposition of spray droplets. A single application of spray at this time is usually quite successful on fir.

White spruce presents a special problem because a cap of bud scales persists on the tip of the expanding shoot, providing protection from spray for small larvae. Delaying spray until the bud caps are shed, or larvae become large enough that bud caps provide little protection, is recommended. In mixed fir and white spruce, a split application is called for, the early one aimed at L4 on fir and the second against L5 on spruce.

Hemlock appears to be well protected by a single application of spray timed at the fourth instar on fir. Even though hemlock buds break about a week later than those on fir and white spruce, the budworm is not well protected as a bud miner on this species. Buds are so small on hemlock that complete concealment of the larvae is impossible (Hansen and Dimond 1982). Delay beyond this point can be costly on hemlock, however, since developing shoots are small compared to those of fir and spruce, and are destroyed with little feeding. Common spray timings for either fir or spruce generally work well on hemlock.

Bud break on red spruce, black spruce, and their hybrids is latest of the budworm hosts, about two weeks later than fir and white spruce (Greenbank 1963, Hansen and Dimond 1982, Varty and Godin 1983). This presents problems in control of budworm damage that are still not resolved. Treatment timed for fir is likely to find the larvae still mining buds on black or red spruce, and well protected from spray. Furthermore, the prolonged period of bud mining on the spruces results in a substantially greater level of destruction of shoots in the bud stage than on fir or white spruce (Hansen and Dimond 1982, Miller and Kettela 1975). One approach on the late developing spruces is to delay spray treatment until buds have flushed, but with high budworm populations, unacceptable loss of foliage in the bud stage may result. But, there is an earlier spray timing that can also be used. Insects on red spruce and black spruce that complete needle mining, find tight buds that they cannot enter until some swelling has occurred. These insects may remain in silken tubes on the surface of buds (Mott 1963, Hansen and Dimond 1982) or among clusters of previously mined needles (Varty and Godin 1983), and are exposed to sprays.

A split application is recommended for these spruces. The first should be when larvae are at peak L3 on spruce, and would correspond to midway between L3 and L4 on fir. The second should occur after bud flare on the trees, peak L5. Some applications, based on this sequence, have failed on spruce (Varty and Godin 1983) possibly because the second application was made too early, with spruce buds barely broken and larvae well protected. Often there is strong pressure and momentum to complete a spray project as soon as possible once started. This may lead to the second applications being applied too early.

Where target forests are a mixture of fir and red or black spruce, the split timings for spruce will provide the best combined protection for both fir and spruces.

Insect Densities and Vigor of Host Trees

These two factors are related because the important component of budworm densities is the number of insects compared to the number and size of new shoots that will be produced, and trees in poor vigor produce less new growth. Thus, an insect-density threshold, used to determine whether or not to spray, needs to be reduced as host tree vigor declines.

When there are one or more insects per bud at L3, populations are considered extremely high, and loss of current foliage will be complete by L4 - L5. When populations number one for each 2 - 4 buds they are considered high and defoliation may be complete by L5 - L6. Lower populations will result in less than total loss of foliage.

Insect densities and tree vigor determine timing of applications because, under extreme population levels, unacceptable damage can occur, even on balsam fir, before the bud mining stage is completed and insects become exposed to sprays. In response to this problem, trials and operational spraying at 50 percent larval emergence in the spring and later at the L3 - L4 larval stage, were tried in Quebec in the mid-late 1970s, when budworm populations were very high (Randall et al. 1977). While these authors noted good results, several other trials were unsuccessful (Blais 1977, Blais et al. 1981). Blais concluded that applications upon larval emergence in spring were largely useless, and that two applications at L3 and L4 produced better results. If, in extremely high populations, an early application was made, this should be followed by two, for a total of three applications. Blais also suggested that at extremely high populations, foregoing treatment should be considered. Little foliage would be saved by spraying, and the high natural reduction in budworm numbers that accompanies years of peak populations may be lost. Spraying, to regain tree vigor, could resume the next year when population pressure on the trees would be lessened.

As with the spruces, multiple sprays are useful for fir protection when budworm numbers are extremely high. The first application should be at L3, in an attempt to reduce bud losses through mining. The second should be made when the insect is more exposed so as to reduce population numbers substantially.

Blais (1977) reported observations on densities of spruce budworm larvae related to the time when unacceptable damage occurred on balsam fir. He worked in four plots with early-instar larval densities of 19, 29, 95, and 118 larvae per 45 cm branch tip. In the two plots with lower populations, 25 percent defoliation occurred at peak L5 and 50 percent at peak L6. Clearly, if balsam fir were the only important target in these plots, a single application could be used and delayed until L5. In the other two plots, 50 percent defoliation occurred at peak L5 and L4, respectively. Here, split applications would be appropriate. One would hope to achieve a moderate population reduction at L3, reducing bud destruction, and a stronger population reduction with a second application at L4.

Forest Management and Insect Management Goals

For much of the period that budworm-infested stands have been sprayed, the principal goal has been to keep stands alive until they could be harvested. This helps lead to an even flow of wood to mills and a regulated pattern of regeneration of stands. Mature stands, where further growth is a secondary objective, can be kept alive by protecting as little as 30-50 percent of the current foliage in each year of treatment. Here, somewhat later applications, either singles or doubles, are favored. Some foliage can be sacrificed in hopes of achieving greater kill of insects.

Presently, however, with much budworm mortality of trees and much salvage of wood having occurred, there is concern in some regions for future wood supplies. As a result, there is an interest in maintaining good growth rates in younger stands, which requires the protection of 60 to 80 percent of annual foliage growth. In this instance, an earlier application is recommended, and since this alone may not give high kill of insects, split applications are warranted.

The size of budworm outbreaks and the inability to treat entire outbreak areas, among other reasons, makes outbreak suppression with insecticides impossible. Management through spraying aims at reducing insect numbers sufficiently, and early enough, to keep the required amount of foliage (see paragraph above) on the trees for that growing season.

There have been a few, rare cases where attempts at outbreak suppression seemed feasible and gained, at least, temporary success (Blais 1973, Dimond 1976). These situations had the following in common: outbreak patches were discreet with clear boundaries; there were no outbreak areas to the west to provide re-invasion; it was possible to treat entire outbreak areas with a strong insecticide; it was possible to follow up with mop-up applications in the next year or two, if necessary. Declining budworm numbers or unfavorable weather for budworm survival may have contributed to success in these cases. Timing of suppressive treatments in these instances should be delayed to the later instars, with maximum mortality of insects the goal. Two, strong treatments should be applied for maximum benefit if different host species are involved and to avoid any gaps in the spray coverage.

Weather

Weather is a major concern in spray application; spray that does not reach the target is wasted. However, that topic involves application technology and not timing. Here we are assuming that all spray is applied under favorable weather. However, weather remains a factor in timing of application, directly and indirectly.

First, there is an interaction between weather and the spring development of both the budworm and its host trees. In a spring dominated by cool, rainy, cloudy weather, foliage of balsam fir develops relatively faster than the budworm, leading to large, expanding shoots sheltering very tiny caterpillars (Varty and Godin, 1982). Under these conditions, spraying can be delayed, without suffering serious damage.

If budworm populations are moderate, one can consider reducing spray acreage where trees are in good condition. With bright, sunny, warm spring weather, on the other hand, the relative phenologies are reversed, particularly if deep frost or snow is retarding tree development. In this instance, earlier spraying is called for.

Secondly, the weather following spray application should be considered, in addition to the weather during application. Treatment with either chemicals or B.t. perform poorly or fail when application is followed by several days of weather that produces inactivity in budworm larvae. The major factor is temperature, and there will be little budworm activity at temperatures of 10 - 15C. Air temperature is not the only factor. Direct sunshine can increase temperatures within budworm larval microhabitats well above air temperatures. Budworm activity is also reduced by rain or high humidity.

Varty and Godin (1982) make a useful distinction between the inner habitat and outer habitat of budworm larvae. The inner habitat is the needle mine or bud mine or silk tube or webbed shoots that a budworm larva constructs. Spray droplets do not penetrate the inner habitat. The outer habitat is encountered when larvae move from needles to buds or to shoots, when larvae feed on needle tips or bud surfaces or enter a needle, when larvae are spinning down on silk threads or constructing shelters. It is during these displacements that larvae will encounter spray droplets, and these occur only above threshold temperatures, and more frequently at high temperatures. If one must make a choice, it is probably preferable to spray in marginal weather, knowing the next few days will be sunny and warm, than it is to spray in ideal weather, knowing that a prolonged rainy, cloudy, cool period is approaching.

Associated Insects

Another insect often accompanies the budworm during outbreaks. This is the spruce coneworm, common to all spruces, but much less abundant on fir. Spies (1983) showed that, in Maine, 15 to 30 percent of the defoliators on spruce were coneworms rather than budworms. He showed that this relationship is persistent and that spatial and temporal variations in budworm and coneworm numbers have been parallel since the 1940's. It is known that, with some chemical insecticides, coneworm larvae survive spraying better than budworm larvae, and the majority of survivors on spruce may be coneworms (Nicholson and DeBoo 1976, Spies 1983). While we know that the phenology, feeding habits on spruce, and types of damage of the coneworm are very similar to the budworm, we know very little about the best timing of spray application for the coneworm. Yet, some failures to protect spruce with sprays may be as much because we failed to kill coneworm as failing to kill the budworm. We presently have no recommendations for increasing the effectiveness of sprays against the coneworm. The topic requires research.

Final Comments

What preceeds outlines an array of factors that should be considered in the timing of spruce budworm spray operations. However, decisions on timing will usually involve a series of compromises, because sizeable spray blocks are a composite of varying insect densities, varying levels of tree vigor, and varying topography affecting insect and host development. For these and other reasons, few stands will be treated at the optimal time. Planning and striving for best timing, however, will reduce chances of failures.

Further research is needed on all aspects of timing of spruce budworm applications; but of particular note is the difficulty of obtaining reliably good results on spruce.

Acknowledgements

For reviewing this manuscript and providing helpful comments, I thank J. R. Blais, Laurentian Forest Research Centre, Ste. Foy, Quebec and I. W. Varty, Maritimes Forest Research Centre, Fredericton, N. B., Canadian Forestry Service.

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AUTOMATED COUNTER FOR DETECTING AND COUNTING EGG MASSES OF THE SPRUCE BUDWORM

Daniel T. Jennings

Northeastern Forest Experiment Station
USDA Building, University of Maine
Orono, Maine 04469

Abstract

An optical-electronic counter (Prototypes I and II) was designed and developed for detecting and counting egg masses of the spruce budworm and the western spruce budworm. The counter scans foliage samples, detects the presence of egg masses based on their characteristic fluorescing properties, and counts the egg masses electronically.

The spruce budworm, Choristoneura fumiferana (Clemens) (Lepidoptera: Tortricidae), is the most destructive forest insect pest in eastern North America. During epidemics millions of acres of spruce-fir forests are defoliated by larvae of this tortricid moth. Recorded outbreaks of the budworm date back to the early 1700's, but in the 20th century, outbreaks are increasing in frequency, extent, and severity (Blais 1983).

To determine spruce budworm population trends and predict damage levels, many Federal and State agencies spend tens of thousands of dollars each year sampling populations. The egg stage is routinely sampled because it is relatively stable (i.e., immobile) and offers an early warning signal of potential changes in population density. However, egg sampling is the most time-consuming aspect of population work (Morris 1955). Collecting samples of host-tree foliage is difficult and requires specialized equipment, such as extendable pole pruners with clamping devices (Morris 1955; Stein 1969). Once collected, the branch samples are examined for egg masses in the laboratory by trained examiners (Dixon et al. 1978), but the examination process is extremely tedious, time consuming, and subject to human error. Examination accuracy is related to budworm population level, the nature of the foliage, and worker experience (Morris 1951, 1955). Because of these difficulties, Morris (1955 p. 240) stated that the greatest need in the further development of sampling techniques for defoliating insects is for some purely mechanical, chemical, or electrical process for measuring insect abundance on a given quantity of foliage.

This paper describes the design and development of a machine that automatically detects and counts egg masses of the spruce budworm. The counter scans samples of host-tree foliage, detects the presence of egg masses based on their characteristic fluorescence, and counts the egg masses electronically.

Discovery of Fluorescence. -- Egg masses of some coniferophagous budworms fluoresce when excited by longwave ultraviolet (UV) light. The initial discovery of fluorescence (Jennings 1968) was made with the jack pine budworm, Choristoneura pinus pinus Freeman, which lays its eggs on needles of jack pine, Pinus banksiana Lamb. The excitation wavelength extends from 300 to 400 nanometers (nm). Initially we sprayed samples of jack pine foliage with a 0.05-percent solution of Fluorescein[1] in 95-percent ethanol. However, we subsequently found that egg masses fluoresce naturally under blacklight (F40BLB lamp) without treatment.

Improving Accuracy and Efficiency of Foliage Examinations. -- After discovering egg-mass fluorescence, we designed a test to determine if accuracy and efficiency of foliage examinations could be improved by examining branches under blacklight. Samples of jack pine foliage were examined by four technicians under both blacklight and daylight, with examination order reversed for half of the examiners. The time required to examine each branch and the number of egg masses found were recorded. Results showed that blacklight significantly increased the accuracy of count and three of the four examiners found egg masses significantly faster ($P = 0.05$) under blacklight than under daylight (Jennings 1968). Most masses missed under blacklight were either parasitized or laid the previous year or years (i.e., old).

Additional tests with the western spruce budworm, Choristoneura occidentalis Freeman, and egg masses on Douglas-fir, Pseudotsuga menziesii var. glauca (Beissn.) Franco, foliage showed that egg masses were found more quickly (48% faster) and accurately (22% more egg

[1]The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U.S. Department of Agriculture or the Forest Service of any product or service to the exclusion of others that may be suitable. This Study is part of the Canada/United States (CANUSA) Spruce Budworms Program.

masses) with longwave UV light than with visible light (Acciavatti and Jennings 1976). Again, most egg masses missed under UV light (89%) were old and parasitized, whereas almost half of those missed under visible light (42%) were new. Morris (1955) indicated that the proficiency of inexperienced examiners is low; they may miss over 50% of the egg masses.

Design and Development of Prototype I. -- In 1976 a study was initiated at the University of Maine, Departments of Physics and Astronomy, Electrical Engineering, and Entomology, in collaboration with the Northeastern Forest Experiment Station to: 1) determine the fluorescence properties of spruce budworm egg masses, 2) determine the fluorescence properties of associated components on balsam fir foliage, and 3) determine the feasibility of using these properties to design and build a machine that scans foliage samples, detects egg masses, and counts the egg masses electronically.[2,3]

A Turner® model III filter fluorometer was used for measuring fluorescence of spruce budworm egg masses and associated components on balsam fir foliage. This fluorometer has a high-pressure mercury arc lamp. A 7-60 filter was used to pass light (ca. 365 nm); the transmission band of this filter extends from 300 to 400 nm and corresponds to the long wavelength UV light used in previous studies (Jennings 1968). Different colored detector filters were used to study fluorescence; preliminary measurements indicated that violet (47B + 2A) and green (58) filters were the most useful. Background fluorescence levels were measured before and after each series of samples.

Results of spectral analyses with the Turner fluorometer indicated that egg masses of the spruce budworm have a characteristic violet and green fluorescence that is distinguishable from most other fluorescing components on balsam fir foliage.[4] Egg mass fluorescence shows activity predominately in the violet region, but the ratio of green to violet fluorescence is also important. By measuring levels of fluorescence and calculating ratios of green to violet fluorescence, egg masses of the spruce budworm can be distinguished from other fluorescing objects (e.g., buds, pitch droplets) on balsam fir foliage.

A prototype illumination and detection system was then designed and constructed. Basic components of the system include: a GE® 100 watt AC mercury arc lamp for source illumination; a highly transparent quartz lens for focusing the UV light source onto the sample; an adjustable field stop (0.7, 1.0, 1.4, or 2.0 mm diam.); two RCA® 8053 photomultiplier tubes (PMT) for detectors; a high-voltage power supply; and blue and green dichroic color filters for filtering light to the PMT's. The adjustable field stop allows for a point-to-point scan of foliage.

Tests of the prototype illumination and detection system confirmed that egg masses of the spruce budworm have characteristic fluorescence that is distinguishable from most other foliage components. With the prototype system, fluorescence levels no longer depend on object size; objects can be scanned point by point (2 mm). The brighter lamp, dichroic beam splitter, and sensitive detectors enabled detection and measurement of large signals (0.1 to 1 volts) for egg masses.

A conveyor belt with variable motor-speed drive was added to the prototype system housed in a light-tight chamber with entry and exit ports. Branch samples are placed on the conveyor belt, passed beneath the scanner-detector system, and discharged at the other end. A rotating mirror images and sweeps the UV spot (2 mm) across the foliage as the foliage passes beneath the scanner-detector system.

In cooperation with the University of Maine, Department of Electrical Engineering, and the Maine Forest Service, the Prototype I

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[2]Cooperative Research Agreement 23-824, U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station, and the University of Maine, College of Arts and Sciences, Department of Physics; A Prototype of a Spruce Budworm Egg Mass Counter; 1976. 6 p.

[3]Carniglia, Charles K.; Jennings, Daniel T. A prototype of a spurce budworm egg mass counter. Studv Plan NE-1151-65. Orono, ME: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station; 1977. 6 p.

[4]Carniglia, C.K.; Jennings, D.T.; Simmons, G.A.; Olsen, E.T. Investigation of the fluorescence properties of balsam fir foliage for the purpose of building an automatic spruce budworm egg mass counter. Final Rept., Cooperative Research Agreement 23-824. Orono, ME: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station, and the University of Maine, College of Arts and Sciences, Department of Physics; 1977. 49 p.

egg-mass counter was tested in 1979.[5] Branches were first examined using the machine (electronic counts) and then by human observers (manual counts). Records were kept of processing time, numbers of egg masses found, and foliage conditions. Efforts were made to collect and test foliage with low, medium, and high egg-mass densities.

Results of Prototype I tests indicated that, when calibrated, manual counts can be predicted ($R^2 = 0.97$, $\alpha = 0.01$) from electronic counts. And, electronic counting showed a highly significant ($\alpha = 0.01$) reduction in processing time. Manual examinations required a mean of 29.5 minutes per branch, whereas electronic examinations required only 8.6 minutes per branch. The mean difference of 21 minutes per branch represents a considerable savings in time and costs when large numbers of branch samples are examined. A patent (U.S. Patent 4,390,787) was applied for and granted to the inventors of Prototype I (Jennings et al. 1983).

Design and Development of Prototype II. -- A new egg-mass counter (Prototype II) is currently being designed and developed at the Forest Service Missoula Equipment Development Center, Fort Missoula, Montana. New design features include: a variable optical scanning system to detect fluorescence of both spruce budworm and western spruce budworm egg masses; programmable "windows" for setting maximum-minimum detection levels and for screening fluorescing components on five host trees (balsam fir, spruce, Douglas-fir, white fir, and grand fir); a stepper motor with variable belt-drive system; and a programmable microprocessor for operation and maintenance. Prototype II also has an "egg hunt" routine for scanning foliage until an egg mass is found, stopping, and then allowing the operator to view what the machine "sees." Field test of Prototype II is expected in 1984.

[5]Cooperative Research Agreement 23-256, U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station, and the University of Maine, Department of Electrical Engineering; Evaluation of a Prototype Spruce Budworm Egg Mass Counter; 1979. 4 p.

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A SENSITIVE PHEROMONE DETECTION SYSTEM

Edward A. Meighen

Department of Biochemistry, McGill University, 3655 Drummond Street, Montreal, Quebec H3G 1Y6

A very rapid, simple, and highly sensitive assay for measuring the release rates of pheromones from insect lures involves the use of cold traps and analysis of the trapped pheromone based on the bioluminescence response of luciferase to long chain aldehydes. The assay is highly reproducible and trapping times as low as 5 min can be used. The sample need only be dissolved in water at room temperature and then injected into the luminescence assay. The release rate of 1 lure can be measured in less than 30 min requiring only a few minutes of the investigators time and permitting the routine processing of a large number of samples.

Introduction

Insect lures containing pheromone formulations are useful as attractants in monitoring and/or controlling insect populations. One of the important factors in interpreting the insect response to the lures is knowledge of the release rates of pheromone under different laboratory and field conditions. Variation in release rates of pheromones from lures will depend upon not only environmental conditions such as wind velocity and temperature, but also on the age, storage conditions, composition and design of the lure (Bierl-Leonhardt 1982; Daterman, 1982). In addition, measurement of the release rate of pheromone lures in the laboratory, can be affected by such factors as the design of the instrumentation (release chamber), the method of trapping the airborne pheromone or measuring its loss from the lure, the degree of sample manipulation, and even the method of analysis. It is also necessary to know the variability in release rate from one lure to another within a batch of insect lures so that the extent of variation in trap catches can be analyzed. Such differences in lure release rates may only be evident under specific conditions such as short (or long) storage of the lures or more extreme environmental conditions. In these latter cases, the information is valuable in terms of deciding the conditions of storage and how, when and for how long these lures should be used under field conditions. Unfortunately, most of this data is generally unavailable for insect lures. The absence of a standardized system for measuring the release rates of lures and the effect of these different factors has turned an apparently simple problem on the surface into a situation where the comparison of lure release rates between different analysis systems and laboratories cannot be conducted in many cases with any degree of confidence.

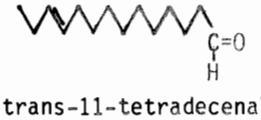
The most common method for measuring the release rate of pheromones from lures involves trapping the released pheromone on a solid absorbent, followed by gas chromatography and analysis by flame ionization detectors (Byrne et al., 1975; Baker et al., 1980; Cross et al., 1980). However, this method is slow, requiring relatively extensive manipulation of the sample and limits the number of analyses that can be performed. Furthermore, agreement between the release rates of pheromone lures measured by gas chromatography and other techniques has not been clearly established particularly with lures containing less stable chemical formulations. For example, the release rate of gossyplure measured by gas chromatography is much lower than that observed by direct release of radioactivity from a ^{14}C-labelled pheromone formulation (Weatherston et al., 1981).

Recently, we have shown that aldehyde pheromones can be detected at very low levels in a luminescence coupled system (Meighen et al., 1982; Grant et al., 1982). In this assay, bacterial luciferase catalyzes the oxidation of the aldehyde to the corresponding fatty acid in the presence of $FMNH_2$ and O_2 resulting in the emission of light as shown below.

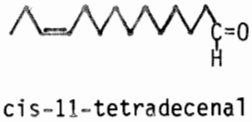
$$FMNH_2^+ \; O_2 + \underset{\text{(Aldehyde)}}{R\text{-}\overset{O}{\overset{\|}{C}}\text{-}H} \longrightarrow R\text{-}\overset{O}{\overset{\|}{C}}\text{-}OH + FMN + H_2O + h\nu_{490nm}$$

As the analyses is conducted in aqueous solution, it is possible to use simple cold traps to collect airborne pheromone and analyze the trapped pheromone directly in water without further manipulation of the sample (Meighen et al., 1983). The luminescence response is proportional over a wide range to the amount of aldehyde injected into the assay and since maximum luminescence is reached in less than a second, analysis is extremely rapid.

The bioluminescent system can be used to measure different aldehyde pheromones even if they contain cis and/or trans double bonds with optimal response to chain lengths of thirteen to sixteen carbons (Meighen et al., 1982). Amounts as low as 20 pg of the aldehyde pheromone of the spruce budworm (trans-11-tetradecenal (96%) and cis-11-tetradecenal (4%), Sanders and Weatherston, 1976) have been detected.



trans-11-tetradecenal



cis-11-tetradecenal

Consequently it has been possible to measure the daily rhythmn of pheromone release and the rise and fall in pheromone levels in the glands of individual female moths (Morse et al., 1982). Other insect pheromones can easily be analyzed including those from such destructive insect pests as the tobacco budworm, the corn earworm and the navel orangeworm (Grant et al., 1982). By enzymic conversion of fatty alcohols and acetate esters to the corresponding aldehyde before luminescence analysis (unpublished experiments) the bioluminescent assay can be extended to a wide range of other insect pheromones.

The present report focuses on the analysis of release rates of insect lures using a combination of cold traps and luminescent analyses (Meighen et al., 1983). As the assay is highly sensitive, trapping need only be conducted for 5 min for a single lure, and analysis requires only a few minutes of the investigators time.

Cold Trapping of Airborne Pheromone

The release chamber and trapping system outlined in Figure 1 is a simple, inexpensive and very rapid method for collecting pheromone released from various emitters including insect lures. In this system, the lure is placed in a 16 mm glass tube about 8 cm from the outlet (Fig. 1). Air prefiltered through Porapak is dispersed by the glass wool to give laminar airflow and then passed over the lure. The pheromone is trapped by passage of the air through two 20 ml vials maintained at below -20°C. Trapping can only be conducted for periods of 1 hour or less since the build-up of ice in the apparatus will decrease the flow rate at longer times.

Water (~ 9 ml), part of which is used to rinse the short inlet tube, is added to each vial containing pheromone and ice (~ 1 ml), the sample is then vortexed for 10 sec and equilibrated at room temperature for 10 min before 1.0 ml aliquots are analyzed in the luminescence assay.

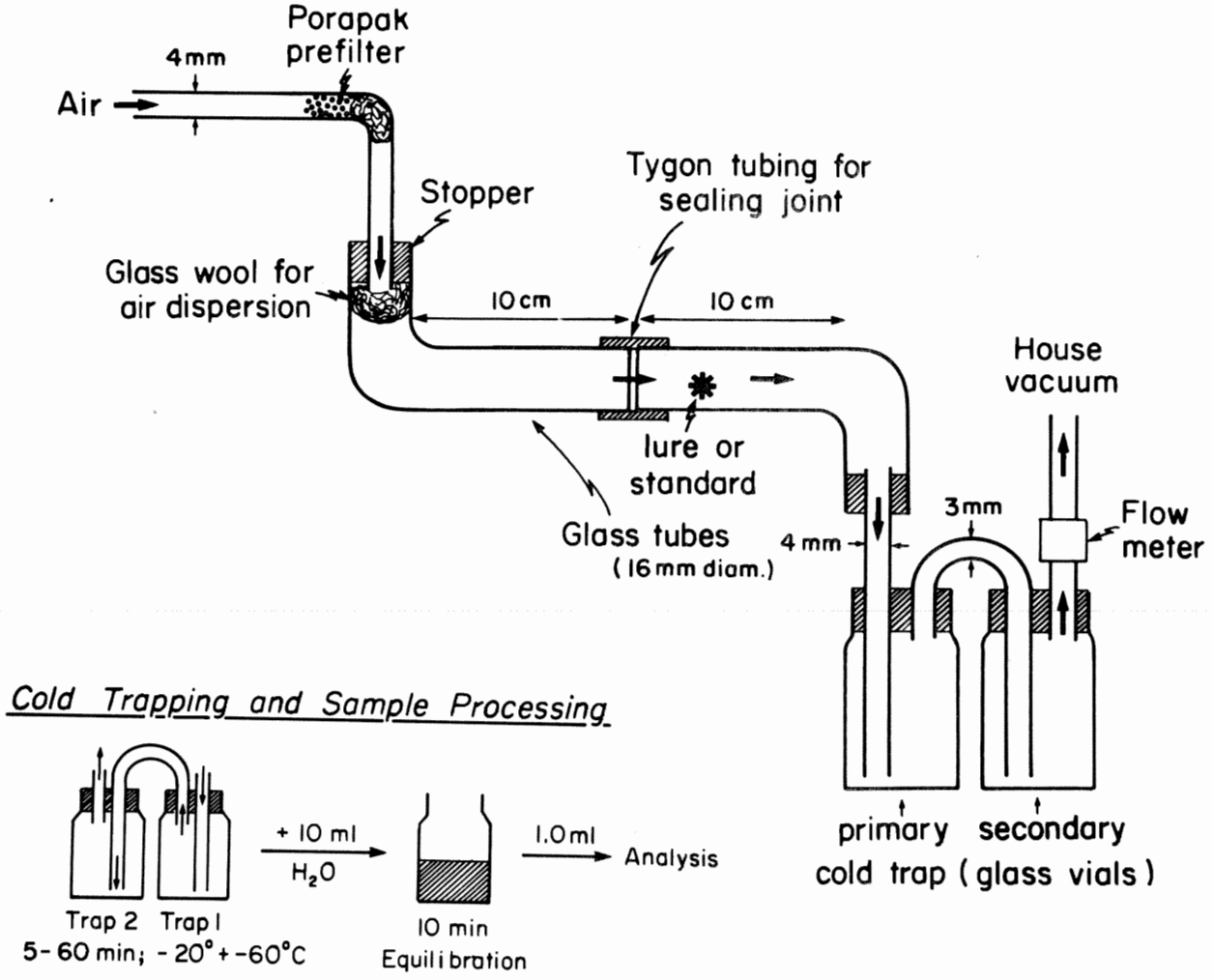


Figure 1. Release chamber, cold trapping, and sample processing for measurement of the release rates of pheromone lures.

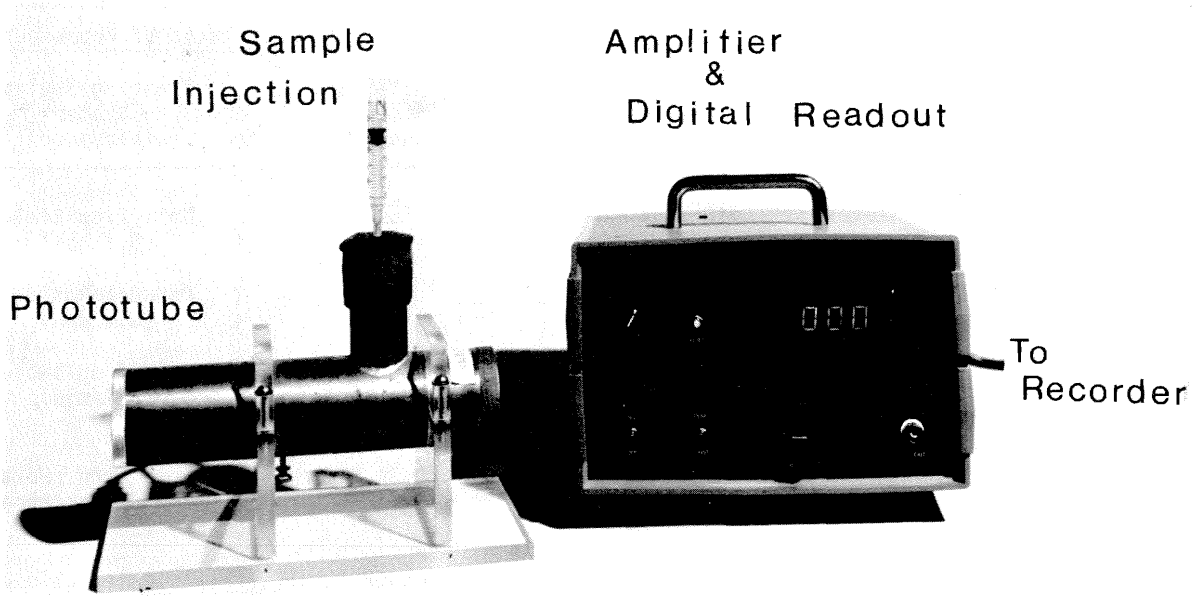


Figure 2. Equipment for the bioluminescence analysis of aldehyde pheromones.

Bioluminescence Analyses of Aldehyde Pheromone

Aldehyde pheromone in water (1.0 ml) is injected by syringe into 1.0 ml of assay medium contained in a 20 ml vial which has been placed in a light tight chamber and exposed to a photomultiplier tube (Fig. 2). The assay medium contains 0.001 M NH_2OH, 0.05 M β-mercaptoethanol, 0.05 M Na/K phosphate, pH 7.0, and 50 μM flavin mononucleotide (FMN). A constant amount (~ 5 μg) of bacterial luciferase (10 μl of a 0.05% solution) is added to the assay medium followed by a small excess (~ 0.5 mg) of sodium dithionite (Meighen & MacKenzie, 1973) to reduce the FMN (yellow) to $FMNH_2$ (clear) just before injection of the aldehyde pheromone. Stock solutions of luciferase (10 mg/ml) were purified from the luminescent bacterium, Vibrio harveyi (Gunsulus-Miguel et al., 1972) and can be stored for at least 2 years in 35% glycerol at -20°C without loss of activity. Enough enzyme is obtained from 10 liters of bacterial culture to conduct over 10,000 assays. Secondary luciferase stocks (0.05%) are prepared by dilution (1:20) of the stock 1% luciferase into 0.05 M β-mercaptoethanol, 0.05 M phosphate, pH 7.0, at 4°C and used within a period of 2 to 3 days.

Light emission is detected by a photomultiplier tube, amplified and the maximum emission is either recorded graphically or on a digital readout. Figure 3 illustrates the response to 21 ng of the trans and cis isomers of 11-tetradecenal, the pheromone components of the spruce budworm. The maximum luminescence (in light units, LU) is directly proportional to the amount of a specific aldehyde pheromone over a wide range (0.2 - 500 ng).

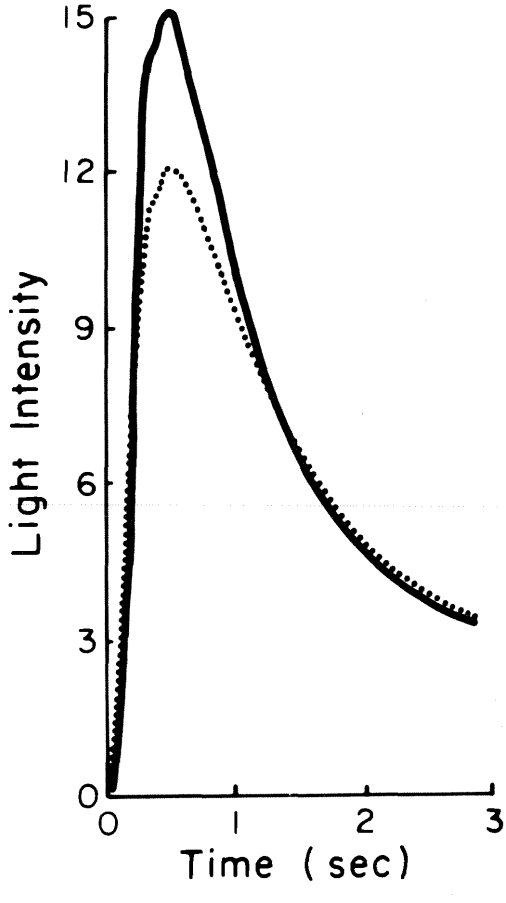


Figure 3. Luminescent response to 100 pmol of trans-11-tetradecenal (——) and cis-11-tetradecenal (••••).

Analysis of the Release Rates of Insect Lures

The combination of cold trapping and bioluminescence analysis leads to a very rapid and sensitive method for measuring the release rates of phromones. The efficiency of recovery of pheromone in the trapping system is not only high, but reproducible from one analysis to another. Using a fixed amount of trans-11-tetradecanal in the release system, an average of 69% of the pheromone was collected in the first trap on analysis of 40 control samples over a period of two months with a standard deviation of only 7%. Consequently, only the amount of aldehyde in the first trap needs to be measured for routine processing of samples without taking into account the level of pheromone ($\simeq$ 16%) in the second trap. For example, if 1 μg of trans-11-tetradecenal or cis-9-hexadecenal are placed in the release chamber, luminescence responses of 35 LU and 24 LU, respectively, will be obtained on analysis of a 1.0 ml aliquot from the first trap corresponding to 10% of the sample. The luminescence response is proportional to the amount of a particular aldehyde pheromone and is limited by the background response (no added pheromone) which is approximately 0.04 LU under these trapping and assay conditions. Thus even amounts as low as 4 ng can be released in this system (in $\leq$ 1 hour) and then detected on analysis of only 10% of the trapped sample. The lower limit of pheromone release capable of being measured in this system is therefore $\sim$ 0.1 μg/day.

Table 1 gives the release rates of a number of different pheromone formulations. A direct comparison of the release rates measured by two completely different systems was accomplished by using a lure containing [1-^{14}C]cis-9-hexadecenal and analyzing the amount of radioactivity released and the bioluminescence response to trapped pheromone. In order to obtain sufficient radioactivity, trapping had to be conducted for 20 hours whereas only 30 min trapping was needed for the cold trap bioluminescence system. Excellent agreement in release rates between these two systems was obtained for 2 day old lures whereas a lower rate ($\sim$ 50%) was obtained in the luminescence system for 4 day old lures possibly reflecting some degradation of the ^{14}C-labelled pheromone. In a similar study in another pheromone release system (Weatherston *et al.*, 1981), the amount of radioactivity released in a flow system was over 18-fold higher than the amount of pheromone released determined by gas chromatography. The closer agreement between the amount of radio- activity released and the luminescent response may reflect the very short times required for analysis in the luminescent assay and the low temperature of the trapping system which minimizes any degradation of the pheromone.

The release rates for PVC, fiber, and flake lures containing the spruce budworm pheromone formulation are also shown in Table 1. A decrease in rate of release of pheromone is observed on storing the lures at 21°C with a half time of about 30 days for all three lures. The variation between individual lures of the same type and batch are relatively low ($<$ 20% S.D. after 20 days) providing the age and storage

TABLE 1

Release Rates of Pheromone Lures

Lure[a] and Storage Conditions	Age	Trapping/Analysis System[b] (airspeed)	Release Rate[c] μg/day
Fiber Z-9-C_{16}-al 0.4 mph	2	Cold Trap/Biolum. (0.4 mph)	3.7
	4		1.8
	2	Porapak/Radioact. (0.4 mph)	3.6
	4		3.8
3% PVC Still Air	5	Cold Trap/Biolum. (2 l/min)	48
	30		31
	60		20
0.3% PVC Still Air	5	Cold Trap [Porapak] Bioluminescence (2 l/min)	4.0[2.4]
	30		2.2[1.5]
	60		1.3[1.4]
Fiber[1 mph] Still Air	6	Cold Trap/Biolum. (1 mph)	5.0[2.2]
	40		2.4
Flake[1 mph] Still Air	6	Cold Trap/Biolum. (1 mph)	0.83[0.8]
	40		0.40

[a] All lures contained the spruce budworm pheromone except for the first fiber lure which consisted of [1-^{14}C]-cis-9-hexadecenal (courtesy of M. Golub, Conrel). Polyvinyl chloride (PVC) lures (130 mg) containing 3% and 0.3% by weight of pheromone were received courtesy of Dr. C. Sanders, Great Lakes Forest Research Centre, Sault Ste Marie. Fiber lures (1.25cm; $\sim$ 0.1mm, i.d.) containing $\sim$ 60 μg of pheromone were from Conrel (Albany Int.) and flake lures (1cm^2) containing $\sim$ 500 μg of pheromone were from Hercon (Herculite Products). The temperature for storage and release was 21°C.

[b] Trapping on Porapak Q and bioluminescence analysis was conducted as described by Szittner *et al* (1982). For radioactivity analysis, trapping was conducted for 20 to 22 hours to obtain sufficient counts ($\sim$ 10 cpm per hour) and the Porapak extracted into the scintillation cocktail (Econofluor).

[c] The values in square brackets refer to the indicated changes in storage or trapping of the pheromone lure.

conditions are identical. Changes in the storage conditions will affect the release rates of the lures (Sanders, 1981) with the relative effects being dependent on the severity of the conditions, and the age and type of lure.

The release rates for the PVC formulations are in excellent agreement with the values reported by Sanders (1981) based on weight loss measurements. For example, after 40 days of equilibration, release rates of 25 μg/day and 2.5 μg/day based on weight loss were obtained for the 3% and 0.3% formulations, respectively.

The large effects of wind velocity and temperature on the release rates of pheromone from the fiber and flake lures are shown in Table 2. A decrease in wind velocity of 10-fold

TABLE 2

Dependence of Pheromone Release Rates On Wind Velocity and Temperature

Conditions		Release Rate[a]	
Wind Velocity (mph)	Temperature (°C)	Fiber	Flake
1.0	21	100	100
0.4	21	60	80
0.1	21	10	20
1.0	31	300	400
1.0	15	80	90

[a]Percentage of release rate at 21°C and 1 mph measured by the cold trap/bioluminescence system for fiber and flake lures containing the spruce budworm pheromone.

causes a drop in the release rate of 5 to 10-fold depending on the type of lure. Similarily, an increase of 10°C in the temperature results in an increase of 3- to 4-fold in the rate of pheromone release. The relative effects of changes in the temperature and wind velocity on release rates have been found to be dependent on one another to some degree. These effects may also be dependent on the past history (age and storage conditions) of the lure.

Knowledge of the release rates of insect lures and the effects of different factors on pheromone release is important for their effective use in controlling and/or monitoring insect populations under field conditions. A standardized system for comparing the release rates of lures from one laboratory to another and between different lures is essential. The cold trap-bioluminescence system has the sensitivity, reproducibility and speed for routine and rapid analysis of a wide range of insect lures.

Acknowledgements

This work was supported by grants from the U.S.D.A. Forest Service Program entitled Canada United States Spruce Budworm Program (CANUSA, east) and the Medical Research Council of Canada.

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THE ROLE OF SEX PHEROMONE TRAPS IN COPING WITH THE SPRUCE BUDWORM PROBLEM

C.J. Sanders

Research Scientist, Great Lakes Forest Research Centre, Canadian Forestry Service, P.O. Box 490, Sault Ste. Marie, Ontario, P6A 5M7.

Abstract

Traps baited with the sex pheromone of the spruce budworm provide the forest manager with an inexpensive, efficient method of monitoring changes in budworm populations even at low densities. Comparison of catches from year to year indicates population trends and provides early warning of outbreaks. Correlations between trap catch and population density suggest that sex pheromone traps can supplement, or even replace, other more costly sampling techniques as indicators of absolute density. Comparability of catches from year to year is affected by many factors. Some, such as climate and stand conditions are uncontrollable, but can be allowed for. Others, such as trap and lure design have been the subject of considerable research and the necessary attributes have been defined. Field tests are in their final phases to determine the best available commercial designs for a coordinated operational program throughout northeastern North America.

Historically, management of North American forests to cope with insect pests, such as the spruce budworm (*Choristoneura fumiferana* [Clem.]) has been carried out with only a short-term horizon; action is taken only when trees are about to die, and then it is limited to accelerated harvesting, salvage cutting or to the application of insecticide to kill enough insects to protect the foliage and keep the trees alive.

This situation is largely a reflection of the level of forest management in North America; investment in the growing stock is minimal, inventories are inaccurate and out of date and growth and yield data are sketchy. But this situation is changing. As the resource becomes increasingly depleted, more intensive management will be essential if the supply is to be maintained. Not only will this necessitate more detailed and accurate inventories and better predictions of growth and yield, it will also require more accurate estimates of losses due to insect and disease, and more accurate predictions of where and when the losses will take place, so that remedial action can be planned well in advance.

Our knowledge of budworm population dynamics has not yet reached the point where we can predict outbreaks with any accuracy, but our understanding is improving. Even now, it may be possible to provide much more advanced warning than was available in the past.

Between outbreaks spruce budworm numbers can drop to extremely low values, lower than many of the other associated defoliating insects. For instance, during the period 1961 to 1965, 800 branch-samples were collected from host trees in northwestern Ontario each year--a total of 4000 branches during the 5 years, but in that time only 3 spruce budworm larvae were found, less than 1 per 1000 branches. Similarly low population densities were recorded by Miller and McDougall (1966) in the early 1960s in northern New Brunswick. Given such low population densities how can we detect the beginnings of the next outbreak?

Conventional sampling using pole pruners is not practical at these densities. The generally accepted threshold density at which it provides meaningful estimates is 1 larva/branch. This level represents a 1000-fold increase over the densities recorded between outbreaks, and may already be too late for preventative action to be taken. Beating-mat samples, long in use by the Forest Insect and Disease Survey Branch of CFS, although easier to obtain than branch samples, suffer the same problem; large numbers of samples are required to reflect changes in population density when populations are sparse (Miller et al. 1968).

The alternative is the use of sex pheromone traps. When ready to mate, female moths of nearly all species release chemical blends which act as a signal and guidance system for the male moths. These sex pheromones are highly potent and species-specific, and are extremely effective in luring male moths to traps. They are now in use or under development for the detection and monitoring of numerous species. Their advantages are their species-specificity (only the target insect is captured in contrast to light-traps) they are inexpensive, easy to use and very efficient. In northwestern Ontario when populations were extremely low in the 1960s traps baited with virgin female spruce budworm, caught an average of 19 males/trap in one year, while Miller and McDougall (1973) caught 152 males over a 2-yr period in 25 traps when populations were extremely low in the early 1960s in northern New Brunswick.

To be successful a sex pheromone trapping system requires 3 basic ingredients, 1) a potent attractant, 2) a formulation for protecting the attractant from degradation and which releases the attractant at a constant rate, and 3) a suitable trap design.

The chemical composition of the spruce budworm pheromone has been identified (Sanders and Weatherston 1976; Silk et al. 1980). There is some evidence that some minor components are missing (Sanders 1984a), but as a lure the known blend [(E)- and (Z)-11-tetradecenal in a ratio of 95(E):5(Z)] is as effective as a virgin female moth (Sanders 1981) and it is unlikely other ingredients will make any major difference.

Four formulations have been tested and found adequate for dispensing the pheromone (Fig. 1). The solid polyvinyl chloride formulation has been used for many years and has been tested extensively (Sanders 1981; Meighen et al. 1983). The Hercon plastic laminate chip and the Albany International (Conrel) hollow fibre have also been widely used both in Canada and the U.S. (D.C. Allen and cooperators pers. comm.). The Bend encapsulated formulation has not been widely tested yet. The important criteria are that the pheromone should be released at a constant, specified rate, that there is little variation among the lures in any one year or from year to year. A release rate in the range of 20-100 ng/h has been selected as the required release rate, which is relatively low and creates some problems for the formulators. Further testing is required before a 'best' dispenser is decided on, probably all four will eventually prove equally suitable; the final choice may be one of cost.

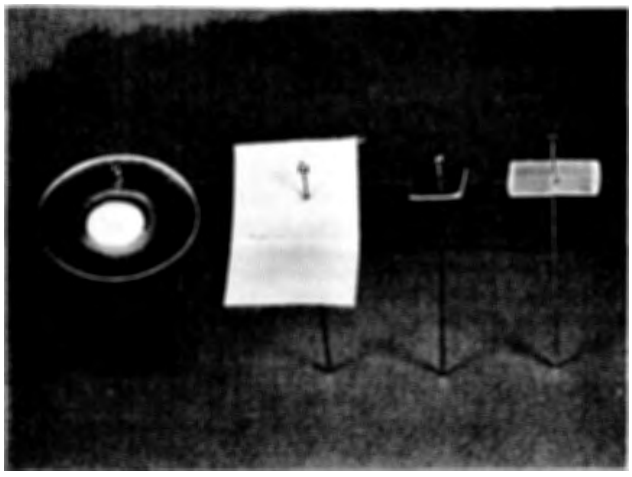

Fig. 1. Formulations for dispensing insect sex pheromones. L-R. Bend capsule, Albany International (Conrel) hollow-fibre (mounted on paper backing), Hercon plastic laminate, polyvinyl chloride (PVC) pellet.

The major variable which has been investigated, both by us in Canada and by CANUSA sponsored researchers in the U.S., is trap design. Initially, sticky traps were used, which have been in common use for many lepidopterous pests for several years, and the Pherocon 1CP was selected as the best suited for monitoring the spruce budworm (Sanders 1978). However, such traps have only a limited capacity before the sticky surface becomes covered by moths and wing-scales, limiting their ability to catch more moths. The 'saturation point' of Pherocon 1CP traps is about 50 moths/trap, a point which is reached quite quickly even with low potency lures when population densities exceed 1 larva/branch (Houseweart et al. 1981). If the traps are to be used only as an early warning system, then trap saturation could be taken as the threshold value for more detailed sampling using more conventional sampling methods. However, Ramaswamy and Cardé (1982) found that funnel traps were probably as effective as the sticky traps at low densities, but with the advantage that they could be used over a much wider range of population densities. This raises the possibility that sex pheromone traps could be used to provide accurate, quantitative estimates of population density, so replacing other sampling techniques, instead of just extending our ability to monitor low density populations. A number of such 'non-saturating' traps are now available (Fig. 2). All operate on the same principal; the pheromone lure is placed inside the trap, together with a piece of plastic, impregnated with dichlorvos (such as Vapona, Fly-tox or No-pest strips) to kill the trapped insects. The question to be answered now is which trap design is best suited for our purpose. It is important that we make the right decision now, before an extensive, long-term trapping program begins, because changing trap design in the middle will necessitate re-calibrating the trap-catches against population density, and will make long-term trend analysis meaningless, or difficult to interpret.

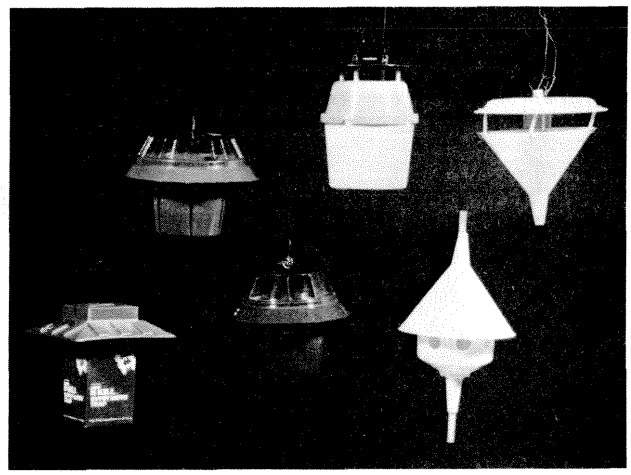

Fig. 2. Six designs of non-saturating, non-sticky traps tested for monitoring spruce budworm populations. top, L-R. Health-Chem plastic canister, International Pheromones Ltd. Uni-trap, Covered funnel trap. Bottom, L-R. Health-Chem milk carton, Baker Chemicals Bag-a-Bug, Double funnel trap.

One measure of a trap's suitability for estimating population density is to see how well trap catches correlate with other estimators of population density over a wide range of densities. Such correlations have now been gathered in a number of places for a number of years (Ramaswamy et al. 1983; Allen and cooperators, pers. comm.; Sanders 1984b). Regression coefficients (r^2) range up to

80%, indicating beyond doubt that sex pheromone traps do have potential for estimating population density. Most of this work has been done with 'homemade' traps, the covered funnel trap or the double funnel trap (Fig. 2).

For standardization of an operational system covering many different jurisdictions, there is considerable merit in using a readily available commercial trap. Attention has now turned to evaluating these. Two traps marketed by Health-Chem for gypsy moths, the milk carton and plastic canister trap (Fig. 2) were used with minor modifications in a number of trials in 1983 carried out in Canada and the U.S. In some instances regression coefficients were quite high, but observations by a number of cooperators on moth behaviour coupled with low catches (Allen pers. comm.) raised questions about suitability of the designs for trapping spruce budworm moths. In other trials variation in catch among traps was high, a feature which suggests catches may be unreliable.

Recently we have made observations on trap-performance in a wind tunnel. The first test was to determine how long a moth had to remain inside the trap to be overcome by the dichlorvos fumes. Moths were placed in a jar with the standard-sized piece of dichlorvos plastic strip and the time taken before the moths became incapacitated was recorded. The experiment was repeated with strips of different age to see if the effects were slower as the strip aged. The results were as follows:

Age of insecticide strip (weeks)	Average time to incapacitate moths (min.)
0	2.06
1	3.13
2	4.00
3	4.42
4	6.52

This shows that there is an aging effect, but that a figure of 5 min. is a reasonable estimate of how long a moth must remain in the trap to be considered 'caught'.

Each trap in turn was then hung in the tunnel, baited with pheromone. Moths were released one at a time in the pheromone plume and their subsequent behaviour recorded, whether they entered the trap, whether they escaped, and how many remained inside for 5 min. Table 1 shows the results and includes the numbers of moths captured in each trap design in a low population of spruce budworm in the field in 1983. The largest numbers of moths entered the 2 trap designs which had the 'all round' openings (the CFT and IPL). However, the moths escaped from the CFT almost as fast as they entered, while in the IPL only 1 escaped out of 22 entering, a function of the inverse funnel inside the trap acting as a barrier to escape. Moths also easily entered (but also easily escaped from) the milk carton trap. Numbers entering the other designs were lower, and observations showed that this was due to difficulties the moths had in locating the openings under the overhanging 'eaves' of the traps. Clearly the IPL trap is the most efficient in capturing the moths attracted by the pheromone in the wind tunnel. Furthermore, the wind tunnel data on the numbers remaining in the traps are in close agreement with the field trapping data, suggesting that the same factors are operating in both situations, implying that the wind tunnel tests are a valid indication of what may be expected in the field.

Table 1. Comparative performance of 6 non-sticky sex pheromone traps in a wind tunnel and in the field.

Trap design	Wind tunnel: Number* entering trap	Wind tunnel: Number* escaping	Wind tunnel: Number† remaining in trap	Field: Number captured
International Pheromone	22	2	20	78
Health-Chem "carton"	17	15	4	3
Health-Chem "canister"	11	9	4	7
Bag-a-Bug	4	1	3	8
Covered funnel	21	17	7	26
Double funnel	14	5	9	39

* Within 5 min. period after release of moth.
† At end of 5 min. period, including those which escaped and re-entered.

Also, during our wind tunnel observations, we recorded where the moths first contacted the trap as they approached upwind along the pheromone plume. The results (Table 2) were rather surprising. Initial contact was anywhere on the traps, from the tops to the very bottom. Only in the CFT and IPL traps did any moths contact the opening where the pheromone is being released.

Table 2. Percentages of male spruce budworm making initial contact on different portions of 6 non-sticky sex pheromone trap designs (shown diagrammatically).

	IPL	Can-ister	Car-ton	B-a-B	CFT	DFT
	0	3	13	13	4	21
	0	17	37	24	0	27
	4	0	0	0	14	0
	60	22	7	13	36	19
	36	58	43	50	46	33

This implies that the pheromone is not being emitted in a very clear cut plume, and this was checked out by releasing titanium chloride 'smoke' from the traps in the wind tunnel. The resulting 'plumes' corroborated the behavioural observations (Fig. 3). The in-filling of air around the downwind side of the traps carries the pheromone with it. As a result the smoke appeared as a fog from those traps with the holes, much of it emitting from the side holes as well as those on the downwind side, and the concentration appeared to be similar from top to bottom of the trap. By contrast, smoke from the CFT and IPL traps tended to appear in more of a plume, presumably because the airflow was smoother, with a distinct flow through the open area below the roof.

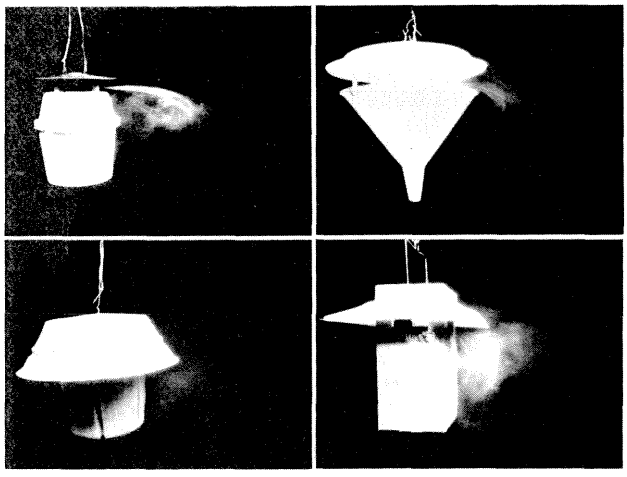

Fig. 3. Flow of titanium chloride fumes from pheromone dispensers in four non-saturating traps. Top L-R. IPL, Covered funnel, Bottom L-R. Health-Chem plastic canister and milk carton.

The important criterion by which to judge the suitability of a trap for population monitoring is not necessarily how many moths it catches, but how closely the catches reflect the true population density. Therefore the final trap choice must await data on correlations between trap catch and larval and/or egg densities. Nevertheless the fact that the IPL trap catches and retains most of the attracted insects is an important point in its favour. There are many factors which influence trap performance, some of these such as trap position, trap height and distance between traps can be standardized. Others, such as the effects of stand composition, temperature, and humidity cannot. Inefficient traps introduce yet another variable leading to variation in trap catch which should be avoided if possible.

Conclusion

Traps baited with the sex pheromone of the spruce budworm can provide information at several levels of complexity for assisting in the long-term management of budworm-prone forests.

At the simplest level sex pheromone traps placed out in the same locations year after year can provide data for time-series analysis, using the catches as a comparative annual index of population density.

At the next level, knowledge of the relationship between trap catch and population density, would allow us to select 'thresholds', i.e, numbers where some further action, such as more detailed sampling, is required.

Finally, the establishment of correlations between trap catch and population density can provide the forest manager with another sampling tool which can supplement, or even replace, some of the sampling that is now done with more costly and time-consuming techniques.

For the first two, time series analysis and thresholds, the cheap and convenient sticky traps are suitable. For the third, quantitative estimates of population density, more expensive non-saturating traps are necessary. Although any of the non-saturating trap designs discussed here are probably adequate for this purpose, the fact that we are embarking on an extensive, long-term monitoring program requiring a standardized trap, means we must ensure that we have the best available trap for the purpose. By the end of 1984 we should know which this is.

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MODELS OF BUDWORM-FOREST DYNAMICS AND THEIR IMPLICATIONS FOR MANAGEMENT

Jery R. Stedinger 1/

Associate Professor, Department of Environmental Engineering, Cornell University, Ithaca, NY 14853

Spruce budworm and balsam fir forest simulation models are discussed. Both the MFRC/IRE and an improved "Maine" model suggest that the forest protection policy which has been used in Maine and New Brunswick is inferior to alternative low egg-density-threshold policies.

Introduction

Several studies of the spruce budworm in the spruce-fir forests of eastern Canada and Maine have been conducted using simulation models. A goal of these studies is the identification of cost-effective spraying strategies which prevent spruce budworm outbreaks from causing extensive tree mortality.

This report dicussses the need for and usefulness of simulation models for evaluating the consequences of alternative management policies. The results of studies by Watt and lead by Baskerville are presented. The structure and variables used in the Maine budworm-forest model are described and the Maine model is used to calculate the spraying frequency which results from alternative spray policies. Spray policies which suppress budworm populations before outbreak densities are reached and severe defoliation occurs appear to be superior to forest-protection policies. Forest-protection policies currently in use in Maine and New Brunswick spray only if tree health is threatened.

Why Use A Simulation Model?

Evaluation of the effectiveness of alternate spraying programs or policies is a difficult undertaking. An evaluation must account for many factors. Budworm survival is of particular importance. It is affected by:

food availability
budworm density
insecticide applications
parasite density, and
prevailing weather conditions.

Food availability is determined by the conditions of the host trees and their response to budworm feeding; the dynamic budworm-foliage relationship is central to understanding budworm population changes, tree-growth loss, and tree mortality.

Also a major concern to budworm-forest management are the consequences of moth dispersal between forested areas in Maine, Vermont, or New Hampshire and into those states from infestations in Quebec, New Brunswick, and other parts of New England. The possible spread of infestations which are not suppressed is an important management concern and the occurrence of moth influxes into an area from other areas complicates the problem.

To predict the probable behavior of the budworm-forest system under a particular management strategy, it is necessary to integrate our best scientific understanding of these processes and their interactions. Because of the complexity of this system, simulation models are best able to keep track of the important information and to represent the major interactions.

Budworm-forest simulation models discussed here are useful for predicting the average behavior of the budworm-forest ecosystem when a particular management policy is followed. For example, suppose the forest is managed to maintain a fixed harvest level. Suppose also that a site will be sprayed whenever tree mortality would commence the following year if the site were not sprayed. Then, via simulation, the average behavior of the forest can be determined.

Results With Earlier Models

An early simulation model for a forest insect pest was constructed by K.E. Watt (Watt, 1964). He considered a hypothetical 6.4 million-acre balsam fir forest which he divided into 625 sites, each of 16 square miles. Each site contained 8-inch diameter trees at a density of 265 trees/acre. To describe insect dynamics, Watt used Morris's Key-Factor relationship (Morris, 1963, p. 124) for spruce budworm survival which specifies that

$$\ell n\, N_{t+1} = .98 + .76\, \ell n\, N_t + .18(T_{max} - 66.5°F)$$

where:

N_t = budworm density in year t, and

T_{max} = mean maximum temperature 1 June through mid-July.

Watt modified this relationship to account for parasite attacks, disease incidence and moth dispersal. Relationships were constructed for tree-growth loss and mortality as a function of previous defoliation. Watt examined the

1/ Currently on sabbatic leave with the U.S. Geological Survey, 410 National Center, Reston, VA 22092

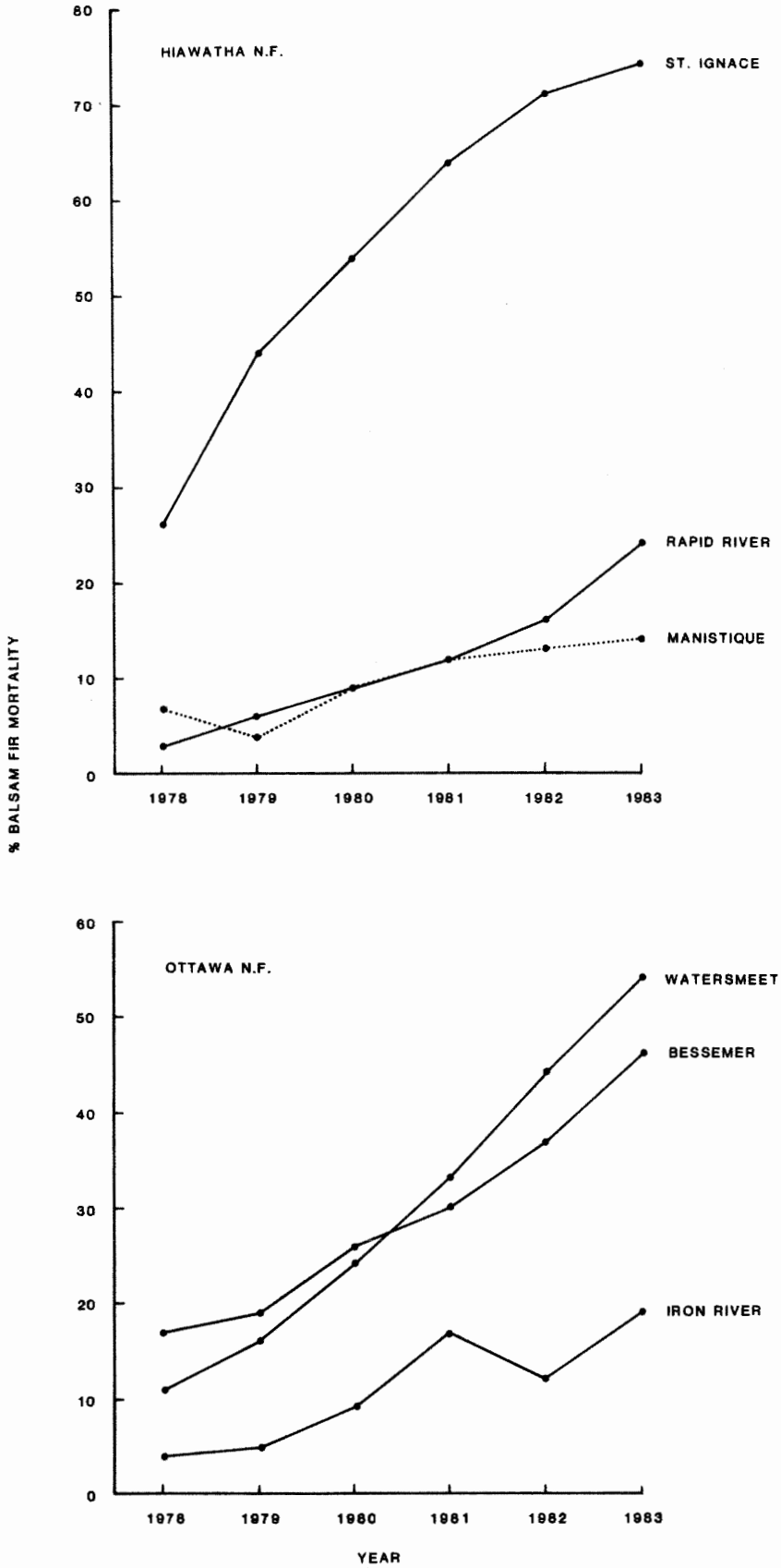

Fig. 3. Average percent mortality of balsam fir on selected districts in the two national forests, 1978-1983.

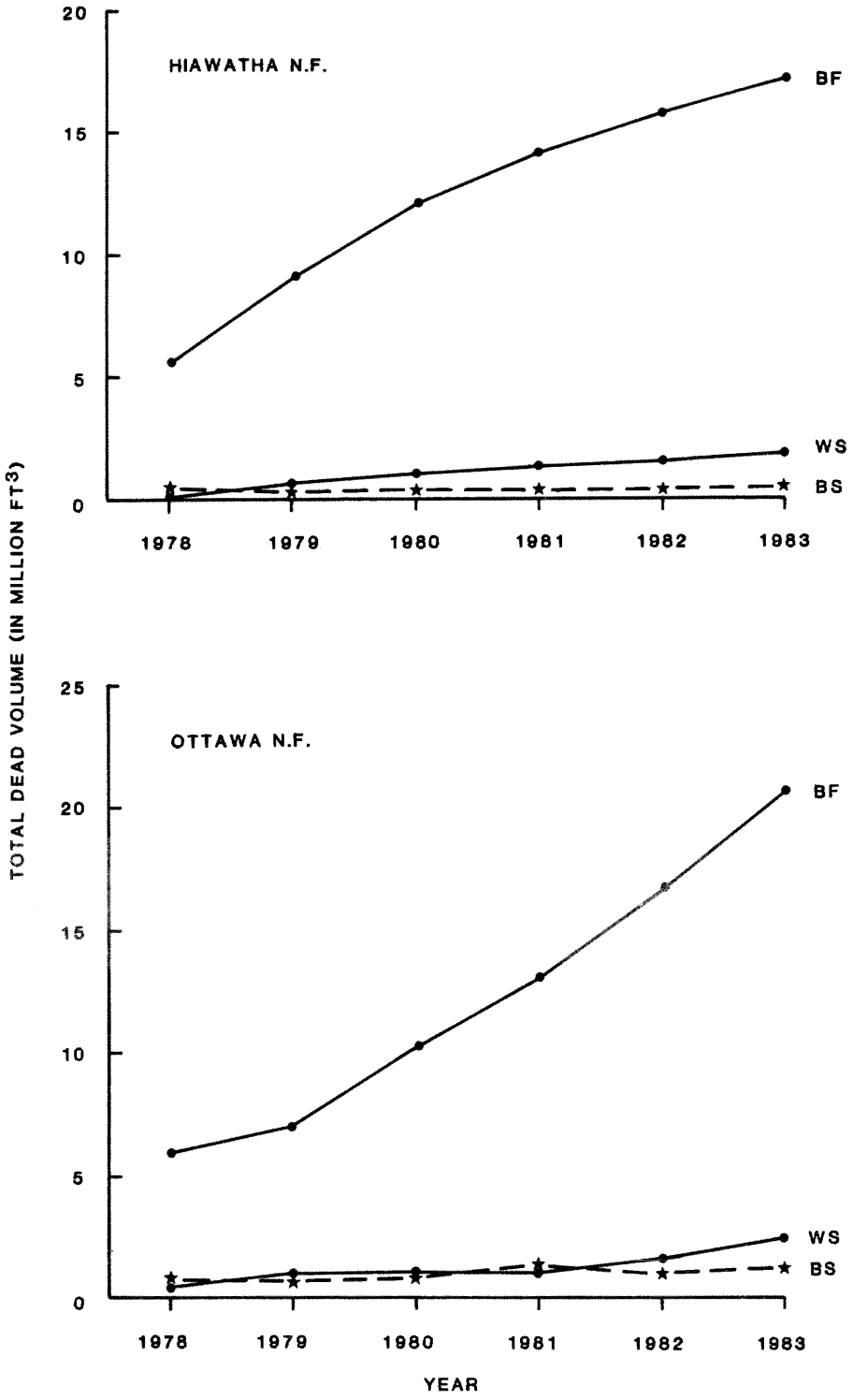

Fig. 4. Total dead volume (in million ft^3) of balsam fir, white spruce, and black spruce on the two national forests, 1978-1983.

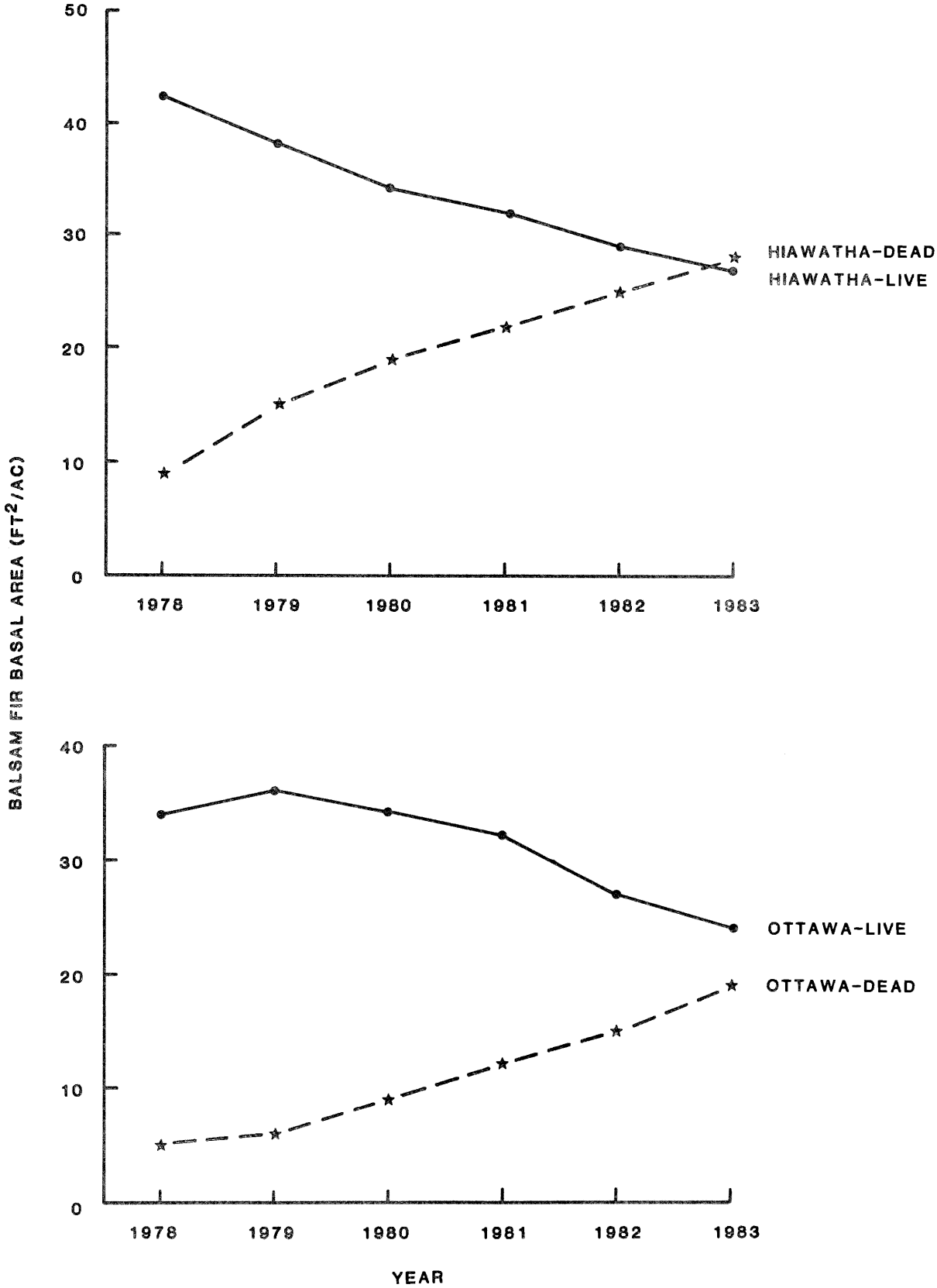

Fig. 5. Average dead and live basal area (ft^2/ac) of balsam fir on the two national forests, 1978-1983.

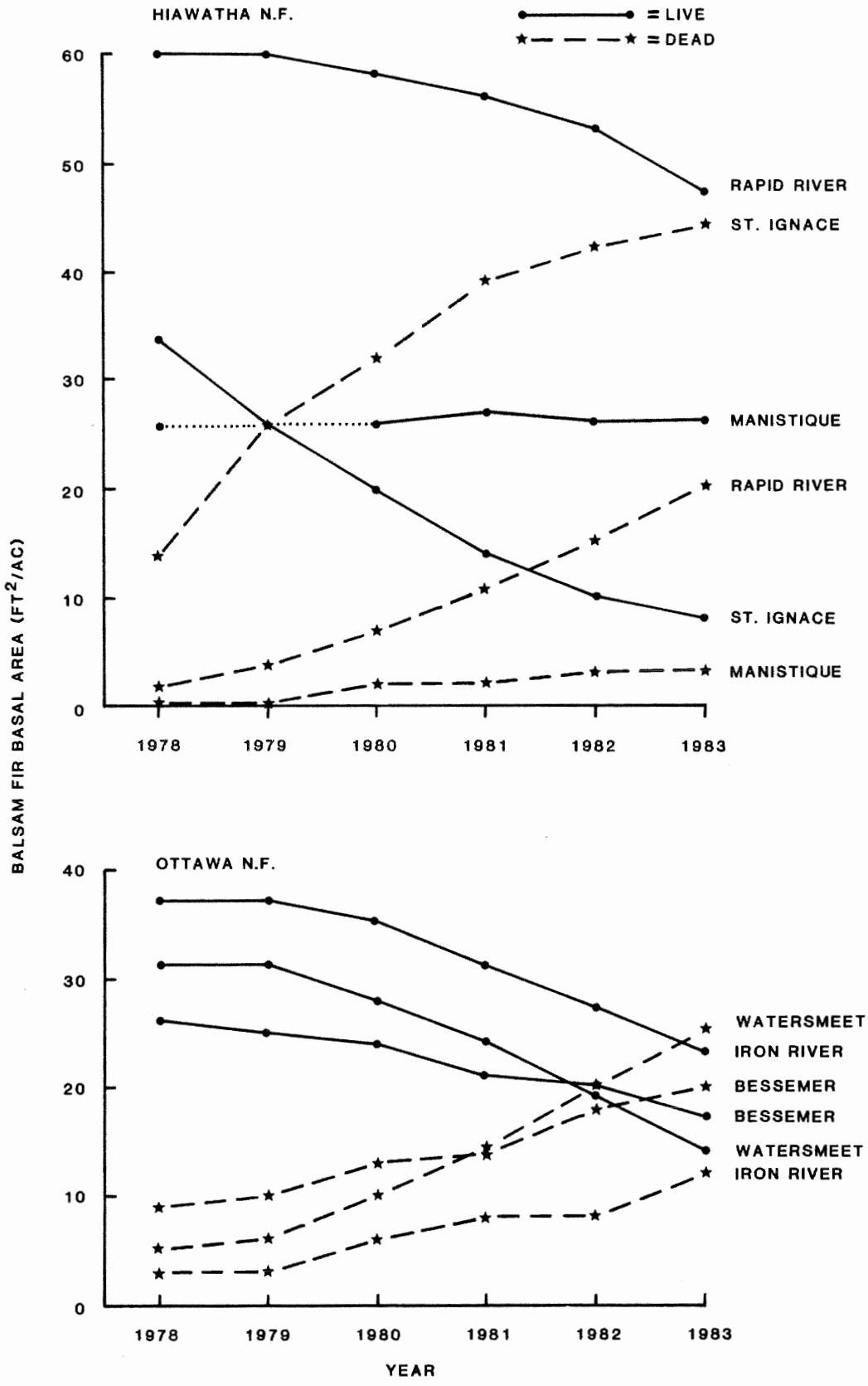

Fig. 6. Average dead and live basal area (ft^2/ac) of balsam fir on selected districts in the two national forests, 1978-1983.

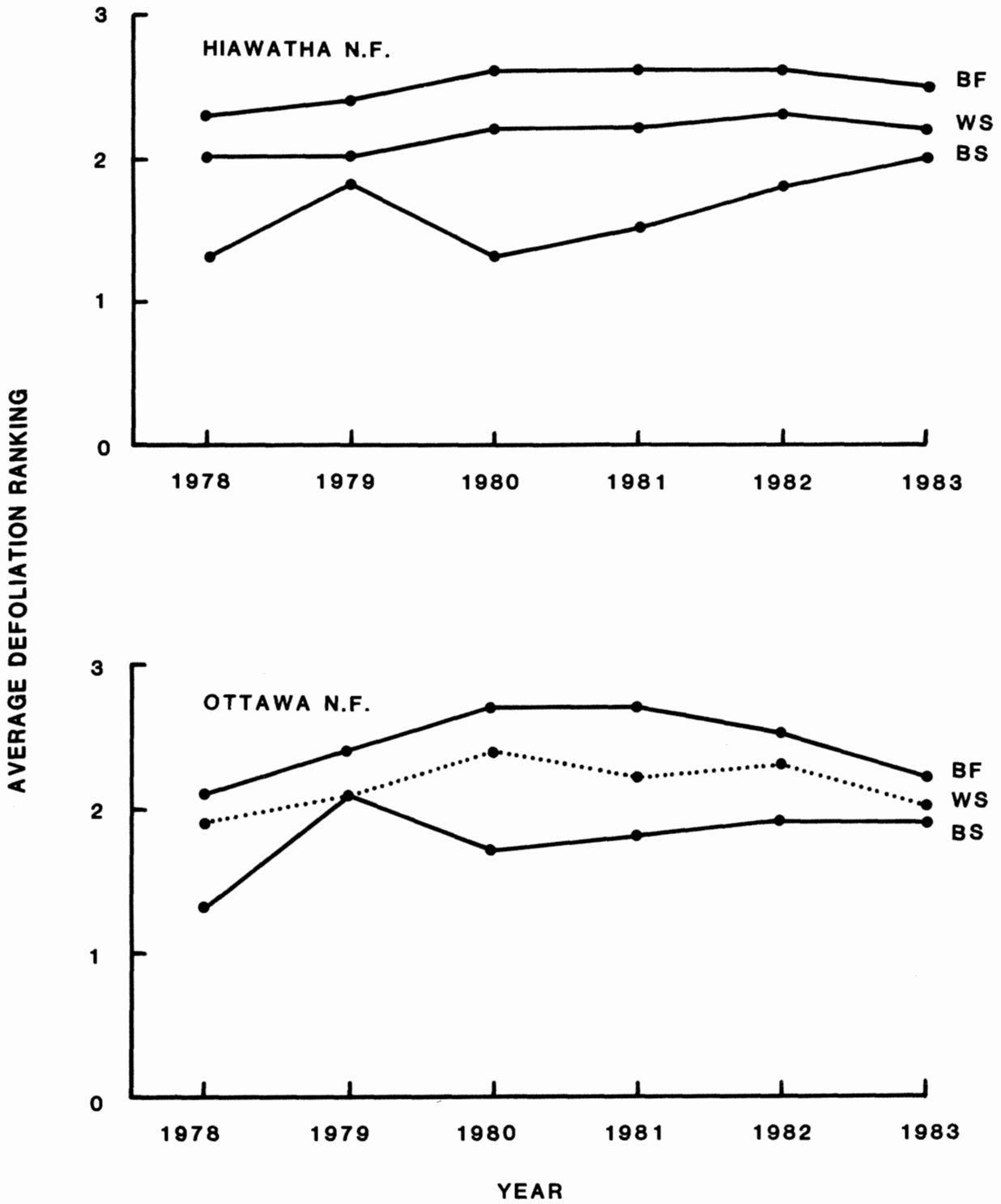

Fig. 7. Average defoliation ranking of balsam fir, white spruce, and black spruce on the two national forests, 1978-1983. Defoliation ranking: (1) no defoliation - no observable feeding damage, 0 to 20% of total foliage missing; (2) light to moderate defoliation - 21 to 50% of total foliage; (3) heavy defoliation - 51% or greater defoliation with no observable top-kill; and (4) severe defoliation - 51% or greater defoliation with obvious top-kill.

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SPRUCE BUDWORM IN MINNESOTA: LOSS ASSESSMENT CURRENT CONDITIONS AND MANAGEMENT OPTIONS

Michael R. Carroll, Michael A. Albers and Jana Campbell

Regional Pest Specialists, Minnesota DNR - Forestry, Box 648, Brainerd, MN 56401

ABSTRACT: The spruce-fir covertype is the dominant forest type in Northeastern Minnesota and today consists of approximately 930,800 acres of commercial forest land. The resource is present as pure stands of varying quality that typically consist of 80% balsam and 20% white spruce. Additional spruce-fir occurs in mixedwood stands as part of the lowland black spruce and hardwood types or as clumps amidst upland aspen and other conifers. Budworm outbreaks have been reported at periodic intervals from 1825 to the present, but populations can always be found somewhere in the northeastern sections of the state. Direct control projects ceased in 1976. Noticeable defoliation in 1983 was limited to 138,700 acres in St. Louis, Lake and Cook counties. Loss assessment projects have been conducted in Minnesota from 1940 to 1982. Stand conditions today reflect the damage of past outbreaks, low management intensity and historic underutilization of the balsam resource. Foresters recognize the continuing threat of spruce budworm damage in Northeastern Minnesota and management targets include: conversion to aspen, red pine or white spruce where possible and increasing the spruce component of remaining stands. As markets allow, harvest is followed by site preparation and the planting of bare root stock. Rotations of 40 to 50 years are being pursued on all sites. High site index stands may be managed for future bolt markets.

Introduction

The spruce-fir covertype in Minnesota (MN) today consists of approximately 930,800 acres of commercial forest land primarily in the northeastern quarter of the state. Additional spruce-fir resources are contained here in stands of mixed species (mixedwood) typed as aspen, birch, cedar and lowland hardwoods and black spruce. Solid spruce-fir stands contain about 20% white spruce, while the mixedwood stands contain spruce-fir clumps with various combinations of aspen, birch, red maple, ash, cedar and pine. The solid spruce-fir stands often contain advance balsam reproduction. In mixedwood stands the understory is hardwoods, brush or balsam depending on seed source. Ownership patterns vary, but large blocks of county, state, federal and industrial land are broken up by scattered small private ownerships of high recreational value often centered around water resources.

Budworm outbreaks have been reported in the state from 1825 to the present. The amount and location of budworm defoliation in Northern Minnesota is surveyed and reported annually by the Minnesota Division of Forestry. Erickson and Hastings (1978) reported this information from 1954 to 1977. Aerial spray programs using a variety of chemicals were conducted on both industrial and public land in the state from 1958 to 1976, to either protect foliage in recreational areas or sustain timber stands until they could be harvested.

Minnesota currently contains an abundance of budworm susceptible stands due to past outbreaks, limited markets and harvest (cutting) procedures. Budworm activity has left a backlog of stands needing salvage or treatment. Aspen is a desirable product for the high quality paper mills and chipboard plants of Minnesota. Spruce has retained a stagnant market in the procurement for the predominantly groundwood paper mills. Balsam fir, however, has had only a limited market, and in many portions of the state it is considered non-marketable if part of a mixedwood stand. In the past, when harvesting removed only the aspen and spruce, development money was not always available to treat the balsam residual. Until recently, intensified management has been limited to select industrial lands.

Loss Assessment

Numerous projects have been undertaken in Minnesota to monitor spruce-fir mortality and growth loss during budworm epidemics. This paper will review seven studies that have had an impact on forest management in the state.

Graham and Orr (1940) began the process by reporting on the 1912-1923 budworm outbreak. The majority of the report consists of budworm bionomics and is still very useful today . It also contained the first loss assessment information available to foresters in the state. They reported using a "large number" of one-tenth acre sample plots in the solid spruce stands of Northern Minnesota to estimate that 85-90% of the merchantable balsam fir in the area, nearly 20 million cords, was lost. They noted that injury to spruce varied so much from place to place that they couldn't estimate volume losses.

Industry in Minnesota has conducted several assessments of the real and potential dollar losses due to budworm outbreaks. The Kimberly-Clark Corporation[1] recognized that the amount of susceptible balsam was increasing on their lands due to several factors: the early emphasis on logging white pine and later white spruce, black spruce and birch: fire exclusion and preferential harvesting of aspen and jack pine. In a series of studies from 1951 to 1956 they used standard inventory procedures to assess the extent of their susceptible

1/Kimberly-Clark of Minnesota. 1956. Internal documents. Balsam fir decay and cull on different sites, with rotation age recommendations. 10 pp. Spruce budworm problems in Minnesota. 18 pp.

holdings. In addition, they documented that top kill from budworm feeding was more important in timber loss than butt rots. They concluded the next budworm outbreak in Northeastern Minnesota would produce a surplus of salvage wood and decided it would be better to harvest mature stands of clean sound pulpwood on a priority basis and leave the overmature, unaccessible stands to regenerate themselves and produce wood for the next rotation. Boise Cascade (1970)[2] later concluded in assessing their holdings that a projected kill of 250,000 cords of balsam would result in a loss of 750,000 to one million dollars. They determined that the loss of this balsam component of their stands would make it too costly to cut the remaining timber when considering the cost of road construction and taxes. Boise Cascade was a strong supporter of direct control operations in Minnesota.

In 1972 the U.S. Forest Service, industry and the MN Forest Pest Management Group cooperated to conduct a survey to determine the amount of tree mortality caused by the budworm on the central portion of the Kabetogoma Peninsula. This survey related defoliation class as determined by aerial survey to three tree condition classes: live, dead and topkill. The ground survey consisted of clusters of 4 tenth acre plots on 47 randomly selected plot centers within the affected spruce-fir acreages. This was the first detailed study that combined aerial damage detection with population monitoring, stand composition and tree loss data. Unfortunately, it was a one year project and its potential value was apparently lost in the days when the major management effort was to utilize direct control operations in an effort to store risk timber on the stump. Batzer (1973), however, began to look at the long range impact of outbreaks. He documented that mortality or growth reduction occurred until four to five years after an outbreak began and that 60% of the loss to balsam fir growing stock actually occurred during the five years after an outbreak subsided. He suggested that decisions concerning suppression should be made during the first three years of an infestation.

The state Division of Forestry conducted a management inventory (called Phase II) of the 105,000 acre Finland State Forest in Lake and Cook counties from 1978 to 1980. This survey period was after a budworm epidemic that resulted in direct control operations in 1974 and widespread budworm caused mortality into 1976. Stands severely defoliated from 1972 on were still marketable until 1976, when drought wiped out the remaining stressed balsam. This produced a surplus of stands needing harvest that local markets could not handle. Regulation schemes were thoroughly disrupted and field survey could not keep up with the continuing mortality. At that time, management was reduced to salvage where possible and limited development work based on site index priority. The inventory project was conducted to reestablish a management base. The field survey gathered information on covertype acres, species composition, size class, basal area, understory composition, site index, mortality and active pest agents. Crews made on site decisions as to when the stand should be harvested. Stands were coded as high risk when active pest agents and current mortality justified harvest within one to five years. Computer systems then generated covertype maps and numerous stand tables and graphics for the foresters use in planning allowable cuts, overall covertype targets and development work. Detailed pest management printouts included a listing of all balsam fir covertypes with high risk by age, site index and location; a list of additional covertypes with balsam fir mortality by covertype, age and location; and a total of the acreages of all covertypes with balsam fir mortality. Printouts indicated that of 68,692 acres of commercial forest, 13,806 acres of various covertypes contained dead balsam fir that needed harvest within the next five years. The alterations procedure that is inherent in Minnesotas' Phase II inventory system follows timber sale closure, declaration of a lost type and mandatory regeneration checks for both artificial and natural restocking. Alterations are still documenting the combined impact of budworm and drought in the Finland State Forest.

Campbell and Albers (1983)[3] cooperated with State and Private Forestry of the U.S. Forest Service to record the location and intensity of budworm defoliation in 1982 and to estimate the volume of spruce and fir lost due to budworm from 1977 to 1982 in Northeastern Minnesota. During this period the only mortality in Minnesota occurred in an 84 township area of St. Louis and Lake counties. Sketch mappers identified stands in this new outbreak area that contained at least 25% balsam fir and/or white spruce. These areas were then catagorized by percent mortality into three classes: 1-19% dead host trees, 20-49% dead and 50-100% dead. From the sketch mapping, the acreage of each stand was established and ground survey procedures using a 10 BAF prism were conducted to determine the number of live, risk and dead balsam fir, white and black spruce within plot boundaries. From the data they computed average volume loss per acre for each of the three mortality categories, overall loss per acre, basal area of host trees and the percent of dead and risk host trees on each sample plot. The study documented that 493,829 cords of balsam fir and 8,036 cords of white spruce were lost during the five year period. This represented 20% of the available volume of balsam fir in the affected area. Black spruce losses were not detected during the ground survey and white spruce losses were negligible. Valuable experience was gained for integrating aerial survey with ground loss assessment in Minnesota's mixedwood stands. Future loss assessments

2/Boise Cascade. 1970. Woodlands division report.

3/Campbell, J., and M. Albers. 1983. Final Report. Spruce budworm: mortality loss assessment in Minnesota, 1977-1982. Mn. DNR - Forestry report to U.S.F.S. - S.P.F. St. Paul, MN, 20 pp.

will only use two mortality categories, greater or less than 50% dead, and the number of prism plots will be increased in each survey area and established along a transect to increase accuracy in stands where the spruce-fir distribution is discontinuous.

Current Conditions

Noticeable spruce budworm defoliation is currently restricted to approximately 138,700 acres of the spruce-fir type in St. Louis, Lake and Cook counties. Other low intensity budworm populations have been detected to the south and west of these areas in mixedwood forests. These stands are monitored annually to detect buildup and spread potential.

Campbell and Albers (1983) estimated that budworm caused mortality occurred on 185,878 acres at the rate of 0.5 cords/acre/year from 1977 to 1982. However, they also report that in Lake and St. Louis counties the allowable cut for balsam fir from 1977-1982 totalled 891,000 cords and only 25% of this sold. This reflects current markets that are depressed due to reliance instate on aspen, jackpine and spruce for the majority of pulp, the high trucking costs to outstate mills and the current Canadian overcutting and monetary discount that makes it cheaper to buy Canadian Kraft than cut and process Minnesota wood. Logging operability continues to be a problem on remote, wet, rocky, or steep sites. Some of these stands are currently left to regenerate untouched.

The question again being asked in Minnesota, is whether the justification exists to undertake budworm related management when the current demand for the resource from public land is inadequate to deal with the backlog of overmature and damaged stands created by poor markets and past outbreaks. Currently, direct control would only be considered for high value recreational stands and microbials would receive first priority. Because balsam-fir and birch from mixedwood stands are non-marketable in some areas of the state, a new governor's task force is mandated to develop ways to handle this residual problem. While new political and management trends may develop, the ground level managers response to a spruce budworm outbreak in his district will continue to be mandated by local stand conditions, markets and available development money.

Management Outlook

Minnesota foresters continue to deal with the spruce budworm on a stand management basis. Essentially two types of solid spruce-fir stands and a third mixedwood type exists in Minnesota.

Operable stands with a good or better site index (greater than 52) are typically on clay soils and possess trees of good form. They are managed on a 50 year rotation. Such sites would be targeted for bolt production if the dimension lumber market expands in Minnesota along the grade specifications established by Sinclair, Garett and Bowyer (1981). Currently these stands are usually harvested for pulp. Many sites harvested in this manner do not receive additional site preparation before planting. On sites where there is partial or no harvest, rock raking is used to level and/or pile the residual and expose mineral soil before planting bare root stock. Direct seeding has not produced desirable stocking levels. In areas of historic budworm outbreaks, white spruce or red pine seedlings have been planted on the appropriate soils. Red pine was planted in pure blocks or mixed with white spruce to break up large spruce-fir stands. White spruce planting was considered successful if 300 stems of white spruce per acre persisted with various amounts of volunteer balsam fir. At 40 or 50 years the forester will have two options: remove the balsam and hold the spruce for sawlogs or clearcut the entire stand.

Additional spruce-fir stands are typified by site indexes of 41 or less with some combination of shallow soils, poor logging terrain and trees of squat form with numerous persistant branches. Operability of the sites will remain low, but if pulp markets strengthen they will be clearcut at 40 to 50 years and planted to spruce. Larch may be a future option.

Operability of mixedwood stands also depends on site factors, but the additional work of sorting mixed products makes them less desirable to loggers. Although attempts have been made to sell the spruce-fir clumps in a stand first and then followup with a winter hardwood clearcut, on most sites residual dense hardwoods and fir need post sale treatment. Rock raking into windrows, roller chopping and chaining and burning have all been attempted with follow-up planting to red pine, jack pine or white spruce. Where possible, clearcuts are enforced to convert to aspen if its site index is 60 or greater.

On a larger scale, ten year regulation schemes are being developed for state forest management units in the northeast. Spruce-fir stands are stratified by site index and targeted for harvest, potential conversion or follow-up development work such as fire, interplanting and release. Extensive planting of white spruce and/or red pine must be avoided due to yellowheaded spruce sawfly Pikonema alaskensis (Rohwer), the North America strain of Scleroderris Gremmeniella abietina (Lagerb.) and other pests in the state. Regulation schemes will have to be continually updated in relation to current pest populations, mortality predictions and the cyclic availability of development money. Markets will remain a problem, and increased utilization of balsam bolts would compound budworm problems if rotations of greater than 50 years were attempted.

The recognized need to promote species diversity and regulate basal area and age structure in historic outbreak areas is accelerating the move from custodial to active management on state, county and industrial land. Campbell and Albers (1983) point out, however, that unmanaged stands

in the Boundary Waters Canoe Area and Voyageurs National Park may serve as sources of spruce budworm populations for Northeastern Minnesota. The effectiveness of silvicultural recommendations would be reduced if outbreaks spread from the unmanaged BWCA and Voyageurs National Park stands.

If short and long term market commit ments for Minnesota woodsheds can be established, foresters would have the ability to regulate spruce budworm impact by integrating site specific inventory data with pest management projections. Ten year regulation schemes could be used to break up susceptible types and remove high risk stands in response to annual budworm population and damage surveys, and mortality predictions based on previous loss assessment projects.

Campbell and Albers (1983) presented the past and future of Northeastern Minnesota budworm conditions. "From the initial outbreak area near International Falls and Ely, budworm populations have spread through balsam fir stands to the south and east during the last 30 years. As the outbreak reached the southern edge of the extensive balsam fir type, young stands in the northern part of the State were maturing and again becoming favorable as host trees. Previously unaffected balsam fir growing in old kill areas have been and are becoming reinfested. Minnesota outbreaks do not occur with long periods of subsidence. Northeastern Minnesota has experienced a continuous infestation for the past 30 years and this situation is likely to continue." If markets do not solidify, foresters will be unable to harvest or treat susceptible stands and the loss cycle will continue.

Acknowledgements:

Special thanks are due Olin Phillips for reviewing this paper and division of forestry employees Chung-Muh Chen, Ray Dolan, Jerry Hecht, Dave Heinzen, John Krantz, Jon Polecheck, Ray Tarchinski and Bruce ZumBahlen for information and insight on spruce budworm impact in Minnesota.

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_____1973. Spruce budworm damage on balsam fir and white spruce: Kabetogama Peninsula 1972. 25 pp. Mn. D.A. Division of Plant Industry and U.S.F.S., S.P.F., Forest Pest Management, St. Paul, MN.

THE SPRUCE-FIR RESOURCE OF MAINE

Douglas S. Powell

Research Forester, Forest Inventory and Analysis
USDA Forest Service
370 Reed Road, Broomall, PA 19008

Abstract.--Three statewide inventories (1959, 1971, and 1982) show trends in area, number of trees, and volume of the spruce-fir resource. In general, there are more sawtimber stands, overstocked stands, and sawtimber volume; fewer pole-sized trees; and less growing-stock volume. Relatively high mortality and removals levels have contributed toward the overall decline of the resource.

Introduction

The Forest Inventory and Analysis Unit (FIA) of the Northeastern Forest Experiment Station, USDA Forest Service, has conducted three statewide forest inventories of Maine: 1959 (Ferguson and Longwood 1960), 1971 (Ferguson and Kingsley 1972), and 1982[1]. In each of these surveys we collected data on the spruce-fir resource, and we are now in a position to analyze some of the important characteristics and trends in this dominant component of Maine's forest land. The data were collected by geographic sampling unit (Fig. 1).

There are several ways to look at this resource. The one that is most relevant in terms of area analyses is the spruce-fir forest-type group. Number of trees is useful in looking at the individual species for tree and diameter-class distribution, as well as defoliation class. Various volume estimates of the fir and spruce species are helpful from the commodity perspective. Components of the change in volume will give some clues as to why and how the species are changing.

The timing of the three surveys also allows us to analyze the impact of spruce budworm. Between the first and second inventories there was little budworm activity, while between the second and third inventories there was relatively heavy budworm impact. So, comparing the 1971 data with the 1982 data may help us to see effects of this pest. At the same time, however, we must remember that the resource is complex and dynamic. Budworm is only one of several factors controlling the change of Maine's spruce-fir forests. Age distribution, overstocking, and man's impact are also important and often cannot be isolated. This complexity calls for careful and discriminating interpretation.

[1]Powell, Douglas S.; Dickson, David R. Forest statistics for Maine: 1971 and 1982. Resour. Bull. Broomall, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. (In publication process).

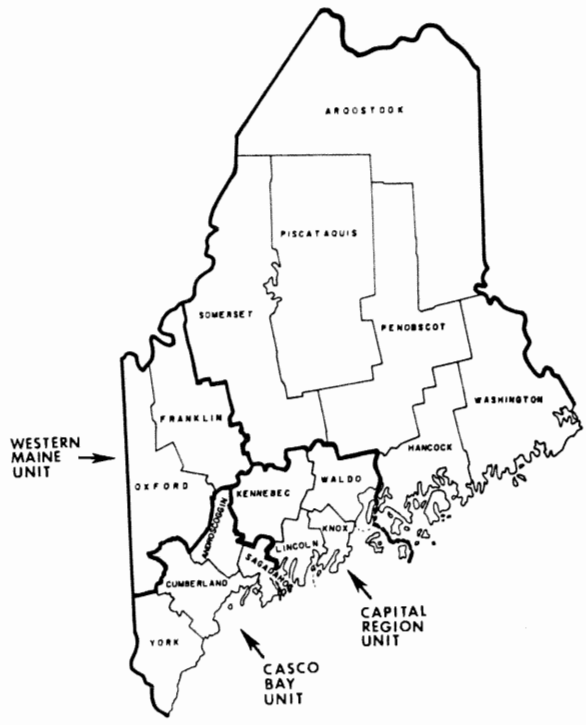

Figure 1.--Except for the three units in southwestern Maine, each county is a geographic sampling unit.

The Spruce-fir Forest-type Group

The spruce-fir forest-type group is a combination of several forest types that share closely associated species or site requirements. The group is used to classify timberland in which red spruce, northern white-cedar, balsam fir, white spruce, black spruce, or tamarack, singly or in combination, comprise a plurality of the basal area stocking of all live trees. In 1982 the area of this type group was 7.8 million acres, or 46 percent of the state's timberland base. The area declined 7 percent since 1971. However, the state showed no decline in timberland, and this means that the acreage lost by spruce-fir was picked up by other forest types.

Stand-size class is a classification based on the size of trees growing in an area. The area of spruce-fir is composed of 4.1 million acres of sawtimber stands (53 percent), 2.9 million acres of poletimber stands (37 percent), and 800,000 acres of sapling-seedling and nonstocked areas (10 percent). This distribution is more weighted toward sawtimber stands than is the state average (50 percent) of all forest types. And even though the area of spruce-fir has declined since 1971, the area of spruce-fir sawtimber stands has increased. The other two classes have declined.

Timberland is also classified by the amount of live-tree biomass per acre--green ton stand-volume class. Spruce-fir stands ranged from 0 to more than 200 tons per acre in 1982. The distribution was somewhat bell-shaped, though its peak was relatively flat between 50 and 125 tons per acre. The 1971 distribution was nearly identical except that there were more stands in the 50-to 125-tons-per-acre classes, with a definite peak in the 75-to 100-ton class. This increase represents the stand-volume classes that moved from spruce-fir into other forest types.

The concensus is that the spruce-fir resource is overstocked. Our surveys support this and show a decided shift in this direction (Fig. 2). If we ignore dead and unmerchantable trees and focus on growing-stock trees, the spruce-fir resource is anything but understocked. In 1971, 79 percent of the stands were full to overstocked and by 1982 this figure was 82 percent. Even more startling is the shift that occurred within the fully stocked and the overstocked classes. In 1971 the area in these classes was relatively even, 41 and 38 percent, respectively. By 1982 these proportions were 21 and 60 percent, respectively. The area in overstocked stands went up dramatically.

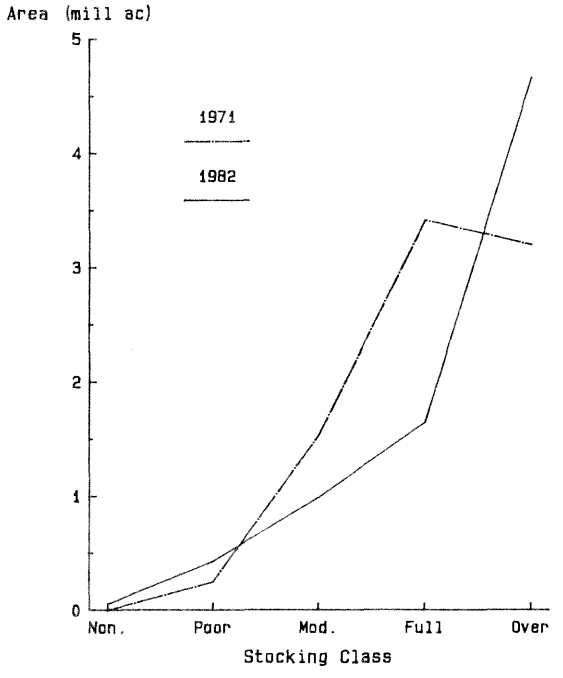

Figure 2.--Spruce-fir area by growing-stock stocking class, Maine, 1971 and 1982.

Keep in mind that stocking is a measure of occupancy of a site and need not be correlated to volume. It is quite possible to have an overstocked stand of fir seedlings with no volume at all. So, what accounts for this big increase in overstocked stands? It can happen in undisturbed stands by increases in number and size of stems. But more common in spruce-fir stands is an increase in the number of seedlings on stands where the overstory has been disturbed by harvesting or spruce budworm attack. Spraying, as a budworm control and tree protection measure, may also have allowed stocking levels to build.

The growing-stock volume of the spruce-fir forest-type group in 1982 was 11.8 billion cubic feet. This was 52 percent of the total volume in the state. Since this type group had only 46 percent of the area, this means that spruce-fir contains more volume on the average than other forest types. This group contains almost 80 percent of the spruce and fir volume in Maine. While this group is composed of many species, spruce and fir together account for two-thirds of the volume. In 1971, spruce and fir accounted for 72 percent of the group's volume. The major species are balsam fir and red spruce. In 1971, fir was number one with 35 percent of the group's volume, and red spruce was number two with 31 percent. In 1982, the roles were reversed with red spruce on top: 32 to 26 percent.

These statistics indicate two things. One, that spruce and fir within the spruce-fir forest-type group are less dominant than before. The resource is being diluted, and this supports the hypothesis that spruce-fir is declining in acreage not due to change in land use patterns, but rather to shifts in species composition. And two, the fir resource within the group is declining, and red spruce is holding its own to assume the lead role.

Number of Trees

Turning from a focus on area dominated by spruce and fir, we look at the species themselves as they are found throughout the state--first by studying numbers of trees and later by dealing with volume.

Tree class is used to group trees by their potential for producing high-quality lumber. Growing-stock trees are divided into two classes: preferred trees or those that are of highest quality, and acceptable trees that are merchantable but not good enough to be preferred. Trees that are alive but unmerchantable due to rot or poor form are cull. And a fourth category is dead trees that includes trees that have recently died and are salvable, and dead trees that are still standing but are no longer of any possible use for lumber.

Figure 3 shows the tree-class distributions for our species of interest. All species in Maine averaged 73 percent in the two growing-stock classes (20 percent preferred and 53 percent acceptable). Balsam fir had 68 percent growing stock (21 percent preferred, and 47 percent acceptable). Thus, fir has a less favorable breakdown, especially in the acceptable class. The spruce species, on the other hand, had 88 percent in growing stock--35 percent in preferred and 53 percent in acceptable. From a timber viewpoint, the spruce resource looks very good. Averaging spruce and fir yields a 77 percent share of growing stock--still above average thanks to spruce.

The cull-tree class is also interesting. The average for all species was 16 percent. Balsam fir, often known as a tree prone to decay as it matures in crowded stands, had a surprisingly low 11 percent cull. But spruce was even better with a mere 6 percent of its trees classed as cull. So, the spruce and fir resource as a whole is in better condition, in terms of cull, than are the other species in Maine.

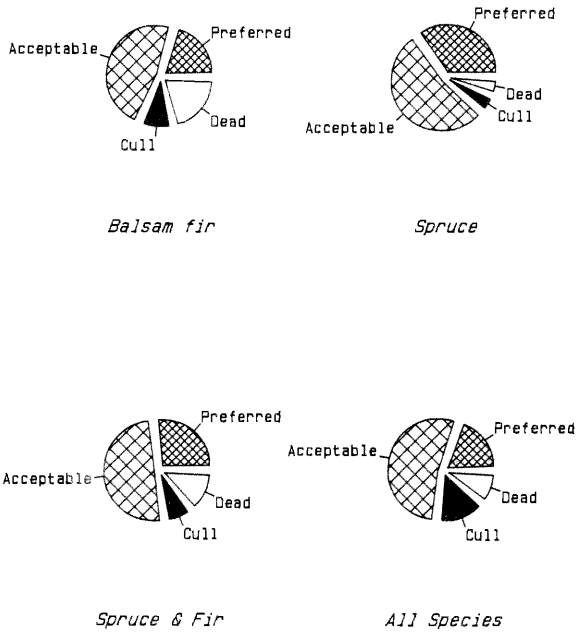

Figure 3.--Tree-class distributions for balsam fir, spruce, spruce and fir, and all species in Maine, 1982. Note: preferred plus acceptable equals growing stock.

Since the spruce budworm kills trees, the dead category may be most pertinent at present. As shown in figure 3, the fir resource is hurting, with 21 out of 100 trees dead. This is nearly double the 11 percent for all species. Spruce is in much better shape with only 6 percent of its trees dead. While all of this mortality is not attributable to budworm, there is no question that balsam fir has borne the brunt of the attack through the latest inventory. Since then there have been reports of increased spruce mortality, so these relationships may be somewhat different today. Our next survey should verify this more recent spruce decline.

Analyzing numbers of trees across diameter classes gives us a perception of the relative size of the species. In figure 4 the percent of all live trees for all species has been calculated for fir and spruce and plotted over diameter class. This not only shows the size relationship of fir and spruce, but also how important these species are to the entire forest resource of Maine. For instance, if you consider all live seedlings of all species in the state, 26 out of 100 of them will be balsam fir! Spruce only contributes about 7 percent to this class. At the 8-inch class, where the two lines intersect, spruce and fir together account for 45 percent of all live trees in Maine.

Figure 4 shows some real difference between spruce and fir. Except for an increase between the first and second class, fir shows a steadily decreasing trend as diameter increases. Its dominant role is played in the smaller size classes. The spruce species show more of a broad, bell-shaped trend. For trees between 5 and 15 inches in diameter, the spruce curve is relatively constant at around 21 percent. So in the spruce-fir resource, fir's niche is in trees smaller than 8 inches in diameter while spruce's niche is in large poletimber- and sawtimber-size trees.

In an effort to assess more directly the impact of spruce budworm on this resource, FIA collected data on the extent of defoliation of the crown of growing-stock trees. No attempt was made to distinguish between current and previous years' foliage, but the crown as a whole was observed from a distance and put into one of our classes: no defoliation, 1 to 30 percent defoliated, 31 to 69 percent defoliated, and 70 to 100 percent defoliated. This procedure is an evaluation of the vitality of the tree and should not be confused with the more standard defoliation surveys, which involve close examination of tree branches. (These intensive surveys have shown higher levels of defoliation, especially in the lighter categories. Personal communication, Thomas Rumpf, Maine Forest Service.) Figure 5 shows the FIA defoliation classes for the three spruce species and balsam fir. In order of increasing levels of some degree of defoliation, the species are black spruce (18 percent), red

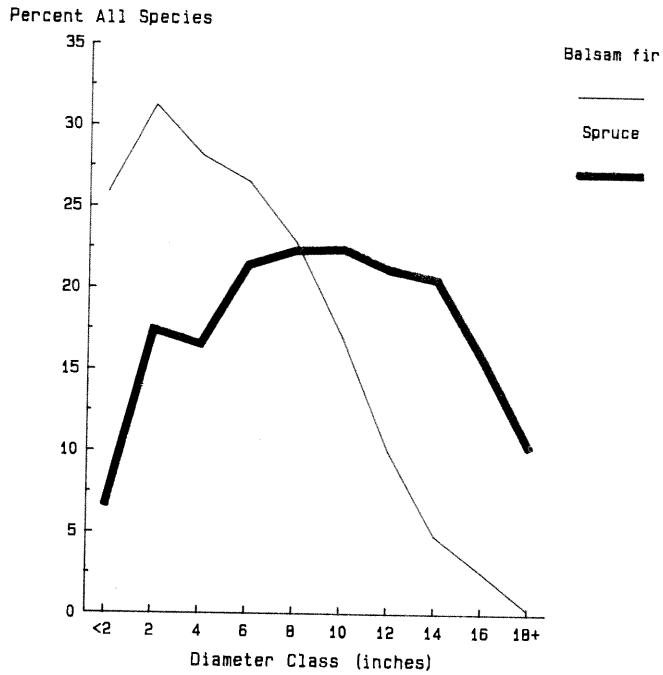

Figure 4.--Percentage of all live trees of all species by diameter class for balsam fir and spruce in Maine, 1982.

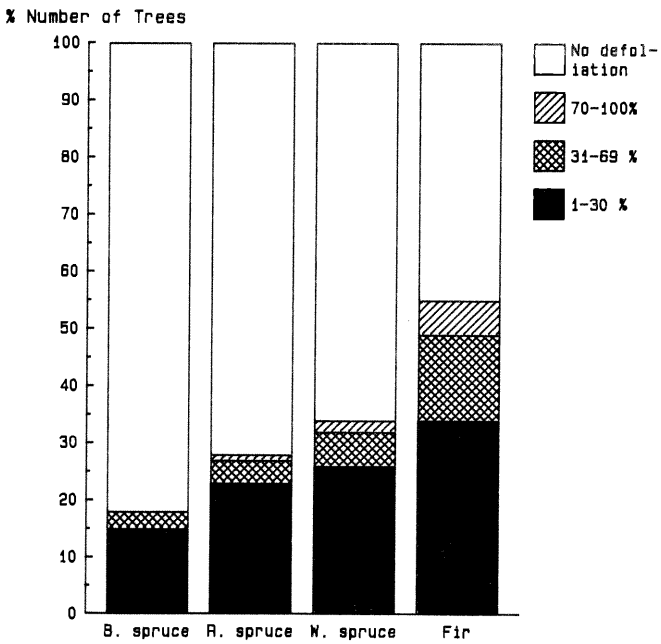

Figure 5.-- Defoliation classes for black spruce, red spruce, white spruce, and balsam fir in Maine, 1982.

spruce (28 percent), white spruce (34 percent), and balsam fir (55 percent). This supports the hypothesis that balsam fir is the preferred host of the budworm, and that spruce species (especially black) are less favored hosts (Baker 1972). Note that for all species the most common defoliation class besides no defoliation is the lightest one, 1 to 30 percent.

The defoliation of the spruce-fir resource is uneven across Maine (Fig. 6). The state average shows that 40 percent of the trees are defoliated to one extent or another. The most defoliation was found in Piscataquis County where 53 percent of the spruce and fir growing-stock trees showed some defoliation. Trees in southern and western areas had the least defoliation damage. But, defoliation does not translate directly into volume loss as we will see later.

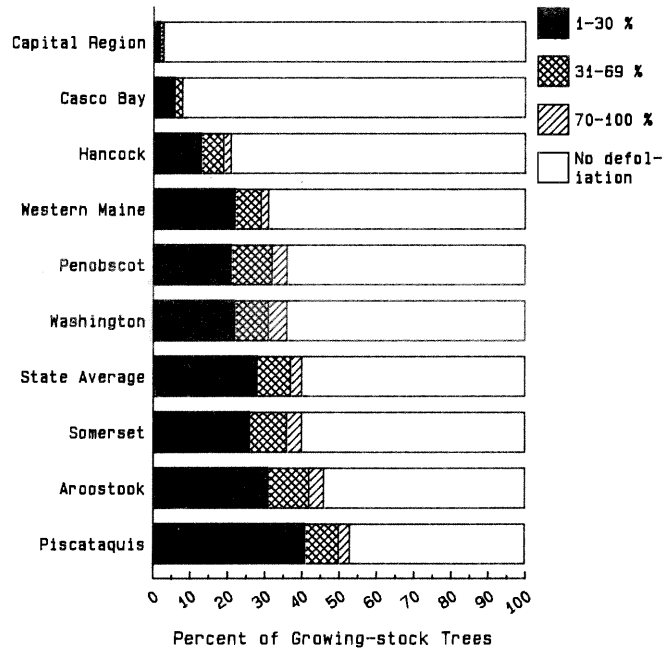

Figure 6.--Defoliation classes for spruce and fir combined by geographic unit, Maine, 1982.

Volume

Now we will turn our attention to the volume of the species and how it has changed over time.

In 1982, spruce and fir growing-stock volume amounted to 9.8 billion cubic feet or about 115 million cords. This is 43 percent of the volume of all species in Maine. In 1971, spruce-fir volume was 10.5 billion cubic feet, which was nearly 50 percent of the state's total volume. Between these surveys the growing-stock resource suffered a 7 percent decline (Table 1). The fir volume was the reason for this as it fell by 20 percent over the 11-year period. Spruce held its own (the 5 percent increase was not statistically significant). During the pre-budworm period between 1959 and 1971, the volumes of both fir and spruce registered significant gains.

Because of these different changes, the composition of the spruce-fir resource shifted. In 1971, balsam fir accounted for 48 percent while spruce was 52 percent (red spruce - 44, white spruce - 6, and black spruce - 2). By 1982, the fir proportion was down to 41 percent and spruce had increased its share to 59 percent (red spruce - 49, white spruce - 6, and black spruce - 4). Notice that the 1959 distribution was nearly identical to the 1971 distribution. As we will see later, these changes are the results of many factors, but undoubtedly, the spruce budworm outbreak had a significant impact.

Besides the shifts in species makeup, the spruce-fir growing-stock resource also changed within diameter classes (Fig. 7). Between 1959 and 1971, spruce and fir volume increased in all diameter classes. Between the last two surveys, increases were limited to trees in the 10-inch class and larger. Major decreases occurred in the poletimber-size trees, especially in the 6-inch class. This resource is characterized by small trees, so if the volume is dropping, one might expect that small trees would be affected. But these small trees are also often old trees growing in overstocked stands. Such trees are certainly susceptible to suppression and natural decline. But the budworm also finds these stressed trees likely hosts, and it damages this segment of the resource more than others.

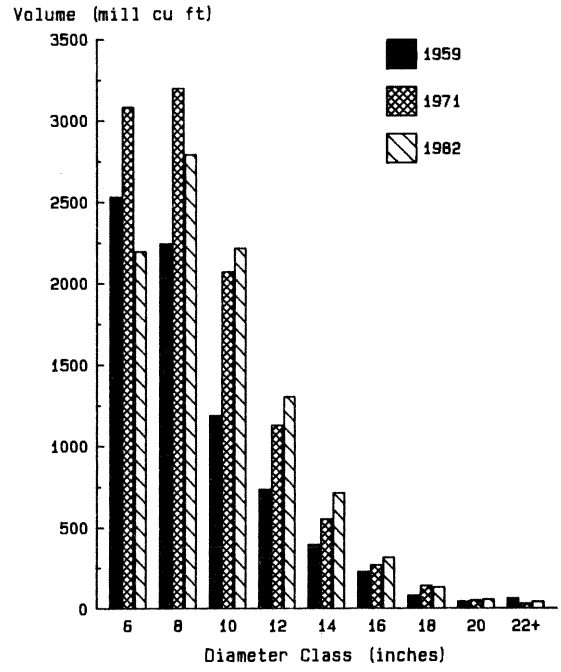

Figure 7.--Spruce and fir growing-stock volume by diameter class, Maine, 1959, 1971, and 1982.

Table 1. The spruce-fir growing-stock volume in Maine.
(Volume in billions of cubic feet)

Species	1959	1971	1982	Change ('71 to '82)
Fir	3.6 (47%)	5.0 (48%)	4.0 (41%)	-20%*
Spruce	4.0 (53%)	5.5 (52%)	5.8 (59%)	+ 5%
Total	7.6 (100%)	10.5 (100%)	9.8 (100%)	- 7%[a]

[a]Significant change (p=.67)

The sawtimber resource is a subset of the growing-stock resource that is most suited to use by the sawmill industry. In our definition of sawtimber, the smallest trees are 9 inches in diameter. This volume is expressed in terms of board feet. As might be predicted from figure 7, the sawtimber volume of spruce-fir has increased steadily from the initial inventory. In 1959 the volume was 11.2 billion board feet, in 1971 it was 15.8 billion board feet, and in 1982 it was 19.2 billion board feet. Between the second and third inventories, while growing-stock volume was declining by 7 percent, sawtimber volume was gaining 22 percent. So, despite the overstocked stands, the budworm outbreak, and the substantial harvesting activity the larger sized trees did surprisingly well. This is why we are seeing an increase in the area of spruce-fir sawtimber stands. Thus, a resource that is considered relatively old by some people is continuing to grow and mature.

There is certainly a dark cloud on the horizon of sawtimber volume, however. The ingrowth to this resource must come from the pole-size diameter classes, and these have shown drastic reductions between 1971 and 1982. By the time our next survey is conducted, these reductions should affect spruce-fir sawtimber volume.

Figure 8 shows where the growing-stock and sawtimber volumes of spruce and fir are concentrated in Maine. The values are expressed in terms of volume per acre of timberland rather than total spruce-fir volume. Piscataquis County, besides being the heart of the state, also seems to be the major spruce-fir area. The ranking reflects a combination of the natural growing conditions and the past history of man's activities in the various regions.

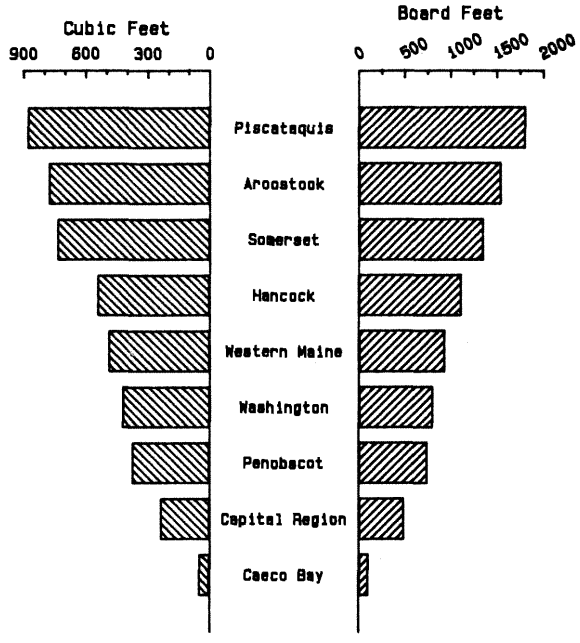

Figure 8.--Spruce and fir volume per acre of timberland by geographic unit in Maine, 1982. The state average on all timberland areas was 575 cubic feet per acre and 1,128 board feet per acre.

More On Growing-stock Volume Change

The growing-stock resource of spruce and fir is declining. But as with other attributes of this resource, the statewide situation is an average of conditions, which differ around the state. Most geographic units showed insignificant changes (Fig. 9). In absolute terms, Aroostook County lost the most volume, 470 million cubic feet. But in percentage terms, Penobscot County fared the worst with a 27 percent decline.

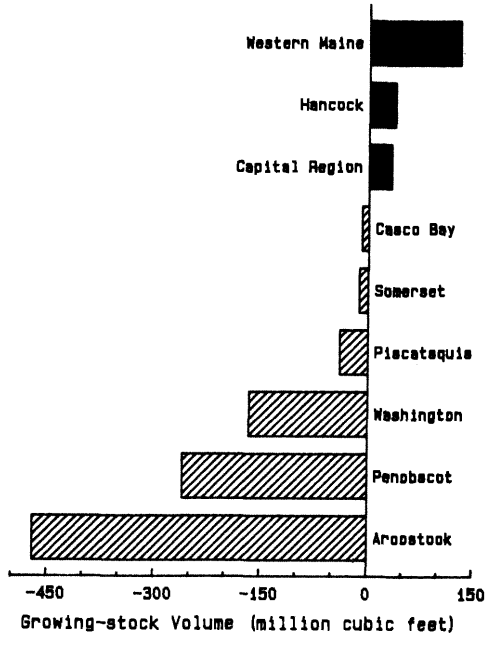

Figure 9.--The change in spruce and fir growing-stock volume between 1971 and 1982 in Maine by geographic unit. Only Washington, Penobscot, and Aroostook counties showed significant change.

It is interesting to compare figures 6, 8, and 9 to see what relationships exist between defoliation, volume per acre, and change in volume. Piscataquis County is a good illustration. It had the worst defoliation conditions and yet it ranked first in terms of volume per acre and showed little change in volume between 1971 and 1982. The degree of defoliation was not well correlated to either volume per acre or volume change. One explanation is that the defoliation conditions may have been relatively recent, while the volume change was calculated over an 11-year period. Another is that even if defoliation translates directly into mortality, mortality is only one of several components that determine the net change in volume.

The annual net change in volume is equal to the difference in inventory estimates divided by the number of years between the inventories. Net change is equal to net growth minus removals. Net growth is equal to gross growth minus mortality minus cull increment (the volume of live trees that were merchantable but are now cull). Gross growth is equal to ingrowth (the volume of trees crossing the 5-inch diameter minimum) plus accretion (the growth on trees that were alive and merchantable at both occasions).

A comparison of these components for fir and spruce will permit a fuller understanding of why the volumes changed as they did between the last two inventories. In figure 10, the components of change are listed across the top of the chart. The circles represent volume of fir, spruce, or spruce and fir combined. The area of the circles is drawn in relation to gross growth, which is set at 100 percent. Empty circles represent positive values, and filled circles represent negative values.

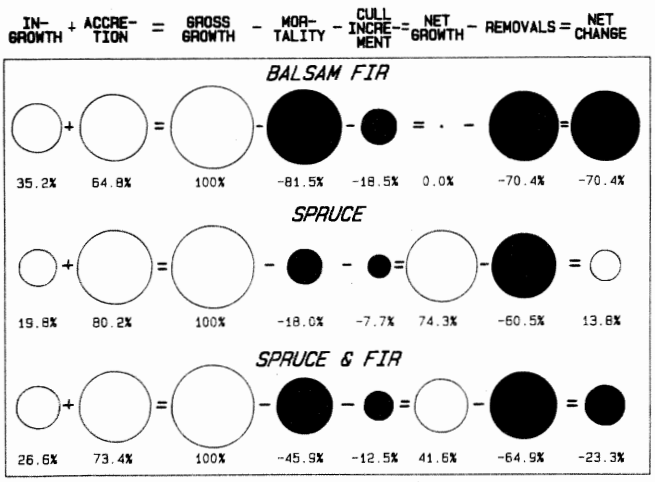

Figure 10.--Components of annual net change for balsam fir, spruce, and spruce and fir in Maine for the period 1971-1981.

For example, balsam fir gross growth is 35 percent ingrowth plus 65 percent accretion. Gross growth is then reduced 82 percent by mortality and another 18 percent by cull increment. This leaves essentially zero in terms of net growth. When removals, which is 70 percent the size of gross growth, is subtracted from net growth, the result is a negative net change that is 70 percent the size of gross growth.

Another way to look at this is in terms of walking along a path. We begin walking, and after accounting for ingrowth and accretion, we have moved ahead 100 steps. We are hit by the fierce wind of mortality and cull increment, and we are blown back to near our starting point. This is net growth. After a brief respite, we are moved backwards another 70 steps by chain saws and feller-forwarders (removals). Where we finally stop is net change. That sequence was repeated each year for fir in Maine during the last period between inventories.

Comparing the components of annual net change for fir and spruce reveals some interesting differences and similarities. While accretion contributes more to gross growth for both species, it is larger for spruce than fir. Ingrowth is more important to fir because the fir resource, as shown in figure 4, has more small trees. These small trees eventually grow large enough to cross the 5-inch threshold, and are then counted as ingrowth. The spruce resource is dominated by larger trees, and more of its growth is put on these trees, which counts as accretion.

The mortality level for fir is much larger than it is for spruce. This was partially reflected in figure 3 in terms of dead trees. Two factors are important here. One is that fir, in comparison to spruce, is a short-lived species. In many stands, the spruce and fir trees are the same age, but the fir is becoming overmature while the spruce has yet to reach maturity. Thus, the fir are dying at a faster rate than the spruce. Another factor is the budworm, which damages the fir component of this resource most severely (Fig. 5). These two factors no doubt contribute to the much greater impact of cull increment on fir than on spruce. Aging and budworm may first cause a tree to be unmerchantable before it finally succumbs.

The difference in net growth is most noticeable. While fir is at a standstill, spruce is increasing at a level three-fourths of gross growth. The negative impact of mortality and cull increment was much greater for fir. Even without the impact of harvesting, fir in Maine is going nowhere.

The removals component was relatively high for both species probably because of the increased industrial expansion of the wood-using plants in the region. Substantial harvesting pressure is being applied to both species. The fact that fir's removals percentage is greater than that of spruce may be a reflection of the impact that spruce budworm has had on the harvesting practices of the spruce-fir landowners. Proportionately more fir was being harvested in sanitation and salvage operations. Spruce was considered to be less vulnerable to budworm attack so it was sometimes left in the stands for cutting at a later date.

The bottom line, net change, is consequently different for fir and spruce. Fir is substantially negative, while spruce is modestly positive. Even though the situation is better for spruce than fir, it would only take slight decreases in gross growth and/or slight increases in mortality, cull increment, and removals to reduce net change to zero or a negative value. If indeed the budworm is killing spruce trees and reducing growth on live trees more now than it did between 1971 and 1981, then spruce might today be at the breakeven point.

If we compare certain components of change for the pre-budworm outbreak period (1958 to 1970) with those for the post-budworm outbreak period (1971 to 1981), we see that some radical shifts have occurred. In Table 2, the annual components are taken as a percentage of the spruce-fir growing-stock volume. These could then be viewed as annual rates of change, similar to the interest or yield one might receive on an investment. The mortality rate for spruce-fir has nearly doubled. The net growth is less than one-third of what it used to be. Removals have increased significantly, especially for fir. And net change has moved from a robust 2.4 percent increase to a negative 0.6 percent. This indicates that a peak of growing-stock inventory occurred somewhere between 1971 and 1981. What was going up is now coming down. Not all of these changes were caused by spruce budworm, but it undoubtedly was an important factor affecting each component and each species.

Table 2. Some components of annual change as a percentage of spruce-fir growing-stock volume.

Components	Fir	Spruce	Spruce/fir
	----------Percent----------		
Mortality			
1958 to 1970	-1.1	-0.4	-0.7
1971 to 1981	-2.2	-0.5	-1.3
Net Growth			
1958 to 1970	+3.8	+3.7	+3.8
1971 to 1981	0.0	+2.1	+1.1
Removals			
1958 to 1970	-1.2	-1.5	-1.4
1971 to 1981	-1.9	-1.7	-1.8
Net Change			
1958 to 1970	+2.6	+2.2	+2.4
1971 to 1981	-1.9	+0.4	-0.6%

Summary and Conclusions

The spruce-fir resource in Maine dominates the state's timberland. It has dominated for centuries and it will continue for centuries. What we are witnessing now are the shifts and changes of a dynamic ecosystem. Pressures of varying degree are being applied from several sources and directions.

The stands are becoming more diverse in species composition though they will always be predominantly spruce and fir. The stands are crowded with trees and have become more so within the last decade. The aging and competition within the stands, in conjunction with feeding by the spruce budworm, have led to more dead trees in the stand. A combination of natural death and harvesting has reduced the numbers (and volume) of the pole-size trees in a resource dominated by small trees.

Spruce and fir, while often mentioned in the same breath due to their close association in the woods, are really two different species that are dissimilar in many respects. They have different silvical characteristics. They do not live the same length of time. In unattended stands, fir tends to dominate the small size classes and spruce the larger ones. They are not treated equally by the budworm and, to a certain extent, by man.

The challenge to the forestry community is not how to preserve the spruce-fir resource because that is, in different senses, both impossible and unnecessary. The challenge is to recognize which pressures are affecting the resource, what the nature and extent of these pressures are, and how to then manage these pressures in such a way as to maintain an adequate flow of products and benefits from this renewable resource. It is not an easy job, but it is one that we, as professionals, can tackle and complete.

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THE INVENTORY EFFECT OF SPRUCE BUDWORM IN NEW BRUNSWICK

J. R. Carrow, Research Scientist
M. D. MacFarlane, Director,, Forest Management

N. B. Department of Natural Resources, P.O. Box 6000, Fredericton, N.B. E3B 5H1

Introduction

Once upon a time the spruce budworm was not a problem in New Brunswick. We had a spruce/fir forest and we had spruce budworm, but as our francophone friends in Canada say, it was "pas de proleme". The forest industry in eastern Canada had developed on a base of white pine, a species fortunately not plagued by serious pests like spruce budworm. As white pine disappeared from our forests in the late 1800's and early 1900's, spruce and fir became more prominent components of the forest, and the industry shifted its attention to these species. Forest composition and industrial demand evolved together, and by the early 1950's a major pulp and paper and sawmilling industry had developed, with the spruce/fir forest as its mainstay. Of course the spruce budworm had been there all along. There is evidence that our forests have experienced at least seven major outbreaks in the past 200 years. Those outbreaks took their toll, but until the 1950's there was sufficient growing stock to satisfy the appetites of both the budworm and man. In other words, we had a clear surplus of spruce/fir growing stock. This is evident in a 1935 report by Miles Gibson, describing the condition of the forest after the 1912-1920 epidemic.[1].

> "The amount of loss thast resulted and the present conditions of these areas are hard to realize without a personal visit, for it is difficult to visualize areas that have not been cut for at least 40 years with 90% of the mature fir and spruce lying on the ground in various stages of decay almost hidden among a dense stand of spruce and fir up to 20 feet in height".

The current epidemic in New Brunswick which began about 30 years ago, is simply a continuation of the spruce/fir forest-budworm cycle which has been repeating itself for centuries. The factor which sets this current epidemic apart from previous outbreaks is that the industry has developed a high economic dependence on the same species favoured by the spruce budworm.

[1]Gibson, J. M. 1935. Report of an inspection of the Restigouche Company land on the Kedgwick River watershed. Unpubl. Rep., N.B. Dept. Lands & Mines.

This dependence, of course, was the rationale behind the decision to initiate a protection spraying program in 1952; some 30 years later, this economic dependence continues to be the justification for annual protection spraying.

New Brunswick's Softwood Inventory

New Brunswick carried out three provincial forest inventories in 1958, 1968, and 1979. In addition, about 1100 permanent sample plots were established in 1955 and maintained since. Inventory data provide a good basis to track growing stock development over 20 years. Before discussing this, it is important to emphasize that during this period the forest was under continuous pressure from budworm, but it was also protected annually through spraying. So what we have generally is a picture of growing stock development in which the natural budworm-forest interaction was suppressed through spraying. This was a new experience for the spruce/fir forest of New Brunswick.

In the early 1950's, most of the softwood forest on Crown land (predominantly spruce and fir), was in the 30 to 50 year age class; this was the forest that resulted after the 1912-1920 budworm outbreak. By 1979, this age class had matured and now, the 60 to 80 year age class occupies 76% of Crown land.

If this forest had been uninfested and grown normally, we expect development would have peaked in the 1960's and then started to decline rapidly in the 1980's, due mainly to fir mortality (Fig. 1). The presence of budworm in this forest has simply accelerated this decline.

Table 1 shows the total merchantable softwood inventory from 1958 to 1979 for the province as a whole, and for the northern and southern halves of the province. From 1958 to 1968, the total softwood inventory increased by 18%, but in the following decade, the inventory declined to about the same level as in 1958.

Of interest is the difference in development of spruce and fir, during that period. In the first decade, the spruce inventory increased twice as much as fir (24% vs. 11%), and in the second decade fir decreased more than twice as much as spruce (22% vs. 9%).

An examination of the trends in growing stock in northern and southern New Brunswick shows that:

1. the major gain in growing stock has been on spruce in southern N. B.

2. the major loss in growing stock has been on fir in southern N. B.

Figure 1

Expected development of predominantly Fir and predominantly Spruce stands after 1912 Budworm epidemic, assuming no further insect attack.

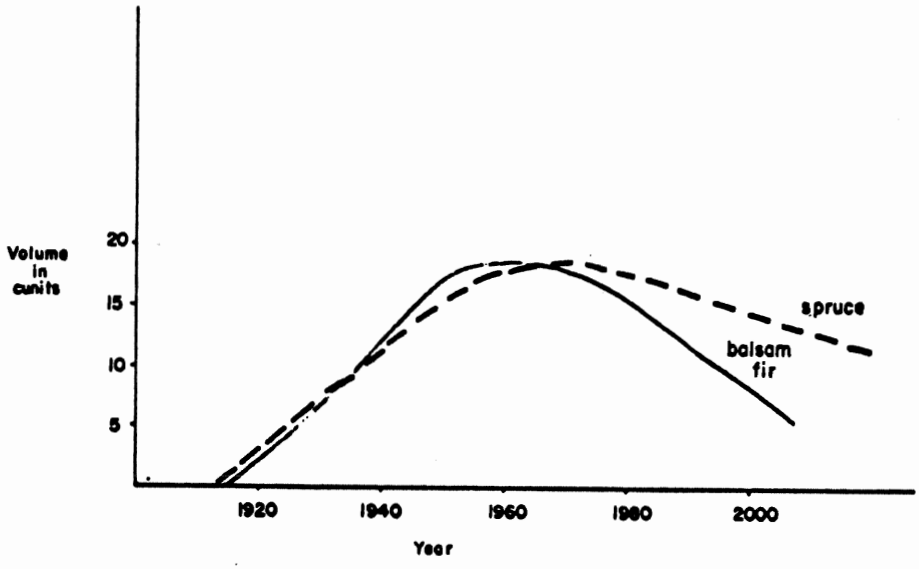


TABLE 1. MERCHANTABLE SPRUCE AND FIR GROWING STOCK IN NEW BRUNSWICK, 1958 to 1979

('000 cunits)

PROVINCIAL TOTAL

	Growing Stock			Change in Growing Stock		
	1958	1968	1979	1958 to 1968	1968 to 1979	1958 to 1979
Spruce	5180	6453	5859	+1273 (24%)	- 594 (9%)	
Fir	5151	5713	4468	+ 562 (11%)	-1245 (22%)	
TOTAL	10331	12166	10327	+1835 (18%)	-1839 (15%)	
			NORTHERN NEW BRUNSWICK			
Spruce	3305	3600	3047	+ 295 (9%)	- 553 (15%)	-258
Fir	3714	3896	3522	+ 182 (5%)	- 374 (10%)	-192
TOTAL	7019	7496	6569	+ 477 (7%)	- 927 (12%)	
			SOUTHERN NEW BRUNSWICK			
Spruce	1875	2853	2812	+ 978 (52%)	- 41 (1%)	+937
Fir	1437	1817	946	+ 380 (26%)	- 871 (48%)	-491
TOTAL	3312	4670	3758	+1358 (41%)	- 912 (19%)	

In the north, the fir growing stock has declined by 374 000 cunits in the last decade, a drop of 10%, but in the south, the inventory of fir has decreased by 871 000 cunits or 48%. Over the 20 year period, the fir inventory has decreased by only 192 000 cunits in the north, compared with 491 000 cunits in the south.

Development of spruce presents a different story entirely. In the south, the growing stock of spruce decreased by only 1% in the last decade, compared with a 15% decline in the north. Over the 20 year period, the spruce inventory increased in the south by 937 000 cunits, compared with a decrease of 258 000 cunits in the north.

The Effect of Spruce Budworm

The reason for considering growing stock development in the south separate from the north relates to lthe difference in protection from spruce budworm in the two parts of the province. Until 1976, the spruce/fir forest was protected throughout the whole province with an annual spray program. However, in 1977, the New Brunswick government imposed what amounted to a one-mile setback zone around all human habitation in the province, preventing the aerial application of chemical insecticides in this zone. The result was that for four years, the forest in this setback zone received no protection from budworm. Because southern New Brunswick is much more heavily inhabited, in both urban and rural areas, much more of the softwood forest went unprotected in the south than in the north. In fact, over 75% of the southern forest was revoved from the protection spraying program.

Since 1981 protection has been restored to part of this one-mile setback zone, using small aircraft. However the effect of not protecting balsam fir for four years has been dramatic. Approximately half the inventory of balsam fir disappeared between 1968 and 1979, and the majority of this loss is attributable to spruce budworm.

Data from permanent sample plots reinforces the effect of lack of protection on growing stock. Figure 2 shows the growth of the spruce and fir components in a plot located in north-central New Brunswick (plot 9-3). This plot is in a stand which has been protected as required, and is now 70 years old. In contrast is a plot (plot 2-a) in an area that was unprotected due to environmental setbacks (Fig. 3). This graph shows the budworm effect on inventory clearly, with a sharp decline in fir growisng stock in the late 1970's, while the spruce growing stock remained static.

This response of fir to lack of protection will surprise no one. Balsam fir is noted for its vulnerability to spruce budworm feeding. Four to five consecutive years of severe defoliation is enough to kill this species.

In contrast, spruce is more tolerant of budworm feeding damage than fir, and this is evident in the negligible loss in spruce growing stock (1%) in southern N.B. from 1968 to 1979, despite the lack of protection.

What is the future effect of the budworm likely to be on merchantable volumes of spruce and fir? In the mature forest where protection is possible, the budworm may become of secondary importance to the natural volume declines due to over-maturity of the forest. By 1990, most of the fir-spruce forest will be in the 70-100 year age class. This is not critical for spruce but fir volume is expected to decline rapidly regardless of budworm attack.

In the long run, the effect of budworm on the younger forest is perhaps the most critical problem facing New Brunswick. These young stands are scheduled for harvest, starting 30 years from now and if budworm caused mortality or growth losses delay or reduce the availability of this wood, there will be severe wood shortages in the Province for a 8-10 year period beginning about 2020. This is illustrated in Figure 4. The difficulty is that the majority of this immature softwood is located on small freehold land, nearly all of which is located in the setback zone where environmental constraints make effective protection spraying more difficult, and more costly.

We have a very tight supply situation for softwood for the next 30 years. We will have no surplus, and virtually every merchantable softwood stand in the province is required to sustain industrial demand during that period. Our strategy in New Brunswick is to direct harvesting into fir and fir/spruce stands rather than into spruce or spruce/fir, and to restrict harvesting to the mature-overmature stands. As well we are directing protection spraying to mature stands that can be maintained in an operable condition, and to immature softwood which will be required for harvest in 15 to 20 years.

This has forced us into management of individual stands, something which is impossible with traditional forest inventory information. However, a new computer mapping system recently acquired by the Department of Natural Resources is making this possible.

In summary, the effect of budworm alone on spruce and fir inventory is very difficult to document. There are reports from the Canadian Forestry Service on how much wood is dead or dying in various jurisdictions. The Department of Natural Resources itself carred out a similar survey in 1981. The numbers are very impressive - 17 million cunits of moribund or dead spruce and fir in the province, or six times the amount we harvest annually. In New Brunswick the amount of dead wood, however, is only of academic importance. The critical thing to know

is the amount of merchantable softwood volume that can be expected over time, and what level of protection of current growth is required to achieve this production. Making this happen will require more than protection. We must rigorously schedule our harvesting so that the inventory of mature softwood does last until about 2020 when our new forests are expected to become operable. In the meantime, utilization will have to be improved and lower volume stands harvested in order to carry us through the next 35 years.

FIGURE 2

Growing stock development in forest area protected from spruce budworm.

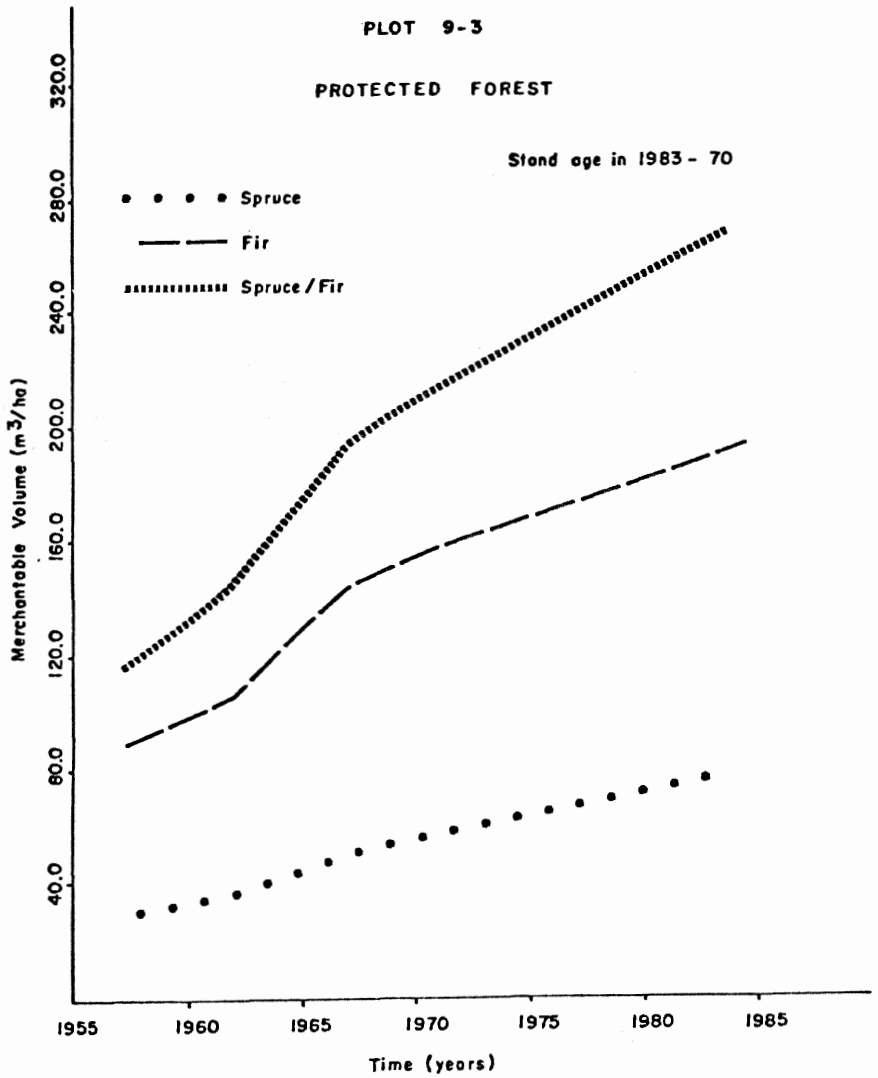


FIGURE 3

Growing stock development in forest area with no protection from budworm from 1977-to 1981.

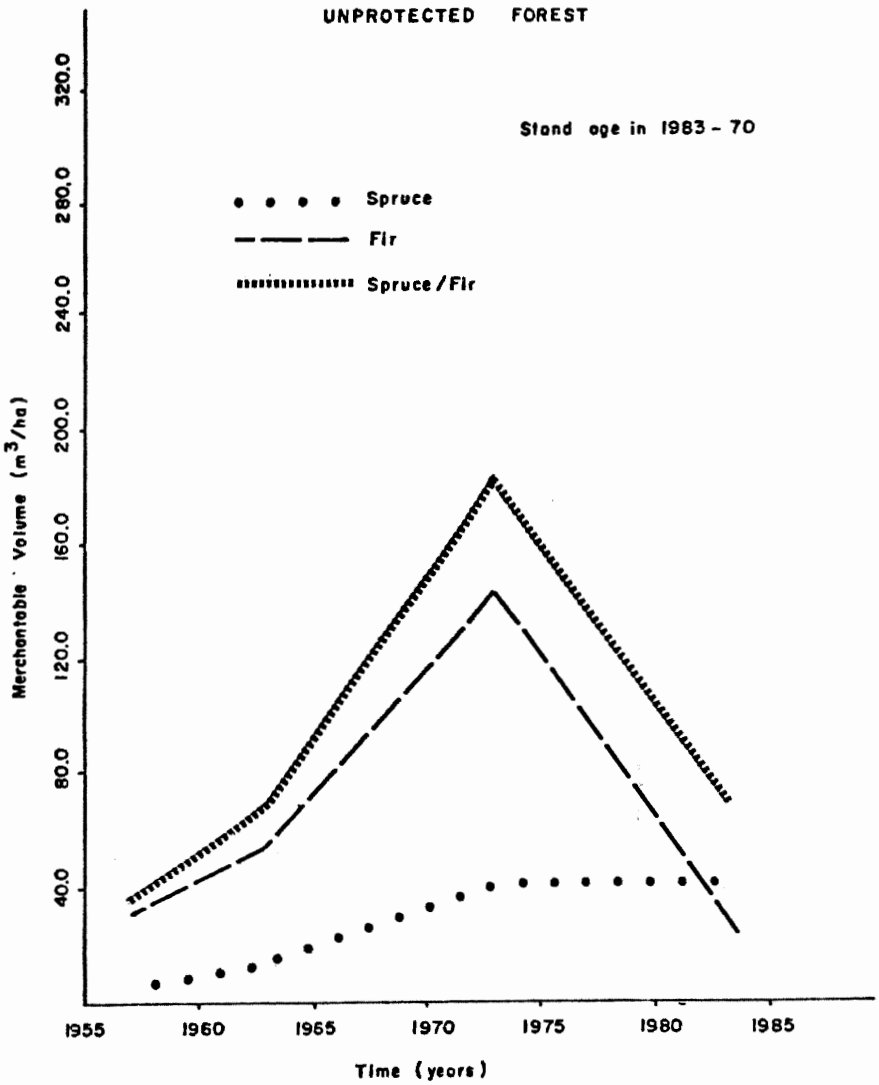
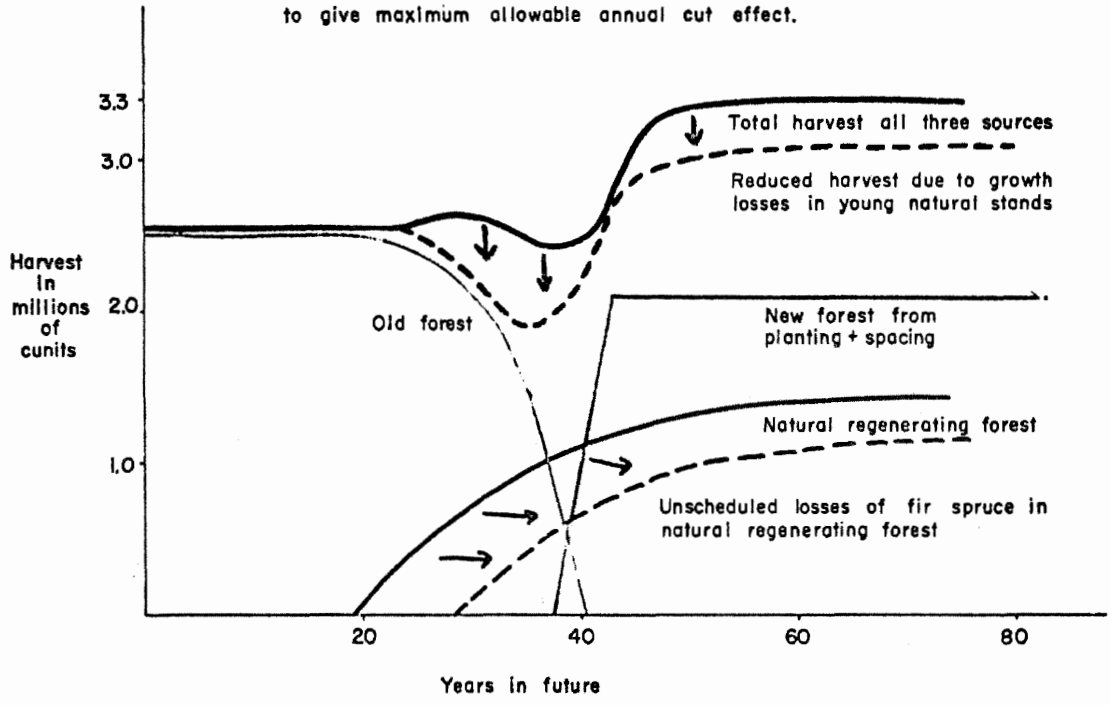


Figure 4

Available harvest with silviculture program level set to give maximum allowable annual cut effect.



COMPUTERIZED MAPPING APPLIED TO THE SALVAGE PROCESS

Thomas J. Corcoran and Harvey M. Schiltz

Professor of Forest Resources and of Forest Engineering, and Research Associate in Forest Resources, respectively. College of Forest Resources, University of Maine at Orono, Orono, ME 04469.

A computerized system, motivated by the need for budworm-related wood procurement strategies, was developed in stages. The initial mapping and information storage/retrieval program was expanded to provide an automated technique for selection of timber harvest sites and determination of scheduled wood flow to associated market locations. An extension to the system implemented an interactive computer graphics module that assists in the optimization of the harvest area spatial layout of all-weather logging roads and associated decentralized processing locations (landings). Further expansion led to the development of a total map-based information system, with features complimentary to the initial data-base that provides inventories of road networks to allow more accurate forecasting of harvest/transportation costs.

The spruce, Picea spp., and balsam fir, Abies balsamea L., are important components of northern New England's forest ecosystem. In Maine, spruce-fir forests cover some 8 million acres of 47 percent of the State's forestland. The economic importance of Maine's spruce-fir resource is indicated by it's annual harvest of more than 2.2 million cords of pulpwood and 600 million board feet of sawtimber (Field, 1980). Between 1975 and 1980, spruce and fir mortality amounted to nearly twice the harvest of these species (Schiltz et al., 1983). Thus, the current spruce budworm, Choristonuera fumiferana Clem., epidemic potentially necessitates the salvage of large quantities of the spruce-fir timber resource.

Program Initiation

An inventory system has been established to monitor spruce budworm infestation severity. To facilitate handling of the inventory data, a computer program was developed to tabulate and display information on budworm levels and stand conditions. The program produces lineprinter maps showing the distribution of budworm hazard ratings throughout the State or any portion of it. The lineprinter maps are based on grid coordinates which divide the State into rectangular units of approximately 240 hectares. These rectangular units are one minute by one minute subdivisions of U.S. Geological Survey 15-minute guadrangle maps and are referenced by State fire control division designations. Although survey information is lacking for smaller subdivisions, the mapping routine will produce maps down to ten acres. Each map character - a dot, letter, number, or other symbol - represents the center of one rectangular unit (cell). In addition to indicating high population levels, budworm hazard ratings are used to determine areas potentially in need of timber salvage operations.

System Expansion

During the development of the tabulation and mapping program, routines were included that allowed the construction of an automated technique for selection of timber salvage sites, transportation network routing, identification of markets, and the optimum cost allocation of wood volumes to specified destinations. The system's construction allows numerous overlays of data to be associated with each identifiable data-point, based on the grid layout. A data-point can contain overlays of information on existing roads, infestation severity, wood volumes, and market locations. Information storage/retrieval flexibility allowed the development of intricate data manipulation routines. These routines include the simulated creation of new roads to access timber salvage sties, a transportation routing technique, and the "classical" linear programming transportation model.

System Methodology and Execution

Specification of boundary cells and transportation network segments comprising the selected base area is required for initiating program execution. Additionally, the potential salvage sites, as identified by pre-selected criteria (eg. infestation severity ratings), require associated timber volume input.

In the second execution phase, routines manipulate the selected data-base connecting all potential source locations (salvage sites) to the existing transportation network. Beginning at the salvage site with the shortest distance to an existing road, a new road is theoretically built. Subsequent passes re-sort the source location data allowing newly constructed roads to be shored by multiple source locations, thus minimizing new road construction. Once all source locations are connected to road network, a shortest path network analysis technique calculates the minimum transportation cost per unit volume from each source to each destination. This process begins at a destination or market location and proceeds outward along the transportation network. The product of the cost per unit distance for each road class and the linear distance between grid cell centers is sequentially summed to provide transportation costs for each source/destination pair. The process continues until all source locations are "costed" or all elements of the transportation network connected to the destination have been processed (Phillips, Corcoran and Brann, 1983).

Lastly, the calculated costs, salvage site volumes, and mill (destination) requirements are utilized in the linear programming transportation model. The result is a list of salvage sites allocating their associated timber volumes to specified market locations. The total transportation cost is the minimum cost obtainable, while still satisfying the constraints of supply and demand. The

Proceedings of a Conference "FROM STUMP THRU MILL" provides an overview of the need for effective transportation planning and efficient utilization of the spruce-fir resource (Corcoran and Gill, 1983).

Harvest Site Planning

A modular component of the system deals with the layout of roads and landings at the salvage site. When salvaged timber is skidded to a roadside landing and roads are laid out - roughly parallel and equally spaced - optimum road spacing is a function of road construction cost, variable skidding cost and landing development cost (if applicable). Standard computational factors include such notation averages as machine speed and load size, operating area designation, timber volume, travel patterns and distances plus costs of road construction, of landing construction, and of relevant machine useage. When manipulated mathematically, they produce as a defined cost-optimum, the spacing between parallel roads and between the systematically located landings. Solution of the model involving multiple unknowns required a heuristically interactive procedure. A mathematical model developed to determine the ideal spacing arrangements and their effect upon costs (Ashley, et al., 1973), became the basis of the graphics procedure outlined below.

Once salvage sites have been selected, an interactive computer graphics routine provides assistance in optimizing the spatial layout of logging roads and landing locations over the harvest area. (Corcoran and Bryer, 1982). The routine allows the operator to input data values, within predetermined limits, and the program calculates and displays the optimum road and landing spacing and associated costs. In addition to tabular output, the routine allows the production of grids that can be used as overlays on aerial photographs or maps (developed by computer displays) in the initial stages of harvest site planning. Furthermore, unusual ramifications of road/landing layout patterns have been described by Bryer (1983).

Description Data-base Integration

As an outgrowth of the "road building" and harvest area spatial layout routines, a map based information module combining layers of map data with related non-graphic data has been organized as a data-base. The structure of the new module includes a road description data-base with parallel linkage to the existing location data-base. The description data-base contains all alphanumeric data associated with the road network. This data includes road names, road numbers, lengths, widths, curve-radii, pavement types, grades, functional class (primary haul, secondary haul, spur, light vehicle) and maintenance information. Descriptive data for special structures (bridges, culverts, intersections) is also stored in the description data-base, while the location data-base has been expanded to accomodate location data for these structures.

The linkage between location data and descriptive data allows a wide range of maps and reports to be requested, entering from either data-base. The graphics sub-system can be used to identify an area of interest and provides indirect access to the data-base. All data or some subset of the descriptive data pertaining to that area can be displayed. Furthermore, a map can be plotted displaying the location and extent of the features or areas selected during the data-base search, using the graphics routines.

Other report request capabilities include basic road mapping, road identification, road and materials specifications, maximum loads for specified travel routes, maintenance planning, (minimum) travel time and distance estimates between two points, and exception reports providing the location and description of all road segments and structures where structural and functional specifications do not coincide. Also, the impact of environmental and other land-use regulations on road networks will be readily available (e.g. protected buffer zones associated with roads or water ways).

Expansion of the map based information module to include landform features and terrain considerations in the new road location algorithm, will require a three dimensional representation of the area to be stored in the location data-base, which currently holds two dimensional data. This feature will enhance the planning of road networks and allow more accurate determination of transport equipment limitations, harvest/transportation costs and wood flow schedules.

Discussion

Successful application of the entire system requires diverse information about potential harvest sites, timber volumes, existing road networks, market locations, market requirements, and landform features. Although detailed information for all parameters is not yet completed on a Statewide basis, each segment of the system is independently useable where the appropriate data is available. In the recent past, the system operatively utilized estimated salvage volumes, estimated road costs, and budworm survey data to provide total timber volume allocation and associated costs. Into the year 1984, a U.S. Forest Service grant (CANUSA) financially supports the system's utilization as a research tool in developing harvest scheduling procedures.

While development was motivated by a forest insect problem, the system's inherent flexibility provides high potential for more generalized use. Whenever the short-term timber supply in need of harvesting is in excess of market requirements (supply > demand), the association of timber sources with market locations - based on a cost minimization - can be utilized to determine where harvesting should be concentrated. Conversely, specific markets that are allowed to participate in a limited short-term supply (demand > supply) can be defined and quantified.

The techniques applied in this system should be readily adaptable to other regions or nations, particularly where the forest resource is quite extensive, roads are limited, and the timber sources and delivery locations are usefully differentiable in terms of macro-policy, whether the policy goals be publicly or privately motivated.

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USING FOREST INVENTORY AND COMPUTER SIMULATION TO EVALUATE HARVEST SYSTEMS

Dennis P. Bradley

Principal Economist
USDA Forest Service
North Central Forest Experiment Station
118 Old Main, UMD
Duluth, MN 55812

The productivity of two chipping systems were simulated and compared based on two different feller-bunchers: tracked machines with a rotating boom-mounted shear, and rubber-tired articulated machines with a fixed front-mounted shear. Identical sets of simulated grapple skidders and chippers were combined with both feller-bunchers. Although the same machine speeds were assumed for both systems, outputs were compared for different shear capacities and machine availabilities. Several new procedures are illustrated.

Using inventories to assess harvest equipment requirements was the primary task of early timber cruisers. They estimated volumes as well as recommended how and when the timber should be extracted. In this report I evaluate two harvest systems using inventory data from northeast Minnesota. But while the timber cruiser in the past had only his experience to recommend what system or systems would be most appropriate, we have several other tools at our disposal. Specifically, simulation and data base management techniques can be used to model the interactions of machines, operators, and stands. And, at least in theory, we can learn which harvest systems are best under various stand conditions.

This study was funded by the CANUSA program and is a hypothetical yet realistic analysis of stand and tree factors, machine capabilities, and operating rules. Only a limited range of equipment and stands could be considered in the time available, but this report identifies the effect of certain decisions made by machine operators in their tree-to-tree and bunch-to-bunch movements. Productivity can be increased and cost reduced if simple rules are applied as tree and stand factors change.

Scope

Two different feller-bunchers working with the same set of two grapple skidders and one chipper were examined using three simulation models developed by the North Central Forest Experiment Station (NCFES).

We did not collect any machine speed and capacity data. Instead, the NCFES Forest Engineering Unit in Houghton provided its best available data. For the tracked feller-buncher, the grapple skidders, and the full tree chipper, we assumed only one set of speeds and capacities. For the rubber-tired feller-buncher, we assumed one set of speeds but two shear capacities.

Similarly, we did not collect any new stand data. Instead, we examined the NCFES's most recent forest inventory data for northeast Minnesota to find all plots with fir-spruce stocking. From these plots, we constructed 12 hypothetical stands representing average stand diameters of 6, 8, and 10 inches and basal areas of 60, 90, 120, and 150 square feet per acre. These 12 combinations represented about 95 percent of the stands in northeast Minnesota with more than 20 percent fir and spruce basal area. Harvest by the two feller-bunchers, skidding, and chipping were then simulated in each of the 12 stand combinations for the relations between productivity and the independent variables of diameter and basal area. Other combinations were used to show the sensitivity of system output to small changes in key operating variables. Finally, a realistic yet much simpler new method of simulating tree-to-tree movements by feller-bunchers was developed that also led to the development of decision rules that may be used to improve rubber-tired feller-buncher performance.

Methods

Discrete event simulation models were used to estimate production under various stand conditions. These models represent the major features of similar real systems: trees, personnel, equipment, and decision rules. Three items were required: (1) stand data for tree locations, diameters and volumes, (2) computer programs to represent machine-man-forest interactions, and (3) machine speed and capacity to estimate tree processing time.

Simulated output was ideal; no allowance was made for machine breakdowns or rest periods, but results were then adjusted to yield so-called "realistic" estimates using machine availability assumptions.

Gathered by observation or theoretical analysis, machine speeds and capacities were not specified absolutely but were randomly sampled from probability distributions for each task (Table 1). In addition, these random samples were controlled to avoid confounding. Although controlling a "random sample" to achieve more rigorous results may seem paradoxical, it is one of simulation's most important advantages.

Stand Data

All northeast Minnesota inventory plots that met several joint criteria of species, diameter, and basal area were examined to find stands most representative of spruce-fir stand conditions. About 1,300 aspen, paper birch, balsam fir, and white spruce plots were examined

and of these 347 were selected. These data were then used to develop distributions of trees per acre, diameter, stem volume, and green weight for 12 diameter and basal area combinations (Tables 2 and 3).

Table 1.--Machine speed and capacity assumptions.

Feller-Bunchers	Tracked	Rubber-Tired
Strip width-feet	34	Variable
Travel speed-mph	1	3
Shearing speed-cmin/tree	25	25
Bouquet drop rate-cmin tree	15	15
Shear capacity-sum of DBH's	25	25/15
Grapple skidders		
Travel speed-mph	5	
Bunch grapple rate-cmin/bunch	75	
Bunch realign rate-cmin/bunch	109	
Bunch drop rate-cmin/bunch	25	
Grapple capacity-sum of DBH's	50	
Chipper		
Chipping rate-cmin/load	100	
Loader capacity-sum of DBH's	25	
Van closing rate-cmin/van	50	
Van capacity-cu. ft. solid wood	670	

cmin = centiminute = 0.01 minute

Table 2.--Tree diameter distributions of stands harvested by simulator.

DBH Class (Inches)	Average Stand Data (Inches) 6	8	10
	(Percent)		
4-5.9	62.7	24.6	8.6
6-7.9	23.6	34.7	23.0
8-9.9	8.4	23.0	26.1
10-11.9	3.3	10.2	19.4
12-13.9	1.2	4.6	11.3
14-15.9	0.4	1.4	7.5
16-17.9	0.2	0.8	2.7
18-19.9	0.1	0.4	0.9
20+	0.1	0.3	0.5
Total	100.0	100.0	100.0

Harvest Models

All harvest simulators used in this study were written in IBM's GPSS V language modified to run on a CDC 172 computer (Bradley et al 1976, 1982, IBM 1973; Winsauer 1980, 1982; Winsauer and Bradley 1982).

Model of a tracked feller-buncher with boom-mounted shear. This model mimicked the operation of a tracked feller-buncher with an accumulating shear on a rotating boom. A specific machine embodying these characteristics is the Drott 40[1/]. This type of machine often operates in a straight path -- along the edge of a stand for clear cutting or in a strip through the stand for thinning. In these models both feller-bunchers worked far ahead of skidding so that skidders never waited in the woods. Both feller-bunchers also tried to create capacity bunches for skidding by combining two or more bouquets. However, although the tracked machine did not retrace its steps to drop bouquets on partial bunches dropped earlier, it carried bouquets forward to the next stopping point. In general, this machine: (1) "looked" ahead to see how far it must travel to its next stopping point, (2) moved this distance and stopped, (3) dropped the bouquet when the accumulator was full, and (4) moved again when all trees at this point had been cut (it may only be one tree).

Table 3.--Other characteristics of stands harvested by simulator.

Stand Characteristics				
Average Stand Diameter (Inches)	Basal Area (Sq. Ft./ Acre)	Density (Trees/ Acre)	Total Stem Volume (Cubic Ft./ Acre)	Green Weight (Tons/ Acre)
6	60	305	2443	56.8
	90	419	3359	78.1
	120	515	4125	95.9
	150	667	5346	124.3
8	60	152	2301	53.5
	90	207	3136	72.9
	120	264	3996	92.9
	150	334	5058	117.6
10	60	75	1901	44.2
	90	102	2585	60.1
	120	135	3419	79.5
	150	167	4232	98.4

Model of a rubber-tired feller-buncher with fixed shear. This model mimicked the operation of a rubber-tired frame steered machine with an accumulating shear fixed in front. A specific machine embodying these characteristics is the John Deere 544. Because this machine must travel to each tree to cut it, it zig-zagged across an arbitrary strip. When its accumulator was full, the bouquet was either dropped at once, carried back and added to an incomplete bunch, or carried to the next tree to be cut and dropped.

Because strip width for this machine was not limited by boom reach as for the tracked machine, a width was chosen, as described later,

[1/] Mention of trade names does not constitute an endorsement by the U.S. Department of Agriculture.

that minimized the total travel distance. In addition because this machine was modeled to retrace its steps to add bouquets to unfinished bunches, a new question arose: How far back should it go to complete a bunch for skidding? That is, at what distance will system output and profit be largest? This model optimized this decision as stand conditions changed.

Model of two grapple skidders and a whole tree chipper. Bunches, from either feller-buncher, were skidded to the landing and chipped into waiting vans. When each bunch was completed by the feller-buncher, its distance from the landing was recorded along with tree diameters and volume in the bunch. When the skidder found each bunch, it either dragged the bunch to the landing if already large enough, or attempted to add the next bunch on the strip to its grapple. Again, even though a feller-buncher tried to create capacity bunches for skidding, some bunches were still smaller than desired. Once the grapple was full, the skidder returned to the landing for chipping. If another skidder was dropping its bunch or if too many trees were already waiting to be chipped from earlier bunches, the skidder waited. Stock piling bunches elsewhere on the landing was not examined in this simulation. The chipper with loader chipped trees as fast as it could, or as fast as skidders brought wood. Trucking was assumed to be perfectly coordinated so another empty van was ready as soon as one was filled and hauled away.

Simulating tree to tree movements. Both feller-bunchers simulated strip harvests on each of the 12 stand combinations. While developing these models, we devised a new procedure to randomly locate successive trees in these strips. This in turn led to a potentially practical way for rubber-tired feller-bunchers to reduce travel distance and cost by choosing an "optimum" strip width depending on stand density (Bradley et al. 1982). If trees are really randomly scattered, the expected number of trees in any sample area is a Poisson random variable proportional to trees per acre, T. Therefore, when this sample area is a strip, the distance along the strip to the next tree is an exponential random variable inversely proportional to trees per acre and strip width. That is, the mean or expected Y-coordinate distance up the strip to the next tree is:

$$\mu_D = 43{,}560/TW$$

where T = trees per acre,
W = strip width in feet, and
43,560 = square feet per acre.

On the other hand, the X-coordinate distance of the next tree as measured from the strip's side is a uniform random variable with mean W/2. Thus, given strip width and trees per acre, the simulator takes random samples from exponential and uniform distributions to determine the locations of successive trees in the strip.

Optimum strip width for the rubber-tired feller-buncher. While developing these procedures it became clear that an optimum strip width might exist that would minimize travel. In fact, this "optimum" strip width is inversely proportional to the square root of trees per acre:

$$W_{optimum} = (3(43{,}560)/T)^{1/2}.$$

For each simulated harvest by the rubber-tired feller-buncher, we calculated the optimum strip width (W) and the corresponding mean Y-coordinate distance between trees (μ_D) for each of the 12 stands in this fashion.

Optimum bunch distance limit for the rubber-tired feller-buncher. The rubber-tired machine was also allowed to retrace its steps to create full bunches, thereby increasing overall system output. The farther it retraced its steps, the less its own productivity but the greater the skidder productivity because bunches were more likely full size. At some distance, however, costs outweighed benefits. The optimum distance depended on the costs of feller-bunching versus skidding and chipping, but precisely how was not clear. However, we conducted an experiment to estimate optimum bunch distance limits for the rubber-tired machine given the speeds and capacities assumed in this analysis. These "so-called" optimums were also used in this study.

Tracked feller-buncher. This machine moved and cut trees in strips somewhat narrower than twice its maximum boom reach. Moving and cutting were treated separately. First, the machine moved forward until either trees in front blocked its path or a tree on the side was about to pass out of reach. Whichever happened first stopped the machine. All trees within reach were then cut before moving again. Thus, two questions were asked: how far is it to the next stopping point? And once stopped, how many trees are within reach?

As explained earlier, when trees are randomly scattered, the number of trees in any sample area is Poisson distributed and proportional to trees per acre. If this question was merely one of scanning the strip for the next tree, as it was for the rubber-tired machine, the answer would be straight forward. However, the shape of the tracked machine's felling area is different. Both the front and trailing edges are curved and the area occupied by the machine in the center of its felling area cannot contain trees.

To resolve this difficulty, random distributions of trees in strips were prepared, and plotted, and a template of the tracked feller-buncher's felling area was "moved" down each. When a tree either blocked the machine or was about to pass out of reach, the template was stopped, the distance traveled was measured, and the trees within reach were counted. From a series of these experiments we developed two equations. First, the distance between stopping points followed an exponential distribution with

the mean distance:

$$\mu_D = 14.68130e^{0.03813}$$

where: e = 2.71828,
S = equilateral tree spacing = $(43{,}560/0.866T)^{1/2}$, and
T = trees per acre.

Second, the number of trees found at each stopping point followed a Poisson distribution with the mean number of trees:

$$\mu_N = 1.78910 + 0.01340T$$

where: T = trees per acre.

At least one tree was cut at each stopping point.

Harvest Experiments

Feller-buncher simulations. Given the 12 stand combinations and the 3 harvesting models, we conducted a series of harvesting experiments. For all feller-buncher simulations, 10,000 trees were cut, and tree diameters, volumes, weights, distances, travel times, cutting times, and bouquet and bunch sizes were recorded. These data were then subjected to the various calculations and adjustments for the machine and system comparisons.

Several additional experiments were conducted on the rubber-tired machine. First, two different shear accumulator capacities were examined; 25 inches as a sum of diameter limit (same as the tracked limit) and 15 inches. Finally, we carried out harvests with optimum and nonoptimum strip widths and optimum and nonoptimum bunch distance limits.

Skidding and chipping simulations. After each stand was felled and bunched the record of bunches was fed to the skidding and chipping simulator. Because bunch distances from the landing ranged from 0 to 660 feet and one skidder was usually too slow for the chipper, two grapple skidders were created to operate simultaneously on their own 10,000-tree set. Each set of trees was skidded and chipped in precisely the same order as felled. Although the two skidders interacted with each other and the chipper at the landing, no skidder interactions were allowed in the woods.

Machine availability and productivity calculations. Although each simulated harvest created a lot of data, we were mainly interested in the production and time requirements to either fell and bunch or skid and chip. Many frequency tables were used to check the conformity of system input and output. For each stand, machine, and system combination, the most important items were production in tons and time in hours. Their ratio, tons per hour, is a so-called ideal productivity and is the major statistic used in all comparisons.

Ideal productivity is defined as the maximum potential output given the operator skill levels implied by the machine speed data listed earlier. Yet because the simulator did not account for mechanical breakdowns or rest periods, these maximums were also adjusted by the following factors to yield a "realistic" productivity.

	Percent of ideal productivity
Tracked Feller-Buncher	60 percent
Rubber-Tired Feller-Buncher	65 percent
Grapple Skidders	67 percent
Full Tree Chipper	80 percent

Results

Feller-Buncher Productivity Comparisons

Both feller-bunchers have 25-inch shear capacity. For stands averaging 6 inches in diameter, "ideal" production rates between the two machines were similar, although the tracked machine showed a slight advantage (5 percent) when basal area was 150 sq. ft. per acre. But if these ideal outputs are adjusted to the more "realistic" availabilities assumed in this study, the rubber-tired machine had a consistent advantage although again differences were small at any basal area (Table 4).

Table 4. Ideal machine and system productivity.

Machine	Shear Capacity (inches)	Basal Area (sq. ft. per acre) 60	150
		(green ton/hour)	
		Average DBH = 6 inches	
TRACKED FB	25	31.0	34.4
RUB-TIR FB	25	31.1	32.8
RUB-TIR FB	15	27.8	29.4
SKDRS	--	37.3	37.7
SYSTEM	--	35.6	35.7
		Average DBH - 8 inches	
TRACKED FB	25	49.8	58.2
RUB-TIR FB	25	54.3	57.6
RUB-TIR FB	15	48.8	51.8
SKDRS	--	53.0	53.2
SYSTEM	--	47.6	47.4
		Average DBH - 10 inches	
TRACKED FB	25	68.5	84.0
RUB-TIR FB	25	87.6	93.2
RUB-TIR FB	15	80.8	85.1
SKDRS	--	63.5	67.0
SYSTEM	--	58.5	60.9

For stands averaging 8 inches in diameter, ideal production rates between the two machines showed larger differences. When basal area was 60 sq. ft. per acre, the rubber-tired machine had about a 9 percent advantage. But when basal area was 150 sq. ft. per acre, the tracked

machine's "ideal" productivity slightly exceeded that of the rubber-tired machine. After adjusting for availability, the rubber-tired feller-buncher was consistently more productive. However, margins decreased continuously from 18 to 7 percent as basal area increased from 60 to 150 sq. ft. per acre.

For stands averaging 10 inches in diameter, "ideal" production rates between machines showed the largest differences. When basal area was 60 sq. ft. per acre, the rubber-tired machine had a 28 percent advantage. And when basal area was 150 sq. ft. per acre, although differences were smaller, the rubber-tired machine was still 11 percent more productive. After adjusting "ideal" productivity to "realistic" levels, the rubber-tired machine was consistently more productive. It had a 39 percent advantage over the tracked machine when basal area was 60 sq. ft. per acre. But when basal area reached 150 sq. ft. per acre, its advantage declined to 20 percent.

Unequal shear capacity: the rubber-tired limit has been reduced to 15 inches. For stands averaging 6 inches in diameter, the tracked machine was consistently more productive than the rubber-tired machine. The margin was 10 percent with a basal area of 60 sq. ft. per acre, and it increased to 17 percent with a basal area of 150 sq. ft. per acre. After adjusting for the availability, the tracked machine is still more productive but differences are less than 8 percent (Table 4)

For stands averaging 8 inches in diameter, although the tracked machine was only slightly more productive than the rubber-tired one when basal area was 60 sq. ft., it was 12 percent more productive when basal area was 150 sq. ft. After adjusting for availability, the rubber-tired machine was slightly more productive at 60 sq. ft. and slightly less productive at 150 sq. ft.

For stands averaging 10 inches in diameter, the rubber-tired machine was more productive than the tracked machine at all basal areas, with an 18 percent advantage at 60 sq. ft. but only a 1 percent advantage at 150 sq. ft. After adjusting for availability, the rubber-tired machine was substantially more productive at all basal areas.

In general then, basal area has a greater effect on the productivity of the tracked machine than on the productivity of the rubber-tired machine. This is consistent with the assumption that the tracked machine has a fixed boom reach and fixed strip width for all stands. In contrast, the rubber-tired feller-buncher operator was allowed to optimize strip-width as stand density changed and was also allowed to choose an optimum distance limit while creating full size bunches.

System Productivity

In contrast to the previous comparisons, both skidder output and chipper or overall system output are unaffected by basal area, regardless of feller-buncher type or shear capacity! In every case, system output was constrained only by tree diameter: larger trees mean higher system output, as one would expect (Table 4).

The Effect of Nonoptimum Strip Widths on Rubber-Tired Feller-Buncher Output.

Previous results showed rubber-tired output when strip width was three times the mean Y-coordinate difference between trees up the strip. To show the effect of nonoptimum strip width on productivity, four simulated harvests were conducted with strip width equal to the mean Y-coordinate difference. Thus, because

$$(W)(\mu_D) = 43{,}560/T$$

and if, as now assumed, $W = \mu_D$

then $W_{nonoptimum} = (43{,}560/T)^{1/2}$.

All four stands used in this nonoptimum simulation averaged 10 inches in diameter and basal areas ranged from 60 to 150 sq. ft. per acre. Shear capacities were 25 inches and the bunch distance limit was set to the previously established optimum. Strip widths for the four stands differed from the optimum strip widths as follows:

Basal Area	Strip Width	
	Optimum	Nonoptimum
(sq. ft. per acre)	(Feet)	
60	41.74	24.10
90	35.79	20.67
120	31.11	17.96
150	27.97	16.15

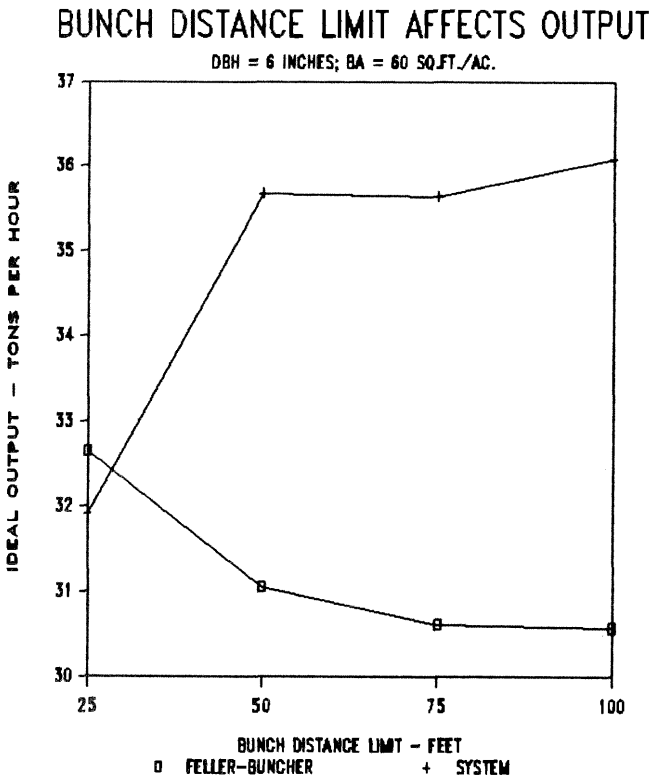
Nonoptimum strip widths in this brief example reduced the rubber-tired feller-buncher's ideal output from 87.6 to 83.8 tons per hour when basal area was 60 sq ft per acre and from 93.2 to 91.0 when basal area was 150 sq. ft. per acre -- 4.2 and 2.4 percent, respectively. Trees felled per hour showed similar relative reductions. The impact on system costs would be less because feller-bunchers represent only a portion of total costs.

The Effect of Nonoptimum Bunch Distance Limits on Rubber-Tired Feller-Buncher Output.

In previous simulations, bunch distance limits were used that traded declines in feller-buncher output against increased system output. The optimum bunch distance relationships for a 6 inch diameter stand and basal area of 60 sq. ft. are now shown for shear capacities of both 15 and 25 inches (Figure 1). Optimum strip widths were used in all cases.

Although rubber-tired feller-buncher output declined dramatically and then more gradually as the bunch distance limit increased, system out-

put leveled off after a very rapid increase. Note also, that although shear capacity affects feller-buncher output, it has almost no effect on system productivity; system output was almost identical once the optimum bunch distance limit was achieved or exceeded, regardless of shear capacity.



Traveling at least 50 feet back in these examples increased system output for the 25 inch shear about 13 percent compared to 25 feet (from 32 to 35.5 tons per hour). For a 15 inch shear system, output increased almost 17 percent (from 30 to 36 tons per hour). The effect on system cost depends on the number and cost of each machine but would probably be less than its effect on productivity.

Summary

Machine and system productivity of two feller-bunchers, each operating with two identical grapple skidders and a whole tree chipper, were compared for several diameter and basal area conditions, machine availabilities, shear capacities, and decision rules.

Equal and unequal feller-buncher shear capacities were compared as well as equal and unequal feller-buncher availabilities. When both shear capacity and availability were equal, the rubber-tired machine was more productive than the tracked machine in stands with low basal area or large trees. This result seemed intuitively correct because although the rubber-tired machine was allowed to adjust strip width to compensate for sparsely stocked stands, the tracked machine, as modeled here, could not. Under these conditions, the tracked machine spent too much time traveling and not felling. When stocking was higher, the tracked machine could harvest many trees at one stopping point and was thereby able to surpass the rubber-tired machine.

When shear capacity was equal but the rubber-tired machine had greater availability (as it often does due to, among other things, a softer, easier ride), the rubber-tired machine was more productive than the tracked machine at all basal areas and diameters.

When the tracked machine had a larger shear capacity and was equally available, it was more productive than the rubber-tired machine for all stands averaging 6 and 8 inches in diameter. The rubber-tired machine was more productive for all stands averaging 10 inches. When the tracked machine had a larger shear but was less available, it was more productive for all 6 inch and 8 inch stands with basal areas equal to or greater than 120 sq. ft. per acre. The rubber-tired machine was more productive for all other diameter and basal area combinations. This last comparison is probably more pertinent to equipment presently on the market.

System productivity, however, is another matter. It must be emphasized that for the range of stands and assumptions examined here, neither feller-buncher significantly affected system output per hour. Only stand diameter affected system productivity. Diameter had the only effect on productivity because first, chipper output is almost exclusively a function of diameter. Thus, large trees mean high output. Second, although skidders were not permitted to interact with feller-bunchers in the woods, both feller-bunchers and skidders attempted to build capacity bunches to ensure that the chipper didn't wait for wood. Again, the main point is that final choice of a system based on one or the other feller-buncher, as modeled in this report, depends primarily on relative machine costs.

This report also suggests how rubber-tired fixed shear feller-buncher operators may increase system productivity and lower cost by choosing optimum harvest strip widths as well as optimum bunch distance limits. These two opportunities applied only to the rubber-tired machine in this study because we assumed that only this machine could vary strip width or could travel back if necessary to drop bouquets on imcomplete bunches. Tracked feller-bunchers with rotating booms are not usually operated this way and were not permitted to do so here.

If optimum strip widths are adopted, rubber-tired feller-buncher productivity can be increased up to 4 percent. While these are only modest gains, adopting an optimum bunch distance limit can have a dramatic effect on productivity. For machines with the large shear, traveling back to create a capacity bunch increased system productivity as much as 13 percent. For

machines with the small shear, the corresponding improvement in system productivity was 17 percent. These optimizing rules for the rubber-tired machine were followed for all system comparisons.

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PRODUCT QUALITY AND CONSUMER ACCEPTANCE OF WOOD PRODUCTS FROM INSECT-DAMAGED BALSAM FIR

Steven A. Sinclair

Assistant Professor, Forest Products Marketing,
Department of Forest Products,
Virginia Polytechnic Institute and
State University,
Blacksburg, VA 24061

Studies concerning the product quality and acceptance of balsam fir lumber in the marketplace are summarized. Balsam fir is apparently well suited for the production of stud-size dimension lumber. Misconceptions concerning the physical appearance of balsam fir lumber need to be overcome. In addition, according to retail lumber dealers growth in the market for balsam fir as a single species is hindered by a lack of reliable suppliers producing consistently high quality lumber.

Introduction

Product quality, as it relates to solid wood products in the absence of structural considerations, is most often simply in the eye of the beholder. We are all familiar with many characteristics of wood which in certain circumstances would be considered defects, however, in other situations they are considered attributes. As examples of this, we find the following products in our marketplace selling many times at premium prices; pecky cypress, wormy chestnut, knotty pine, and birdseye maple to name only a few.

Unfortunately, I have not (as of this writing) discovered wormy balsam fir selling at a premium in the marketplace. However, there are several entrepreneurs producing paneling and other decorative products from insect-damaged softwood timber. The blue stained southern and western pines, results of bark beetle attacks, have found a small niche in the marketplace and are sometimes marketed with such names as blue pine or homestead pine. These are typically processed into narrow tongue-and-groove strips for interior paneling. There is no reason to presume that budworm-damaged balsam fir could not be manufactured into similar decorative products.

While such decorative products can provide high value outlets for insect-damaged timber, the volumes of decorative products that our markets are able to absorb is small in relation to the volumes of insect-damaged timber. For balsam fir, its primary market as a solid wood product is dimension lumber. It is most commonly graded and marketed as part of a species group but can also be graded and marketed as an individual species. An example of this is provided by the National Lumber Grades Authority's standard grading rules for Canadian lumber (NLGA 1978). Under these rules balsam fir may be marketed under the following four commercial names or species groups, each with a different identification stamp:

Commercial name	Identification stamp
Balsam fir	B Fir (N)
Alpine fir	Alpine Fir (N)
Spruce-pine-fir	S-P-F
Northern species	North Species

According to NLGA rules, lumber marketed as balsam fir under the identification stamp of B Fir (N) would clearly be balsam fir lumber. However, shipments of lumber marketed under the other commercial names and identification stamps also can contain balsam fir, in part or in total, though it is not required that balsam fir make up any part of a shipment under any of these three stamps. Similar parallels can be drawn from the grading rules of the Northern Hardwood and Pine Manufacturers Association (NHPMA 1979) and the Northeastern Lumber Manufacturers Association (NELMA 1980).

Standard grading rules of the NHPMA allow balsam fir dimension lumber to be graded and sold in three categories: balsam fir, eastern softwoods, and eastern woods. The NELMA grading rules allow balsam fir dimension lumber to be graded and sold in four categories: balsam fir, eastern spruce and balsam fir, eastern softwoods, and eastern woods.

Product Quality of Balsam Fir Dimension Lumber

To compare grade yields of living balsam fir to yields from budworm-killed trees, studies were conducted with 100-inch bolts at a commercial sawmill in northern Minnesota (Govett et al. 1983). These bolts were harvested from eight test plots where more than 400 severely weakened balsam fir trees had been individually tagged for observation in the spring and early summer of 1979. As was expected, the majority of these test trees died during the following 2-year period. Each year, monthly observations of each test tree were conducted from early spring through late fall to determine the time of tree death. Observable characteristics followed the pattern reported by Belyea (1952); cambial discoloration represented the point of death. The observation procedure is described by Govett (1982).

In the first grade yield study, conducted in the early fall of 1980, bolts were sawn from 18 healthy trees and from 32 trees that died during the previous fall. The second study, conducted in the summer of 1981, examined the potential product quality of lumber sawn from the following four categories:

1. Trees stressed by considerable budworm defoliation but not yet dead (21 trees).

2. Trees standing dead approximately 6 months or less, having died over the preceding winter or in spring or early summer (24 trees).

3. Trees standing dead about 1 year, having died in summer or early fall of the previous year (33 trees).

4. Trees standing dead about 18 months, having died over the winter of 1979-80 (21 trees).

All 100-inch bolts in each study were sawn at the same commercial mill; a circular headrig (1/4-inch kerf) and a single-arbor bull edger were used. The sawyers were instructed to maximize production of 2- by 4-inch and 2- by 6-inch dimension lumber with a minimum of 1-inch boards sawn. Sawyers were instructed not to heavily slab bolts to remove decay since enhancement of grade yields by such a practice would be at the expense of volume yields.

All lumber sawn for each grade yield study was graded as 8-foot lengths after air drying and surfacing by the Chief Inspector of the Northern Hardwood and Pine Manufacturers Association. All 2- by 4-inch lumber was graded under Light Framing, Structural Light Framing, and Stud grading rules; all 2- by 6-inch lumber was graded as Structural Joists and Planks. A record was kept of the primary defect preventing each piece of lumber from receiving a higher grade to ensure that increasing grade downfall after death was attributable primarily to factors associated with budworm-caused mortality rather than by other factors or by chance.

The aggregate grade yields of lumber sawn in each tree category in both studies are shown in Table 1. The larger percentages of lower grade lumber associated with increasing time after death are almost wholly a result of the progression of deterioration in the dead standing tree. Less than 5 percent of the lumber produced from dead trees was degraded because of insect holes. More than half of all dimension lumber sawn from trees dead 1 year or longer graded lower than No. 2 or Standard due to the onset and progression of decay in the dead standing tree.

Table 1. Lumber grade yield of 2- by 6-inch, 2- by 4-inch, and 1-inch balsam fir, by tree class and grade[a] (Govett et al. 1983).

Size and grade	1980 lumber yield		1981 lumber yield				Percent of total lumber produced in size
	Healthy	Dead 1 year	Stressed or dying	Dead 1/2 year or less	Dead 1 year	Dead 1-1/2 years	
	Percent						
2- by 6-inch (38- by 140-mm) dimension lumber							
Select structural	16.4	1.4	23.5	6.3	7.7	0.0	
No. 1	0.0	0.0	5.9	5.1	0.0	0.0	
No. 2	29.1	4.3	17.7	15.2	19.2	0.0	37.3
No. 3	41.8	44.3	23.5	40.5	34.6	42.6	
Economy	12.7	50.0	29.4	32.9	38.5	57.4	
2- by 4-inch (38- by 89-mm) dimension lumber							
Construction	42.8	2.5	44.4	16.2	5.0	2.9	
Standard	27.3	10.0	15.2	6.8	10.6	2.9	
Utility	20.8	63.3	22.2	59.0	52.5	66.6	57.9
Economy	9.1	24.2	18.2	18.0	31.9	27.6	
1-inch (19-mm) boards							
Nos. 1 & 2 Common	57.1	0.0	14.3	9.1	5.2	0.0	
No. 3 Common	28.6	0.0	71.4	0.0	10.5	0.0	4.8
Nos. 4 & 5 Common	14.3	100.0	14.3	90.9	84.3	100.0	

[a]Lumber grades are S-dry for 8-foot lengths. Grade downfall in 2- by 6-inch lumber from the healthy tree category is primarily due to excess wane allowed in sawing and heart rot.

Table 2 places all dimension lumber into three grade categories: Standard & Btr or or No. 2 & Btr, Utility & Btr or No. 3 & Btr or Stud, and Economy. It points out the relatively high yields of Utility or No. 3 & Btr or Stud, compared with Standard & Btr or No. 2 & Btr. If dead standing balsam fir is to be used in the production of dimension lumber, it is probably better suited to producing Utility or No. 3 & Btr or Stud.

In sawing dead balsam fir, some volume losses might be expected due to breakage in the mill; this problem, however, did not have a significant effect on the volume yields in this study.

Govett et al. (1983) concluded that balsam fir bolts apparently are well suited to the production of common stud sizes of dimension lumber. Lumber sawn from bolts of both healthy and stressed trees exhibited both straightness and a good general appearance. The relatively rapid onset of decay in dead standing balsam fir in Minnesota caused a significant downfall in lumber grade soon after tree death, from Standard & Btr or No. 2 & Btr to Utility or No. 3. Progression of decay with increasing time after death caused greater downfall of lumber to the Economy grades.

A mill's decision to saw dead balsam fir may hinge primarily on the type of market in which the lumber will be sold. Mills predominately selling Stud, No. 3, or Utility & Btr. grades should experience less adverse effects when sawing recently killed trees than mills producing lumber for sale in grades of Standard & Btr. or No. 2 & Btr. The latter mills may experience significant grade yield falldown by sawing trees standing dead for even a few months in areas where decay rates for standing dead timber are similar to those in northern Minnesota.

Consumer Acceptance of Balsam Fir Dimension Lumber

Carpenter and Quinney (1965) describe the consumer acceptance and sometimes preference for balsam fir lumber in northern Minnesota, where more than 75 percent of the retail lumberyards sampled carried balsam fir lumber. However, only 8 percent of the retail lumberyards in the Twin Cities area handled balsam fir lumber. The reasons for these differences were thought to be low production outputs, relatively high prices, and the lack of reliable suppliers. In the northern area, most of the yards obtained their stock of balsam fir lumber directly from nearby mills or from captive mills. In yards in both areas that carried balsam fir, the species apparently was widely accepted and in many instances preferred.

Carpenter and Quinney (1965) identified four primary requirements for the increased use of balsam fir lumber. The two most important factors are that the material should be kiln dried and that the price should be slightly below that of competing western species. Appearance was stressed as many sellers noted that balsam fir's light color, straight grain, and small knots enhance its salability. The fourth factor was reliability of supply. Once customers have accepted the species, the yards must be assured a dependable supply of lumber manufactured in a consistent manner.

Table 2. Dimension lumber grade yields for 2- by 4-inch (38- by 89-mm) and 2- by 6-inch (38- by 140-mm) material combined by tree category (Govett et al. 1983)

Tree category	Standard & Btr or No. 2 & Btr	Utility & Btr or No. 3 & Btr or Stud	Economy
		Percent	
		1980 Study	
Healthy	57.8	89.3	10.7
Dead 1 year	9.1	63.5	36.5
		1981 Study	
Stressed or dying	56.2	79.5	20.5
Dead 1/2 year or less	24.4	73.7	26.3
Dead 1 year	17.8	68.3	31.7
Dead 1-1/2 years	3.5	59.3	40.7

Ostaff and Petro (1977) echoed the need to kiln dry balsam fir, particularly lumber cut from budworm-killed balsam fir. They cite instances of shipments that were rejected because the lumber contained live larvae of the sawyer beetle. This was particularly damaging in large export sales but also damaging in domestic markets. Consumers tend to respond negatively to the sight of live insects emerging from the wood in their homes. Kiln drying usually is sufficient to kill insect larvae and prevent such problems.

A more recent survey concerning the marketing of balsam fir dimension lumber was conducted by Govett and Sinclair (1984). Their findings are based on responses from 77 retail lumberyards located in the north-central and northeastern United States. The following shows the average market share for balsam fir sold as a single species; however, a portion of the market share for spruce-pine-fir no doubt includes some balsam fir.

Species or group	Average percentage of total softwood lumber sales
Spruce-pine-fir	36.8
Douglas-fir and hem-fir	30.4
Eastern spruce	7.7
Other west coast species	7.5
Southern pine	7.5
Northern pine	6.5
Other softwoods	1.9
Balsam fir	1.7
Total	100.0%

Table 3. Attitudes of retail lumber dealers concerning statements related to lumber or lumber customers, by percentage of respondents agreeing or disagreeing with each statement (Govett and Sinclair 1984).

Statement	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
			Percent		
The quality of softwood dimension lumber produced on the west coast is highly superior to lumber produced from northern mills.	2.6	15.8	18.4	42.1	21.1
The quality of southern pine dimension lumber is highly superior to lumber produced from northern mills.	11.0	42.5	27.4	12.3	6.8
It is very difficult to obtain a steady supply of dimension lumber produced by local northern mills.	3.9	13.2	32.9	38.2	11.8
Most customers have a very strong preference for dimension lumber produced on the west coast or southern United States.	6.6	32.9	12.8	36.8	7.9
The quality of dimension lumber produced by local northern mills is very inconsistent.	1.4	12.2	32.4	40.5	13.5
Most customers have a very strong preference for lumber that is kiln dried rather than air dried.	1.3	11.8	7.9	43.5	35.5
Do-it-yourself or walk-in customers purchase 2- by 4-inch studs almost totally on the basis of general appearance, straightness, and low price.	0.0	0.0	1.3	40.8	57.9
Very often 2- by 4-inch balsam fir studs have large or loose knots and tend to warp and twist to a large degree.	4.3	15.7	58.6	15.7	5.7

Problems identified by Carpenter and Quinney (1965) were still prevalent in the results of the Govett and Sinclair (1984) study. For example, the following summary shows that only 45 percent of the respondents reported that balsam fir was currently available from one or more suppliers of dimension lumber:

Species or group	Average number of suppliers	Percentage of yards reporting species or group available from one or more suppliers
Spruce-pine-fir	4.4	92
Eastern spruce	3.3	70
Balsam fir	1.7	45
Northern pine	1.5	62

Table 3 shows that 50 percent of responding retail lumber dealers either agreed or strongly agreed that it is difficult to obtain a steady supply of dimension lumber from local sawmills. However, lack of availability may not be true for all areas. Nearly all of the respondents agreed that walk-in customers purchase 2- by 4-inch studs almost totally on the basis of general appearance, straightness, and low price. Unfortunately, approximately 20 percent of the respondents believe that balsam fir studs often have large, loose knots and tend to warp and twist. This last perception is largely incorrect and evidently due to a lack of familiarity with the species.

Table 4 ranks dimension lumber of five species or species groups according to perceptions of retail lumber dealers (Govett and Sinclair 1984). Douglas-fir had the highest average rank and southern pine the lowest. Table 5 ranks the importance of characteristics of 2- by 4-inch studs to large-order customers (Govett and Sinclair 1984). Being straight and kiln dried are considered the most important characteristics.

Summary

Lumber grade yield studies have shown healthy balsam fir can produce relatively good yields of high quality stud-size lumber. Grade yields of budworm-killed timber drop rapidly after tree death with more than half of the dimension lumber volume being lower than No. 2 or Standard only one year after tree death.

Balsam fir lumber is readily accepted, even preferred, in areas where the species is familiar to retail lumber dealers. Problems with reliability of supply and inconsistent quality hinder wider market acceptance. In addition, some retail lumber dealers have misconceptions concerning the appearance of balsam fir studs.

Table 4. Perceptions of retail lumber dealers on the quality of studs produced from various species or groups, by percentage of respondents for each ranking from best quality (1) to worst quality (5) (Govett and Sinclair 1984).

Species or group	Ranking used by respondents[a]					Average rank
	1	2	3	4	5	
Douglas-fir	68.4	14.0	10.6	3.5	3.5	1.6
Eastern spruce	19.6	33.9	16.1	14.3	16.1	2.7
Balsam fir	9.2	22.2	24.1	24.1	20.4	3.2
Northern pine	7.3	20.0	32.7	23.6	16.4	3.2
Southern pine	0	14.8	14.8	27.8	42.6	3.9

[a]Columns and rows do not total 100 because several respondents assigned less than five ranks.

Table 5. Importance of various characteristics of studs to large-order customers of retail lumber dealers, by percentage of respondents who ranked characteristics from unimportant (1) to very important (5) (Govett and Sinclair 1984).

Characteristics	Ranking used by respondents					Average rank
	1	2	3	4	5	
Straightness	1.4	1.4	13.9	25.0	58.3	4.4
Kiln dried versus air dried	4.2	18.3	21.9	16.2	39.4	3.7
Low price	1.4	7.1	50.0	18.6	22.9	3.5
General appearance	2.7	4.2	45.8	30.6	16.7	3.5
Absence of wane	4.3	10.0	40.0	27.1	18.6	3.4
Absence of stain and decay	4.2	19.7	33.9	22.5	19.7	3.3
Absence of insect holes	7.0	22.5	25.4	28.2	16.9	3.2
Strength	9.7	26.4	37.5	18.1	8.3	2.9
Stud of a western species	20.0	32.9	17.1	17.1	12.9	2.7

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DYNAMICS OF SPRUCE BUDWORM EPIDEMICS

Dr. Yvan Hardy, Dean

Faculte Forestiere & Geodesie
Laval, U.
Quebec, PQ G1K 7P4

Introduction

Spruce budworm outbreaks have been known to occur in eastern North America for at least 300 years. Blais, who has reviewed this period (1983), has concluded that outbreaks are becoming longer, more frequent, more severe, and envelop substantially larger acreages.

In fact, the first 200 years of known budworm history are characterized by regional outbreaks that did not spread to adjacent forests and were essentially local in character. Some of these outbreaks were quite severe and caused tree mortality, but consecutive outbreaks in a given region were usually separated by at least 60 years.

Toward the end of the 18th century, a first break was observed in this pattern with the occurence of an outbreak which started around 1760 and covered most of southern Quebec, Maine and New Brunswick (Blais, 1968). For the most part, the 19th century was characterized by local outbreaks, but epidemic activity was observed in the southern part of the range (southern Quebec, Maine and New Brunswick).

The major break in the pattern occured with the 20th century. The first 60 to 70 years produced three major outbreaks each one more severe and more widespread than the last. The 1910-23 epidemic which occupied some 10 millions hectares of forest in eastern Canada was the first to gain access to the Gaspe peninsula and the Ottawa River watershed.

With 25 millions hectares, the 1940-58 outbreak more than doubled the size of the previous epidemic while new regions such as Quebec North Shore suffered tree mortality for the first time. Following its general collapse, sizeable residual outbreaks kept going particularly in central New Brunswick and north eastern Maine --- a phenomenon observed for the first time.

Between 1964 and 1967 a new outbreak started which proved to be the most widespread ever recorded with some 55 millions hectares in eastern Canada only. This outbreak which is still underway occupied at one time or another most of the range of balsam fir and marked the shortest interval between two consecutive outbreaks ever recorded. Sizeable tree mortality occurred for the first time in many regions previously considered less vulnerable, New Foundland, Cape Breton Island, Anticosti Island among them.

Causes of Outbreaks

Review of Past Concepts

For a long time, spruce budworm outbreaks were associated with the dynamics of the classic spruce-fir forest. This school of thought prevailed for a long time and strongly influenced budworm management programs in the 1960's. Blais (1952) pointed out the role of staminate flowers of fir on the growth and development of budworm larvae and in 1960 the same author proposed that spruce budworm outbreaks were to be considered as one element leading to the climax of natural fir associations. Mott (1963) summarized these thoughts when he stated that large tracts of mature spruce-fir forest where balsam fir is the dominant species were the best conditions leading to the initiation of an outbreak. Although particular forest conditions were a must, the key factor that really triggered an outbreak was climate. Among others, (Wellington (1952), and Greenbank (1963), helped establish the concept that outbreaks were preceded by 3 to 5 consecutive pre-summer droughts and above normal temperatures.

In short, spruce budworm outbreaks were clearly associated with the dynamics of boreal spruce-fir ecosystems. Given the right climatic conditions an outbreak would develop in mature and overmature stands thus killing the trees and hastening the reurn of a climax forest association.

The first challenge to this concept came with the current outbreak in Quebec when it was observed that it did not originate in the spruce-fir forest. Hardy et al (1983) analyzed the vegetation from seven locations in Quebec where the outbreak gained its initial momentum between 1967 and 1972. Their findings showed the same regular pattern everywhere. Although fir and spruce were the most abundant single species, they were far out numbered by the other species present, some of which, e.g. sugar maple, yellow birch, and white pine etc., occurred almost everywhere (Table 1). On the other hand, the spruce-fir components of the stands usually belonged to the 30 - 50 age classes, rarely showing signs of over-maturity.

The vegetation analyses were extended to include other parts of the spruce budworm range including Manitoba, Ontario, New Brunswick and Maine. The same findings were reported, and the young age of the host-trees was again observed while the forests associated with the epicenters were either northern hardwood or a transition type, fir-yellow birch.

Table 1. **Relative Abundance of the Principal Tree Species Found in the Epicenters.**

X: abundant species .: presence 1: Host species
2: Meridional species 3: Other species *: Pioneer species

Tree Species	Manitoba	Ontario										Quebec					Nouveau-Brunswick					Maine
	Spruce Wood	Burchell Lake	Chapleau	Cobden I	Cobden II	Cobden III	Cobden IV	Arnprior	Low	Lac Dumont	Lac Duval	La Malbaie	Pohenegamook	Perce	Port-Daniel	Quebec Sud	St-Jacques	Lac Madawaska	Chatham	Nashwaak	Lac Lambert	Oxbow	Fish River Lake
1 Abies balsamea		x	x	x	x	x	.	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
1 Picea glauca	x	.	x		x	x	.	x	.	x	.	x	x	x	.	x	.		.	.		.	
1 Picea mariana		x	x	x			.			.	.			.	.				.				
1 Picea rubens		.	.					.			.		x	.	x	x	.	x	x	x	x	x	x
2*Acer rubrum				.	x	x	x	.	x	.	x	.	x	x	x	x	.	.	.	x	.	x	.
2*Acer pensylvanicum												.	.		.	.	.					.	.
2 Acer saccharum				.	x	x	.	x	x	x	x		.	x	x	.	x	.		.		.	.
2 Betula alleghaniensis				.			.	.	x	.			.	x	x	x	x	.		x	.	.	.
2 Fagus grandifolia					.	.			.		.						.			.	.		x
2 Fraxinus americana					x	.	x	x	.														
2 Ostrya virginiana					x	x	x	.	x	.	.												
2 Pinus strobus		.	.	.	x	x		x	.	.	x								.		.		
2*Quercus macrocarpa	x																						
2*Quercus rubra	.				x	.	x		.	.	x												
2 Tilia americana						.	x	x	.	.													
2 Tsuga canadensis				.	.	.		.	x							.		.		.	.	.	.
2 Ulmus rubra				.	.	.	x	x															
3*Acer spicatum		.	.		.	.		.	.			.			.	x	.						
3*Betula papyrifera	.	x	x	.	x	x	x	x	x	x	x	x	x	x	x	x	.		.	.		x	.
3*Populus tremuloides	x	x	x	.	x	.	x	x	x	x		.	x	.		.			.	.		.	
3*Populus sp.		.		.	x	x	.	x	.	.	.	.								.		.	
3*Prunus sp.	.					.	.		.						.		.						
3Thuja occidentalis		x	.	x	.	.	x	x	.	.		.	x				.	x	.		x	.	.

The New Budworm

Tothill (1922) and Bailey (1924) were the first to hint at the changing status of the budworm. Tothill noted that in less than a century the budworm changed from an innocuous insect to a major pest, while Bailey believed that these changes had been brought about by the removal of white pine from parts of Maine, New Brunswick and Quebec and its replacement by balsam fir.

Like any other living organism, the spruce budworm must satisfy some specific physical and biological requirements in order to survive. When both physical and biological (food) requirments are met in the same geographical area, insect outbreak conditions can occur since its needs are entirely fulfilled (Eidman, 1949 in Dajoz, 1980). Unless a third factor becomes involved (pathogens, predators, etc.) outbreaks could become chronic in an area where food and physical requirements are met.

Taking these considerations into account and the bioclimatic zonation concept formulated by Cook (1929), Bergevin (1984) attempted to determine where the budworm physical requirements are best met.

The mean summer and annual temperatures were analyzed using meterological normals of 30 years for every epicenter recorded from Maine and New Brunswick to Manitoba. The results, incorporated in the summer and annual isotherms, defined a corridor which transected Maine, eastern Canada and the adjacent states in a east-west pattern. When superimposed over a forest association map, (Figure 1) this corridor included all epicenters; and the northern component of the maple association or a common northern variation, yellow birch-fir, not the climax spruce-fir boreal forest, dominates the corridor. This non host type which dominates the corridor corresponds to the zone of normal abundance for budworm according to Cook and should, by definition, counteract outbreak activity because of its biological resilience (absence of food, plus predation). However, changes in forest composition were observed everywhere, spruce and fir being the single most abundant species in most areas.

Invasion of the corridor by spruce and fir is a recent phenomenon related to man's influence on the forest ecosystem. Blais (1983) suggested that fire protection, clear-cut logging, use of pesticides against budworm favoring spruce-fir stands as well as abandonment of marginal farm lands have all contributed to favor an abundant regeneration of spruce and fir. The budworm was formerly forced to wait for specific climatic conditions to take advantage of the plentiful food source located outside the corridor, causing sporadic and local outbreaks. Now both can be secured most of the time from within the corridor thus explaining the changing character of the outbreaks.

The dramatic changes that took place in the eastern forest are best illustrated by a number of recent articles dealing with forest composition or forest vulnerability of the spruce budworm. Gaudet (1979) pointed to the abundance of white spruce on Prince Edward Island, a species that displaced the normal components of the Acadian forest region (Rowe, 1972). Reporting on Canada's forest inventory, Bonner (1982) produced a type map which showed that most of the northern hardwood regions had now become a mixedwood type (Figure 2). More significantly, the Blais and Archambault (1982) budworm vulnerability rating for Quebec's forests to the spruce budworm showed the St. Lawrence valley forests as the most vulnerable -- these forests are normally northern hardwood associations. Likewise Mac Lean's (1982) vulnerability ratings for the forests of New Brunswick and Nova Scotia exhibit a similar pattern, with high ratings associated with northern hardwood transition types.

Conclusion

The spruce budworm has adapted very well to its changing environment. From an almost innocuous insect, the budworm became, in less than a century, the most injurious forest pest of the northeast. Since this change can be related to changes in forest composition, the wisdom of our current forest management policies can be questioned. The current harvesting and reforestation practices increase the spruce and fir content of the meridional forest and this trend should be altered. The budworm's dynamic reaction to the transition types thus created not only affects the meridional forest where the problem originated, but impacts the boreal forest as well since the corridor can always be counted on as a reliable source of infestation for the adjacent climax spruce-fir forests. Future trends will depend on forest management policies in our respective countries. Although it may be a legitimate objective, from the economic viewpoint, to produce more spruce and fir, it would be ecologically and maybe economically more rewarding to avoid destabilizing the natural equilibrium of the major forest associations capable of supporting budworm.

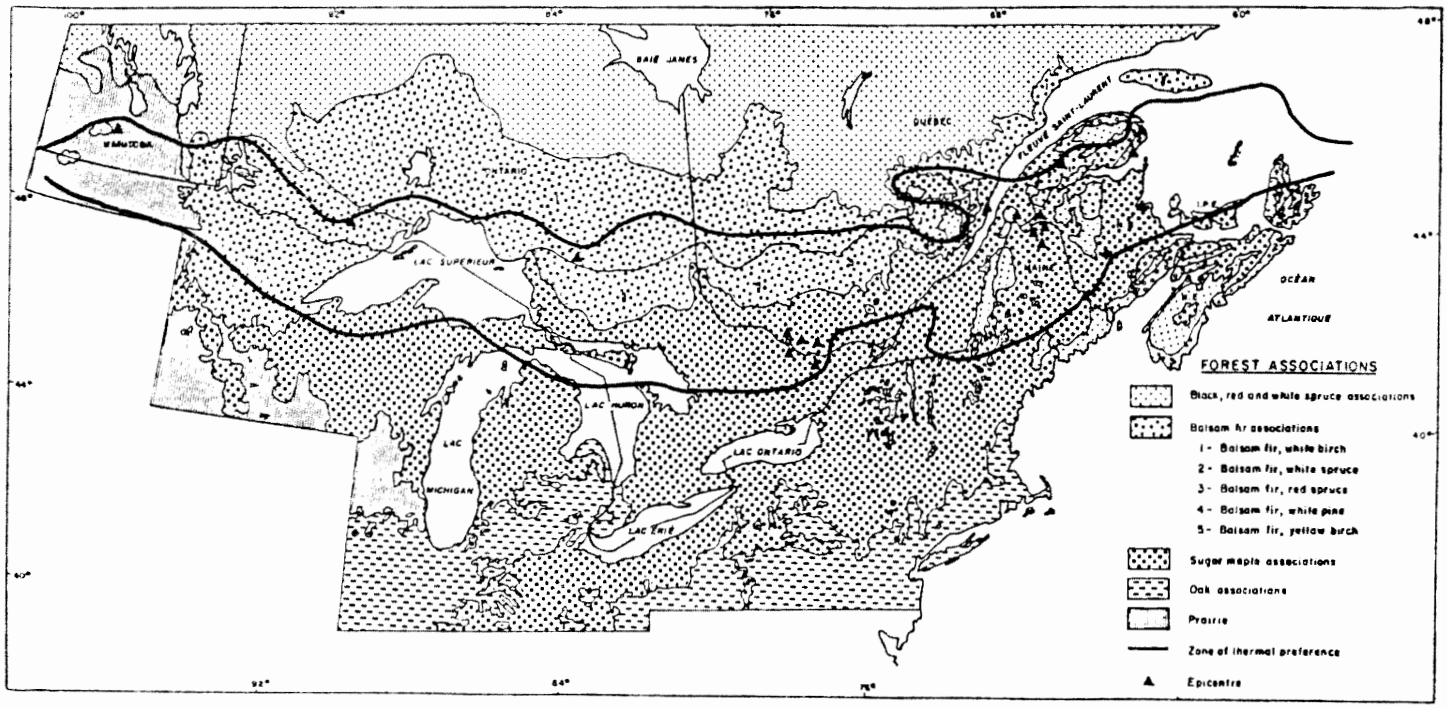

FIGURE 1
Zone of thermal preference of the spruce budworm in eastern North America in relation to the major forest associations

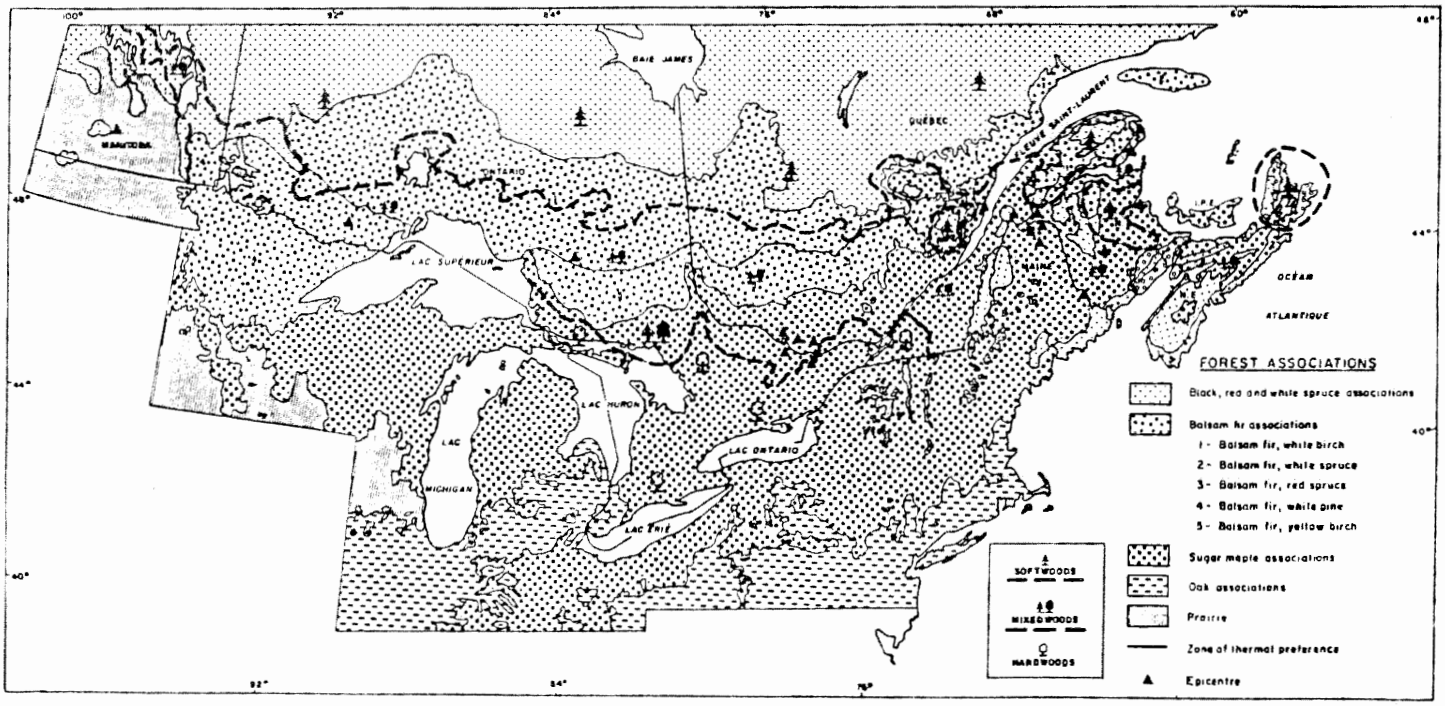

FIGURE 2

Evolution of the cover types of eastern Canada (Bonner, 1982) in relation to the major forest associations

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ELECTRICAL METHODS FOR EVALUATING GROWTH AND DECAY POTENTIALS OF FIR/SPRUCE SITES [1,2]

Walter C. Shortle

Research Plant Pathologist, USDA Forest Service, Northeastern Forest Experiment Station, P.O. Box 640, Durham, NH 03824

Abstract.--Measurements of cambial electrical resistance provide a rapid, simple and quantitative means to estimate growth potentials that can help assign risks to sites producing fir and spruce wood. Measurements of internal electrical resistance help refine estimates of risk by giving an indication of decay potential that affects wood quality.

Electrical Method Developed To Detect Wood Decay

The design of a pulsed electric-current meter to measure the resistivity of tree tissues was proposed in 1972 (Skutt, Shigo, and Lessard 1972). The concept was based on two principles: (1) water and inorganic ions accumulate in wood becoming decayed in living trees (Good, Murray, and Dale 1955, Ellis 1959, Shigo and Sharon 1970, Shortle and Shigo 1973), and (2) resistivity of a solution decreases with increasing ion content (Siggia 1968). If temperature is constant, asymptotic or normalized, then the water and ion content of tissues should determine the degree of resistance to a pulsed electric current. The relationship of resistivity to progressive stages of decay in trees was shown to be related primarily to increasing water and potassium ion in the discolored and decaying wood (Tattar, Shigo, and Chase 1972). It has been shown recently that in whiterot systems, which are most common in living trees, early ionization is due to potassium ions; but in brownrot systems, which are more common in butt rots of conifers and in utility poles, early ionization is due to hydrogen ions (Shortle 1982). However, whether in trees or wood products, whether whiterot or brownrot, accumulation of water and ions in tissues is the first in a series of progressive steps leading to wood decay. This ionization step can be detected by a pulsed electric-current meter equipped with proper electrodes.

1/ Paper presented at SAF Region VI Technical Meeting: Forest Management and the Spruce Budworm. Burlington, Vermont, April 24-26, 1984.

2/ Portions of the research discussed here were supported by CANUSA.

Electrical Method Applied to Cambial Zone

Potassium ions accumulate in plant meristems (Meyer, Anderson, and Böhning 1960). Therefore, it seemed possible that the same electrical method used to detect decaying wood also might be useful to observe variations in cambial activity, which in turn affects the periodic growth rate and thickness of phloem. A different electrode from that used in wood was attached to the meter, and the relationship of cambial electrical resistance, CER, to tree growth and vitality was first applied to oak (Wargo and Skutt 1975). Dominant trees had a lower CER than intermediate and suppressed trees. Trees with healthy crowns had a lower CER than those with severely defoliated crowns.

Similar methods for determining CER were applied to hybrid poplar and red maple (Shortle et al. 1977). Faster growing maples and poplars had lower CER values than slower growing maples and poplars regardless of size. This difference in CER values could be used for selecting crop trees during thinning operations in a sugar bush to increase growth rate of stems in the residual stand of sugar maple (Shortle et al. 1979).

CER values were related to phloem thickness as well as to periodic growth rates, which is as expected if vascular cambial activity was determining the degree of ionization to which the meter was responding (Carter and Blanchard 1978, Cole and Jensen 1980). Seasonal variations, not dependent on temperature, in maple, pine, and oak, were also consistent with CER varying in response to cambial activity (Davis, Shigo, and Weyrick 1979). The importance of variation in cambial thickness with season was not fully appreciated for several years, but was important in working out the controlling mechanisms for CER values (Blanchard, Shortle, and Davis 1983). Seasonal variations of CER, independent of temperature effects, limit the time for collecting data for site comparisons to the growing season during which the cambial zone is fully expanded. For our studies, mid-June to mid-August was the most useful period for measuring CER in Maine, New Hampshire, and Vermont.

The Method First Applied to Fir and Spruce

During the summer of 1978, several thousand trees were measured in cooperation with International Paper Company (Region VI) on continuous forest inventory plots. These plots (580 m^2) were inventoried from mid-June to mid-August. After standard tree measurements had been made, the CER of each tree (> 12 cm dbh) was determined using a standard procedure (for details see Davis, Shortle, and Shigo 1980). Two measurements per tree on opposite faces took about 10 sec/tree or about 8 to 10 min/plot, depending on tree spacing, number of stems, and ease of walking between trees.

At the end of the summer, the results for all plots were combined for the seven major tree species observed (balsam fir, red spruce, yellow and paper birch, sugar and red maple, and beech) --150 to 500 observations per species. A mean CER was calculated for each species, and periodic growth rates over the 5-year-inventory period were compared in a two-class system (Table 1). Trees with CER values lower than the species mean were growing faster than those with CER values higher than the species mean. This was consistent with earlier studies done primarily in maple.

TABLE I. Periodic growth rate for low and high electrical resistance classes for seven tree species.

Species	Growth rate (mm/yr) resistance class [a/]	
	Low ER	High ER
	OVER ALL STEM DIAMETERS	
Balsam fir	2.6*	2.0
Red spruce	2.6*	1.4
Yellow birch	3.4*	2.2
Sugar maple	4.6*	2.6
Red maple	3.4*	1.8
Paper birch	2.4*	1.6
Beech	3.6*	2.2
	WITHIN STEM DIAMETER CLASS	
Balsam fir	3.0*	2.2
Red spruce	2.6*	2.0
Yellow birch	3.4*	2.4
Sugar maple	4.4*	2.6
Red maple	3.6*	2.0
Paper birch	2,4*	2.0
Beech	3.4*	2.4

* Statistically significant $p=<0.05$.

[a/] Low resistance class is one in which all trees have an electrical resistance less than the population mean resistance for that species, or less than the mean resistance for each 2.54-cm diameter class containing a minimum of 10 trees; high resistance class is one in which all trees have an electrical resistance greater then the population mean, or greater than the diameter class mean.

First Efforts Toward a Hazard Rating System

In 1979 under the sponsorship of the CANUSA Spruce Budworms Program, research was begun to develop a simple site-classification scheme using CER values to identify sites on which tree growth was poor (low growth potential). The stands on these sites were postulated to have a greater risk of mortality under outbreak conditions than stands on sites in which trees were growing substantially better (high growth potential). In addition to the high-risk sites, which have a low growth potential, and the low-risk sites, which have a high growth potential, there will be transitional sites, which are either declining or recovering. Monitoring CER over time would indicate the direction of change in growth potential.

During the summer of 1979, 10,000 trees were measured in 90 stands on 90 sites producing fir and spruce wood in Maine, New Hampshire, and Vermont. The predominant canopy was balsam fir (Abies balsamea) and red spruce (Picea rubens). Sampling was done along a transect with a 10-factor prism until at least 100 trees (8 to 10 points) were measured. Both outbreak and non-outbreak areas were included in the study with spruce budworm infestations ranging from none to severe. The mean electrical resistance for each stand/site was calculated for balsam fir or red spruce so the range and distribution of CER values for each species could be determined.

Mean CER values for balsam fir ranged from 9 to 18 kΩ on sites with moderate to heavy infestations; whereas red spruce values remained essentially constant at 7 to 13 kΩ. At the end of the growing season, 8 of the 90 stands were sampled for periodic growth rate to see how growth varied over the observed range of site values. In each stand, 10 canopy fir trees were selected at random and felled, and 5-cm-thick disks were taken at 20 cm and 140 cm above ground and at the base of the live crown. Air-dried disks were sanded and periodic growth was measured along the longest and shortest radii. Published results (Davis, Shortle, and Shigo 1980) are summarized in Table 2 along with results from studies in 1980 (Blanchard, Shortle, and Davis 1983).

Balsam fir growing on sites in which the CER of canopy trees averaged < 10 kΩ was adding an average of twice the increment of canopy trees on sites in which CER averaged > 12 kΩ (Table 2). Most sites in outbreak areas were of the latter category. If we assume that balsam fir growth before the outbreak was distributed similarly to non-outbreak areas, then growth was lost as < 10 kΩ sites progressively became > 12 kΩ sites, while sites already in > 12 kΩ status suffered the greatest mortality.

TABLE II. Periodic growth of trees on sites of high and low growth potential determined by cambial electrical resistance.

Year, species, and infestations	Mean periodic growth, mm/yr [a]	
	Mean CER < 10 kΩ [b]	Mean CER > 12 kΩ
1979, Fir, Non-outbreak	3.2	1.3
1979, Fir, Outbreak		1.5
1980-81, Fir, Non-Outbreak	2.9	1.4
1980-81, Fir, Outbreak		1.4
1982, Fir, Non-Outbreak	2.8	1.4
1982, Spruce, Non-Outbreak	2.4	1.3

[a] For details of 1979-81 data see Davis, Shortle, and Shigo 1980; Blanchard, Shortle, and Davis 1983; 1982 data was collected using 1980 plot sampling methods (3 fir sites < 10, 4 > 12; 4 spruce sites < 10, 2 > 12). Mean periodic growth represents 4 years prior to season of measurement.

[b] Mean CER of all canopy trees measured on each site, high growth potential < 10 kΩ, low growth potential > 12 kΩ.

To test the hypothesis of greater vulnerability for > 12 kΩ canopy trees than for < 10 kΩ canopy trees, acute stress in the form of girdling was applied to a small sample of such trees in the summer of 1982 (Shortle 1983). Balsam fir and red spruce trees were indexed for growth potential at the beginning of the growing season--high, CER < 10 kΩ; low, CER > 12 kΩ--and half of each class was girdled. During the growing season, CER was measured and the condition of the bole and crown was observed every 2 to 4 weeks. Other studies had showed that rising CER preceded foliar symptom during tree mortality (Blanchard and Carter 1980).

CER increased in trees indexed as low growth potential before those indexed as high growth potential (Figure 1); and CER increased in fir before spruce. Bark beetle infestations followed the rise in CER in fir and spruce. Decreased CER followed infestations in fir as cambial tissues became infected. Foliar symptoms in fir and spruce lagged well behind changing CER and bark beetle infestations. Thus, CER indices of growth potential appeared to predict the expected sequence of damage due to stress. Fir of low growth potential (CER, > 12 kΩ) succumbed first followed by fir of high potential (CER, < 10 kΩ), and spruce of low potential, and finally spruce of high potential.

In summary, work to date indicates that measurements of cambial electrical resistance taken on a sufficient number of canopy trees during the growing season on sites producing fir and spruce wood may be a useful index of vulnerability to outbreak during periods of high stress. Empirical limits of < 10 kΩ for high growth potential sites and > 12 kΩ for low growth potential sites seemed to work well for balsam fir, and may be applicable to red spruce and other tree species. Trees of high growth potential at the beginning of the stress period are likely to shift to the low end of the normal range of growth, while those of low growth potential are more likely to die. Sites with trees in the transitional range of 10-12 kΩ may be declining in growth potential during a period of stress, or recovering from a period of stress. Thus, it is important to measure CER of trees over time to determine not only the level of growth potential, but the direction of change (decline, recovery, stable).

A Second Risk Factor--Internal Defect

The use of internal electrical resistance, IER, measurements to estimate the potential of living trees to internal decay is more complicated than the use of CER measurements because the target, columns of discolored and decayed wood, is not in a fixed position like the vascular cambium. Living trees may have no columns of discolored and decayed wood in the butt section where CER measurements are taken, or they may have columns only on one face. The distance of the column of decayed and decaying (often discolored) wood from the vascular cambium is highly variable, but very important to tree survival.

Studies on balsam fir during the 1981 growing season indicated that two general patterns existed in balsam fir (Shortle and Ostrofsky 1983). The IER increased to > 250 kΩ with increasing depth in most trees on some sites (Figure 2), a pattern consistent with sound healthy conifers. However, IER then decreased to < 100 kΩ, indicating early stages of column development in most fir of the 50 to 75 age classes we studied. The IER of red spruce in this age range generally stayed above 250 kΩ.

IER of most balsam fir on other sites remained below 100 kΩ, indicating that columns of decayed and decaying wood were spreading toward the vascular cambium (Figure 2). Wood of fir < 100 kΩ in positions where wood should be > 250 kΩ was interpreted as being in progressive stages of decay.

release of parasites, viruses, and the use of insecticides as control measures. He concluded: "for all kinds of control, control is vastly more effective if applied 10 years or more before peak pest densities," (Watt, 1964). Though Watt's model is in some respects naive, subsequent work also has shown the advantage of early control action.

An active Canadian effort to develop a New Brunswick budworm-forest simulation model began in 1972. Early models are reported in Stander (1973) and Jones (1974, 1976). The last Jones model is the basis of the Report of the Task-Force for Evaluation of Budworm Control Alternatives (Baskerville, 1976). That model will be referred to as the Maritimes Forest Research Center/Institute of Resource Ecology (MFRC/IRE) model reflecting the institutions involved in its construction.

The task-force report uses a 450-site representation of New Brunswick's forest. The MFRC/IRE model mimics the survival of budworm populations in each site during five life stages: eggs, first and second instar, third through sixth instar, pupae, and adults. In addition, the response of the trees to budworm feeding is modeled by accounting for their production of new foliage and retention of old foliage.

The task-force report considers the impact of several policies on the forest and on the economic activities of the forest industry. The report considers three policy sets: no-control, historic-crop-protection, and preemptive control (Baskerville, pp. 139-164). (1) It is projected that if control operations were ended in 1976, the resulting budworm outbreak and continued cutting would deplete the forest's inventory by '1995' with no recovery until after '2025'. (2) The historic crop protection policy is shown to protect the forest from substantial mortality; but on average, 11.3% of the forest area must be sprayed each year. With this policy, the forest is frequently in poor condition because it is allowed to go to the brink of mortality before spraying occurs to provide relief. Deletion of areas to be harvested from the spray areas results in only a marginal decrease of 0.7% in the average area sprayed. (3) The preemptive strategies are the most promising. By spraying sites whose egg densities exceed 160 eggs per square meter of foliage, the average area sprayed is reduced to 7.3% of the forest. If the spray threshold is lowered to 86 eggs per square meter of foliage, then on average only 3% of the forest is sprayed per year. Again, early control action seems to be advantageous.

The Maine and MFRC/IRE Budworm-Forest Models

Before proceeding to a discussion of results derived with the Maine budworm-forest model (Stedinger, 1977), it is advantageous to discuss the Maine and MFRC models' representation of the forest. An increased understanding of the model will allow the reader to better understand what questions the model can address.

The budworm-forest simulation model is best thought of as a budworm-foliage model. The model carefully keeps track of budworm densities, foliage consumed by budworms, foliage response, and the effect of foliage depletion on budworm survival. The simulation model also includes a prediction of tree mortality, which is less reliable than the other relationships because of the failure of field studies to determine the relationship between defoliation and tree death rates. Tree-growth loss has not been modeled at all.

The two models' representation of budworm population dynamics is based mostly on data collected in the Green River study reported in Morris (1963). Later research at the MFRC has also been incorporated. Budworm survival and success is modeled during each of the six life stages: eggs, first and second instar larvae, third and fourth instar larvae, fifth and sixth instar larvae, pupae and adults. The availability of foliage affects larval survival during the six instar stages. Budworm densities during all stages were expressed as individuals per ten square feet of foliage. Results are given here in individuals per square meter.

The Maine model's forest-dynamics submodel describes the behavior of the budworm's host trees in a 36 square mile site. A fixed portion of this area is assumed always to be covered by spruce-fir. The model describes the trees on a site by their age distribution and the density of foliage on the trees' branches. These variables summarize the important history of the forest and its potential for harvesting and budworm infestation. The MFRC/IRE model is very similar. Because budworms prefer and survive better on the current year's growth, the models differentiate between the current year's growth, referred to as new foliage, and needles produced in previous years, referred to as old foliage.

Model Validation

Stedinger (1977ab, 1984) discuss the differences between the Maine and MFRC/IRE models. The differences relate primarily to the density-dependent larval survival functions employed and the relationships assumed between budworm densities and foliage consumption, and foliage consumption and budworm survival. Also reported is a detailed analysis of the implications of these differences on overall model characteristics.

Model validation is a crucial step in the modeling process. It is important to demonstrate that when the individual parts of a model are joined together, the complete model adequately reproduces the behavior of the real system. The rigor with which a model can be validated is constrained by the quantity and quality of available data. Concurrent measurements of budworm population densities, defoliation rates, relevant weather conditions, moth invasion densities and spraying history would be necessary for a rigorous model validation; such complete histories are not available. The most reliable and easily generalized data available for budworm-forest model validation are histories of the defoliation rate of new foliage in unmanaged budworm outbreaks. Stedinger (1977ab, 1984) discuss historical defoliation patterns and shows that the MFRC/IRE model is inconsistent with field experience whereas the Maine model with the improvements it incorporates performs reasonably.

Simulation Results

In the "managed" budworm-forest simulations reported here, the forest is assumed to be managed to achieve a sustained yield. This means that the tree-age distribution in each site is close to a steady-state distribution. We will investigate the amount of spraying required to protect the forest if different spraying policies are implemented. One simple policy is to spray any site whose egg density the previous summer exceeded 320 eggs per square meter. This policy sprays when budworm densities are relatively low; hence it is a low egg-density-threshold spray policy, referred to as the 320 spray policy.

A second policy, shown in figure 1, is called the "forest-protection policy," abbreviated FP. This policy sprays any site whose egg and foliage density map into the shaded region at the bottom of the figure. These are forest states in which tree mortality might occur if spraying does not protect the foliage. This is an approximation of the forest-protection policy in use in Maine and New Brunswick.

The third spray policy shown in figure 1 sprays any site whose egg and foliage density map require spraying to protect tree health or whose egg density exceeds 650 eggs per square meter. This will be referred to as the 650 spray policy.

In addition to the dispersal of moths by prevailing winds among the 80 modeled sites, the model includes a mechanism, such as the passage of a cold front, which deposits a large number of moths in a limited area. This occurs in any year with a 20% probability. When it does occur, it deposits 3.16×10^6 eggs/acre (about 160 eggs per square meter).

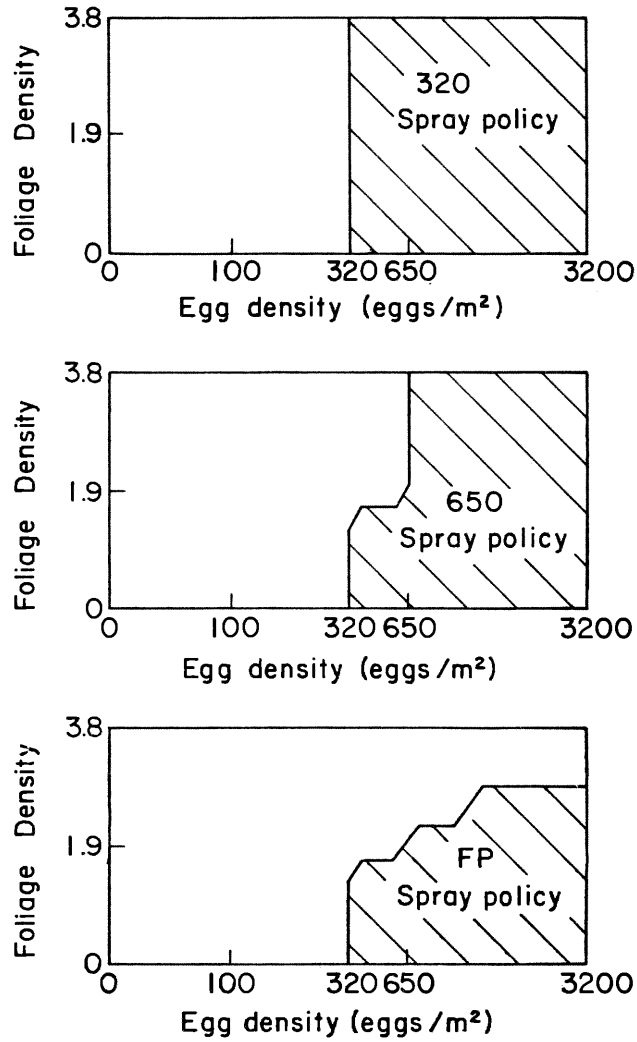

Figure 1. Three spray policies used in forest simulations. With each policy a site is sprayed if its state as determined by the site's egg and foliage densities falls in the shaded regions.

Table 1 reports the simulation results with the three policies. Reported in the table for each policy are the resultant spray frequency or average proportion of the forest sprayed each year, average egg density, and average defoliation rate (as a percentage of new foliage produced each year). The low egg-density-threshold spray policy is clearly superior to the other two policies. Its use results in less than half as much spraying and in almost no defoliation. These results show that the suppression of budworm populations before they reach outbreak densities is superior to spraying only when tree health is threatened. By waiting, one allows infestations to spread to other areas; when an area is sprayed, its budworm population is soon reestablished by moth flights from areas which are not sprayed. Thus by waiting, more spraying is required and one can be fairly confident that epidemic budworm levels will persist indefinitely without the assistance of moth invasions from remote outbreaks. Given that current strategies allow moderate budworm density populations to persist in many places and given that the basic budworm host (i.e., the white/red spruce and fir trees) remain in moderate condition, there seems to be no reason why the current outbreak in New England should collapse. (See also Blais, 1974).

Table 1. Summary of simulated budworm-forest behavior with the 80-site Maine budworm-forest model.

Policy	Spray Frequency (Sites Sprayed/Year/Modeled Site)
320	0.062
650	0.156
FP	0.162

Policy	Average Egg Density (eggs/m^2)
320	87
650	330
FP	427

Policy	Average Defoliation as a Percentage of New Foliage Produced
320	6.5
650	26.4
FP	38.2

Also of interest is the budworm-forest dynamics predicted by the MFRC/IRE model with these policies. The average spraying frequency obtained with the MFRC/IRE are reported in Table 2. With this model, the FP policy does slightly better than the 650 rule because of the very poor condition of the stands and the resultant decrease in budworm survival (see Stedinger, 1977a, pp. 3-35-3-38). With the MFRC/IRE model, the FP policy results in an 18% decrease in the volume of wood harvested due to tree mortality from that harvested with the 320 rule. Tree-growth losses due to defoliation which decrease the sustained yield even farther.

Table 2. Spray frequencies in simulations with MFRC/IRE model and its estimated standard error. a/

Policy	MFRC/IRE Model
320	0.058
650	0.187
FP	0.141

a/ These results were actually computed using a spatially-simplified 10-site model. Compare with second row of Table 3 which also used a 10-site model.

Sensitivity Analysis

An extensive sensitivity analysis with the Maine model was conducted to determine if possible model errors could cause low egg-density-threshold policies to be inferior to forest-protection policies. The superiority of low density-threshold policies is not affected by what are considered to be possible errors (Stedinger, 1977a, pp. 3-46 to 3-60). For these sensitivity runs, a one-dimensional compression of the two-dimensional Maine model was used. Table 2 shows the results of an error of -16% or +20% in the modeled scale of budworm survival. As the values in the table show, such an error has a large effect on spray frequencies, but not on the superiority of low density-threshold policies. However, if budworm survival has been underestimated, then an egg-density threshold lower than 320 eggs would be preferable.

Table 3. Spray frequencies are given for three policies when large larval survival was scaled by indicated factors. b/

Scale Factor	Spray Policy 320	650	FP
0.84	0.042	0.084	0.132
1.00	0.078	0.185	0.179
1.20	0.170	0.263	0.215

b/ These results are computed with spatially-simplified 10-site model.

The New Brunswick Task Force Report using the MFRC/IRE model identified 86 eggs per square meter as a good spray threshold. Both the Maine and MFRC/IRE models indicate that low egg-density threshold policies are best though they point to different optimal spraying thresholds. Research on budworm survival in the 10-400 egg per square meter range would allow better identification of an appropriate egg-density threshold for spraying. An operational spraying strategy could have a threshold which is a function of geographical location, stand age, or other important considerations which relate to budworm survival or to the ability of moths to disperse into or out of an area.

Conclusion

The simulation model indicates that if budworm outbreaks are initiated by limited "point sources," such as infrequent moth inflights or small epicenters, then it is advantageous to suppress budworm populations before they build up to outbreak densities. If suppression operations take place only in areas with high budworm densities and severe defoliation, then infestations spread and sprayed areas are soon reinfested by moths from surrounding unsprayed areas. Interestingly, the superiority of early control action has also been observed in other multi-site budworm simulation studies (Watt, 1964; Baskerville, 1976).

Use of a low-egg-density-threshold policy has the advantage that the forest is maintained in a healthy vigorous state without tree growth loss rather than on the brink of collapse as occurs with the forest-protection policy. It also minimizes the potential for widespread tree mortality should weather, technical difficulties, or political events prohibit the execution of a spray program for one, two or three years. This policy is, in some sense, resilient against unexpected events (Stedinger, 1977a, p. 4-45 to 4-58).

Unfortunately, use of a low egg-density-threshold policy may be politically unstable because it eliminates the immediate danger of widespread tree mortality. This would encourage political institutions and budget-conscious decisionmakers not to vigorously maintain necessary low-budworm-density monitoring networks and early suppression spray programs; the result would probably be an unintentional return to a forest protection policy.

It is interesting that current management strategies are stressing effective forest management and manipulation, and use of dead and dying timber, to decrease forest vulnerability, and to minimize the need for spray operations rather than employing low-density budworm suppression programs. Thus, forest managers have chosen to take advantage of management opportunities which are not well described or available in the Maine and MFRC/IRE budworm-forest models.

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RISK-RATING PROCEDURES: THE SIGNIFICANCE OF FOREST INVENTORY INFORMATION

Charles E. Olson, Jr.

Professor of Natural Resources
The University of Michigan
Ann Arbor, MI 48109-1115

Risk-rating procedures should be simple, easily understood, and readily adaptable to local conditions. Both the number of variables and the number of classes within each variable should be kept to five or less. One procedure for short-term risk-rating which can be used with ground or air photo determinations of defoliation and mortality is described.

Introduction

Several procedures have been developed for assessing short-term or long-term risk from spruce budworm activity (Batzer and Hastings 1981; Witter and Lynch 1984). Some rely on ground techniques, some on aerial techniques, and some on a combination of aerial and ground techniques. Variables measured, or considered, in long-term risk-rating often differ from those in short-term risk-rating procedures. Differences in objectives are the basis for many of these differences.

The most useful risk-rating procedures are those which are simple, easily understood, and readily adaptable to local conditions. Such procedures seldom evolve unless there is agreement on what is to be accomplished and the meaning of terminology. Let's be sure you understand what I mean by two key words in the title of this paper.

Risk can have many connotations. It can have a meaning which is value-oriented, as in values at risk and risk of loss; occurrence-oriented, as in risk of attack; or control-oriented, as in risk of spread (of a damage agent). The first of these, with a value orientation, usually includes elements of each of the other two. Because there is little need to take corrective or preventive action if there is no value at risk, I associate risk-rating with value.

Inventory can be considered the determination of value at some point in some utilization cycle (Olson 1983). Because value can seldom be measured directly, we usually concentrate on those things we know how to measure which are correlated with, and let us predict, value. Foresters traditionally measure tree diameter and height to determine the value of the wood in a tree. This may not be the most appropriate way to determine the value of a shade tree, or a stand of trees as wildlife habitat. In deciding what to measure, we should select whatever provides the most cost-effective basis for determining the desired value(s), at the appropriate point(s), in the intended utilization cycle(s).

Selecting What And When To Measure

Selecting the right variables to measure for risk-rating requires an understanding of both the biology and ecology of the damage agent. When the damage agent is the spruce budworm, Choristoneura fumiferana (Clem.), there are a number of factors to consider (Witter et al. 1984). Some of these are:

1. Active feeding is usually confined to the months of May, June, and July.
2. Attack is seldom fatal in the first season.
3. Mortality is greater when:
   a. over half of the stand is of host species, balsam-fir (Abies balsamea (L.) Mill.) or spruce (Picea spp.).
   b. the stand is very open or dense.
   c. large amounts of foliage of host species are exposed (trees not overtopped).
   d. average age of host species is more than 50 years.
   e. the site is very wet or very dry.

Some of these factors are closely related to each other (e.g., stands over 50 years of age usually have large amounts of foliage of host species exposed). The degree of correlation often varies between regions and within regions (Blais 1968; MacLean 1980; Lynch et al. 1984).

Selecting the right variables to measure for risk-rating requires an understanding of possible utilization cycles. If rotation age is kept below 50 years (Flexner et al. 1983), individual trees will seldom reach sawtimber size. Deterioration caused by secondary insects and fungi soon renders pole-sized trees susceptible to breakage. Salvage is seldom practical more than two years after death of balsam-fir, or three years after death of spruce. The number or proportion of dead trees already present in a stand is a factor affecting probable loss if prompt action is not taken.

Selecting what and when to measure also requires common sense. Because active feeding usually begins in May and extends into July, ratings made during these three months are single point assessments of moving targets. Salvage or preemptive cutting can seldom be accomplished before the next cutting season, and it is appropriate to delay risk-rating for spruce budworm until the active feeding period is over. In Michigan's Upper Peninsula, August and September usually provide the best flying weather. Photographs taken, or field work, in August and September provide ratings for consideration in October and November when cutting plans are made for the following harvest season. Delaying risk-rating until August or September presents one problem. Brown needle mats which are one visible indicator of feeding activity are often gone - removed by wind and rain. This is not, however, a serious problem.

Long-Term and Short-Term Risk-Ratings

Long-term risk-rating procedures are designed to assist forest managers in planning stand management and harvest operations over long periods. They are usually based on conventional inventory data. Such data usually include, for each stand:

1. Number of live and dead trees, by species.
2. Basal area, by species, from which stand density determinations can be made.
3. Stand age.
4. Site quality, including information on relative wetness or dryness.

These are the data needed to assess four of the five mortality factors identified on the previous page. Several regression equations have been developed to predict potential for loss from such data (Witter and Lynch 1984). Such equations are readily implemented within computer-based forest information systems. They are not as readily implemented in the field, and seldom meet the need for short-term risk-rating under outbreak conditions.

Most short-term risk-rating procedures are designed to assist forest managers minimize loss once an outbreak has begun. They are designed to identify those stands with the highest probability of loss in the short-term, and require current information for each stand. Such data are seldom available from normal inventories based on remeasurements at five-year, or longer, intervals. Short-term risk-rating procedures should be considered supplements to normal inventory procedures. As such, their function should be to provide information on the more dynamic and changing variables. Has the stand been attacked yet? If so, how severe is the attack now? How quickly must the stand be salvaged to avoid unacceptable loss?

Managing Costs

The most visible signs of spruce budworm attack are defoliation and mortality. Ground procedures for assessing present damage and predicting future loss of individual trees have been developed based on these two variables (Mog and Witter 1979). Combining data for individual trees provides a risk-rating for a stand. This is a short-term risk-rating, and requires current, usually annual, data. McCarthy et al. (1982; 1983) reported that equivalent measurements could be made from large-scale, small-format, color, air photos without the need to send ground crews into each stand. Use of such methods may not reduce costs, but should provide more information at acceptable cost, when compared with costs of obtaining the same information from ground methods alone.

Because it is seldom feasible to measure all of the trees in a forest population, foresters commonly base decisions on measurements of a sampled sub-set of the total population. Cost of field measurements usually restricts the number of samples that can be measured. Air photo techniques can provide a larger sample size for a given cost, and are adaptable to either random or systematic sampling designs. For air photos to be useful, available personnel must be able to make the needed interpretations. Experience has shown that the needed skills can be provided with two to three days of training.

Designing A Short-Term Risk Rating Procedure

Experience indicates that procedures utilizing both ground and aerial techniques are more effective than those using either technique alone. To provide readily comparable data, both ground and aerial techniques should utilize the same rating procedure. This results in a total procedure which is simpler and easier to understand than when different variables are measured on the ground and from the photos. Such a common procedure has been designed for short-term risk-rating in Michigan's Upper Peninsula (Olson et al. 1982).

Basic Considerations

A low cost, simple procedure for risk-rating should rely on as few variables as possible. Variables selected should be easily measured by the personnel expected to make the measurements. After reviewing several types of rating procedures, we concluded that neither the number of variables nor the number of classes within a variable should exceed five, and preferably be limited to four. Humans are three-channel processors whose efficiency declines when confronted with decision processes requiring integration of more than three inputs. Four or five variables can fit into a 3-channel system if variables are appropriately combined. More than five subdivisions within a variable provides more detailed ratings than the precision of our current knowledge justifies.

Because forest terrains are seldom flat, forest areas have few dependable landmarks, and light aircraft used in taking small-format air photos seldom have precision altimeters, it is seldom possible to accurately determine the scale of 35mm air photos of forest areas. When photo scale is not accurately known, the ground size of sample plots located on those photos cannot be determined. To overcome this problem and still provide the cost advantages of sampling procedures and 35 mm photographs, we decided to base our rating procedure for spruce-fir stands on stand averages and proportions. The resulting procedure is not dependent on constant plot size or a given sample size, and may be used on the ground, with air photos, or with a combination of ground and photo measurements.

Variables Selected for Measurement

The procedure designed for Michigan's Upper Peninsula is based on measurement or estimation of four variables:

1. Relative density of the stand, based on the rater's estimation that the stand is open,

average, or dense.

2. Proportion of stand in host species, determined by dividing the total number of host trees by the total number of trees of all species.

3. Average defoliation ranking of live trees of host species, based on the following scale:

   1 = No to 20 percent defoliation.

   2 = 21 to 50 percent defoliation.

   3 = 51 percent or more defoliation, without top kill.

   4 = 51 percent or more defoliation, with one meter or more of top kill.

4. Proportion of host trees already dead, determined by dividing the number of dead host trees by the total number of live and dead host trees.

Values of each of the last three variables can be calculated for each host species separately, if desired. Some modification of the rating tables would be required if this is done.

Rating Tables

Three tables were developed for determining the contributions of the four selected variables to a final Stand Rating Index (SRI). Individual values in each table represent best estimates of the appropriate weight to be assigned to that cell in the table. Among the factors considered when making these assignments were:

Value of host species at risk. When large numbers of trees of host species are present, the potential for loss is greater than when fewer trees of host species are present. Thus, dense stands have more value at risk than open stands, and stands with a high proportion of trees of host species have more value at risk than stands with a low proportion of trees of host species.

Number of years the stand has been attacked. Duration of attack was assumed to be correlated with average defoliation ranking for the stand. High defoliation rankings indicate multiple year attacks with a higher probability of future short-term mortality.

Present mortality. The presence of significant numbers of dead host trees usually indicates multiple year attacks. Additional mortality in the short term is likely. Because dead trees deteriorate quickly, prompt salvage is necessary to reduce loss. When mortality is very high, however, deterioration may be sufficiently advanced to make salvage unlikely.

All of the values in the tables are subject to modification and adaptation to local conditions without altering the basic procedure. This has made the procedure adaptable to requirements of different organizations, or local utilization and salvage practices.

Table 1. Contribution to Stand Rating Index (SRI) based on stand density and proportion of stand in host species.

Proportion of Stand in Host Species	Stand Density		
	Open	Average	Dense
0.00 - 0.30	1	1	2
0.31 - 0.60	2	3	4
0.61 - 1.00	3	4	6

Table 2. Contribution to Stand Rating Index (SRI) of average tree defoliation ranking.

Average Defoliation Ranking	Contribution to Stand Rating Index
0.0 - 1.2	0
1.3 - 1.9	1
2.0 - 2.9	2
3.0 - 4.0	3

Table 3. Contribution to Stand Rating Index (SRI) based on present mortality of host trees.

Proportion of Host Trees Already Dead	Contribution to Stand Rating Index
0.00 - 0.09	0
0.10 - 0.29	2
0.30 - 0.49	4
0.50 - 1.00	6

Procedure

The procedure presented here is based on the use of 35mm, color, air photos at a scale close to 1:4,800. Interpretation of the original, positive transparencies was completed stereoscopically with adjacent, overlapping photos. For a more complete description of the procedure, and its development, see Olson et al. (1982).

Modification of this procedure for ground use is straightforward. Plot size is often larger in ground surveys, for non-productive travel-time between plots can be a significant cost factor. With the photos, we found a plot which included between 12 and 20 trees was a good size. Larger plots included so many trees that interpreters sometimes lost track of which trees had been tallied. Others things being equal, many small plots usually provide as good, or better, results as fewer larger plots.

The procedure presented here will not provide a quantitative prediction of future loss. Instead,

it provides a numerical index, or Stand Rating Index, that can be used to compare spruce-fir stands and rank them in terms of probability of short-term loss.

Step 1. Select the size of sample plot to be used.

Step 2. Determine locations of sample plots on the photos. These locations may be randomly or systematically selected.

Step 3. Place a template defining plot size over each plot location. A small piece of clear acetate with a marked plot outline works well.

Step 4. Tally all trees within each plot by species, and record a Defoliation Ranking for all living trees of host species. Keep a separate tally of the number of dead trees by species.

Step 5. Compute the proportion of the stand in host species by dividing the number of host trees in the total tally (all plots in a stand) by the total number of trees tallied for the stand.

Step 6. Compute the Average Defoliation Ranking for the stand by summing the defoliation rankings for each living host tree and dividing by the number of living host trees.

Step 7. Compute mortality of host trees by dividing the number of dead host trees by the total number of living and dead host trees.

Step 8. Estimate the density of the stand as Open, Average, or Dense.

Step 9. Look up the contributions to the final Stand Rating Index from each of the tables and sum these individual contributions to obtain the final SRI.

Interpreting the Results

If we use the procedure presented above and determine ratings for six stands, we might get the following results. How can these results be interpreted?

Contribution from Table #	Stand 1	2	3	4	5	6
1	2	4	6	2	4	3
2	2	3	2	3	1	3
3	0	4	2	2	0	4
SRI (sum)	4	11	10	7	5	10

Stand 2 has the highest SRI. It is a dense stand with about half of the trees of host species, live host trees are heavily defoliated, and one-third to one-half of the host trees are already dead. If this stand is not cut soon, there will be little left to salvage.

Stands 3 and 6 both have ratings of 10. On the basis of present damage, defoliation plus mortality, Stand 6 is in worse shape than Stand 3. You might decide to cut Stand 6 first, and delay cutting Stand 3. Or, you might decide the high mortality in Stand 6 will make logging difficult. A decision to cut Stand 3 preemptively may be more in keeping with local realities.

Stand 1 has a lower SRI than Stand 5 (4 vs. 5). Neither stand has significant mortality, but higher defoliation in Stand 1 may prompt its earlier cutting.

Stand 4 has a high defoliation rating and significant present mortality. Its SRI is lower than that of Stand 3 only because it conatins less spruce and fir. It has less value at risk. Some users of this procedure have elected to increase the values in Table 2, to give greater weight to levels of present defoliation. If all values in Table 2 are doubled, the results would be:

Contribution from Table #	Stand 1	2	3	4	5	6
1	2	4	6	2	4	3
2	4	6	4	6	2	6
3	0	4	2	2	0	4
SRI (sum)	6	14	12	10	6	13

The primary effect of this change is to more clearly group the six stands into two groups, those with values of 10 or more, and those with values below 10.

Final Remarks

As this meeting has shown, great progress has been made in building the knowledge base from which to more accurately forecast both long-term and short-term losses due to spruce budworms. Implementation of this knowledge should result in better management decisions. This will only happen if the information can be effectively condensed into some acceptable index, for experience has repeatedly shown that managers presented with too much information tend to ignore all of it. Regression equations based on twenty, or even ten, variables are seldom acceptable to forest managers, although this appears to be changing as more and more managers become accustomed to computer-based forest information systems. Still, risk-rating procedures which are not simple, easily understood, and readily adaptable to local conditions will probably see little use.

Acknowledgements

Work leading to this report was supported by the Canada/USA (CANUSA) Spruce Budworms Program. Many people contributed. The contributions of John A. Witter, Ann M. Lynch, Bruce A. Montgomery, and Patricia J. Sacks at The University of Michigan; Jack McCarthy, Lisa A. Bergelin, and Chester Karpinski, Jr. while they were graduate students at The University of Michigan; and the encouragement of Daniel M. Schmitt and Robert L. Talerico of the U.S. Forest Service, were most important.

The criticisms of the many people who attended our four Workshops on Spruce Budworm Damage Assess-

ment with 35mm Air Photos at Sault Ste. Marie and Iron Mountain, MI in 1982, and Orono, ME and Burlington, VT in 1983, proved invaluable.

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STAND MANIPULATION TO TAKE ADVANTAGE OF NATURAL MORTALITY FACTORS

Gary A. Simmons and Norman C. Elliott

Department of Entomology
Michigan State University
East Lansing, MI 48824-1115

The value of stand manipulation for increasing levels of mortality of early larvae of the spruce budworm was assessed. The geographic regions and situations in which manipulation techniques would likely be effective are identified and recommendations are made for managing stands to increase early larval mortality.

The term "larval dispersal loss" has usually referred to mortality occuring to spruce budworm larva during two periods--immediately after egg hatch in August or September and again after emergence from overwintering hibernaculae in April or May (Miller 1958). During these times the tiny larvae often spin and dangle on silk threads and are then launched by puffs of wind (Kemp and Simmons 1979). The difficulty of studying these phases of the budworm life cycle led Miller to refer to mortality as "larval dispersal loss" even though the total mortality could be ascribed to a variety of causes including predators, maladaptation, weather and other factors, in addition to larvae landing on unsuitable host material. When we refer to "larval dispersal losses" we take the broad, all encompassing interpretation by Miller and expand somewhat to include "all mortality occurring, beginning with egg disposition until 3rd and 4th instars are established in feeding sites in the spring."

This phase of spruce budworm population dynamics has been studied by different investigators in several locations throughout eastern North America, and with related budworm species in other parts of the continent (Henson 1950, Miller 1958, Morris and Mitt 1963, Foltz et al. 1972, Shaw and Little 1973, Kemp and Simmons 1979, Batzer and Jennings 1980, Kemp et al. 1980, Beckwith and Burnell 1982, Nyrop et al. 1982, Règnière and Fletcher 1983, and Jennings et al. 1983). Whether one studies the literature, conducts system simulation studies or investigates field dynamics, the overwhelming conclusion is that mortality during this period is consistently high. For example, Miller (1975) gives values of 60-80%, Kemp and Simmons (1979) from 76-99% and Nyrop et al. (1982) around 86-87%.

Over the past 10 years my students and I have investigated various aspects of the budworm's biology, forest character and cultural treatments of the forest to see if the forest could be manipulated to take advantage of the multitude of mortality factors that affect the budworm during the early part of its life cycle. We have developed both field studies (Kemp and Simmons 1978, 1979, and Nyrop et al. 1982) and computer simulation studies (Kemp et al. 1980, Nyrop et al. 1982). Based on these studies and those contributed and reviewed by later speakers, I believe we can make specific recommendations to you.

The recommendations we make are appropriate to geographic regions on the southern edge of spruce-fir type such as portions of Minnesota, Wisconsin, Michigan, New York, Vermont and New Hampshire. Techniques are also appropriate on small parcels of land where intensive, multiple use practices are currently employed or are desired. The last qualifiers are that a substantial portion of the land area (30-50%) is not needed for producing trees and that treated stands should contain mixtures of budworm non-hosts such as aspen, birch, red maple or northern hardwood species.

General Guidelines

1. Keep spruce and fir under 50 years of age.
   This assures young, vigorous trees that are able to sustain an outbreak without undue tree mortality.

2. When stands are less than 20 years old, create strips of open area between stands of trees.
   Strips should cover 30 to 50% of the total land area. Each open strip should not be less than 3 chains in width and each forested strip should not exceed 5 chains in width. Open strips can be created by cutting, bulldozing, rollerchopping, burning, herbiciding or combinations of methods. The open strips and forested strips should take maximum advantage of budworm mortality factors such as dispersal, parasites and insect and bird predators. The reason for early treatment of stands is to start grooming stands early for windfirmness.

3. Open strips need to be maintained at approximately 10-15 year intervals.
   The advantages of open areas are lost with time due to forest succession. Thus, the open strips will require attention occasionally. The same methods mentioned in 2 can be used to recreate open areas.

4. Discriminate against balsam fir in the forested strips.
   The higher the percentage of fir and the older it is, the more likely it is to suffer damage during a budworm outbreak. Ideally, the combination of spruce and fir should not exceed 60% of the basal area of the forested strips.

5. Discriminate against individual spruce or fir trees that dominate the height of the forested strips.
   Individual spruce and fir trees that stand above the canopy are attractive to ovipositing spruce budworm moths. By selecting against these kinds of trees you are making the stand less desirable from the budworm's point of view.

The utility of the above techniques is obviously limited to circumstances where spruce and fir stands are small, isolated and contain mixtures of other tree species. In addition, the methods discussed are most appropriate where intensive, multiple use is the objective of management. Small, private woodlots and isolated stands along the southern distribution of spruce-fir type are, to us the places where these methods show promise.

In areas where spruce-fir is common, widespread and extensively managed with large scale aerial spraying operations, these methods are both inappropriate and likely to be uneconomical. Some of our research experience was obtained in these kinds of settings and the results were not satisfactory. Further, we feel these techniques will not work well in mature stands--if stands are beyond 30 years of age we believe these techniques may create more problems than they alleviate.

Thus, the approach we suggest is one additional set of tools to choose from that can match particular circumstances. These techniques do not provide a cure-all to be applied over large geographic areas.

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EFFECTS OF SILVICULTURAL PRACTICE ON BIRD PREDATION

H. S. Crawford

Principal Research Wildlife Biologist
USDA Forest Service
Northeastern Forest Experiment Station
Orono, ME 04469

Several species of birds were effective predators on endemic spruce budworm populations. Populations of these birds can be improved by silvicultural practices that increase: (1) the degree of hardwood admixture with softwoods, (2) the proportion of spruce to fir, and (3) the diversity in horizontal and vertical habitat structure. Group selection and shelterwood cuts were favored.

Recent evidence indicates that birds may limit increases of endemic spruce budworm (*Choristoneura fumiferana*) populations. Crawford et al. (1983) estimated that birds ate approximately 87% of SBW pupae and larvae in endemic situations and concluded that "birds have the ability to consume substantial numbers of late-stage larvae and pupae of the spruce budworm and hypothesize that under favorable conditions birds may prevent budworm populations from becoming epidemic." What are the favorable conditions that would enhance control of SBW by birds?

Important Predators Of Spruce Budworm

Bird predation has little effect on epidemic spruce budworm populations, though many species eat the pupae and larvae (Crawford et al. 1983). Insects are so numerous that the number eaten by birds is small in relation to the total available. When the budworm is not at epidemic levels, fewer bird species eat the insect but the proportion of the population eaten is greater. Predators that maintain high population densities and high feeding rates over the lower ranges of the insect's density and that respond to initial rises in endemic numbers are most important in insect suppression. In northern New England, species that met these criteria were the blackburnian warbler (*Dendroica fusca*), golden-crowned kinglet (*Regulus satrapa*), Nashville warbler (*Vermivora ruficapilla*), white-throated sparrow (*Zonotrichia albicollis*), black-capped chickadee (*Parus atricapillus*), solitary vireo (*Vireo solitarius*), red-breasted nuthatch (*Sitta canadensis*), magnolia warbler (*D. magnolia*), and yellow-rumped warbler (*D. coronata*), (Crawford et al. 1983).

Response Of Birds To Forest Change

Several studies have shown that changes in forest habitat cause changes in the number and species composition of birds. Clearcut harvest of Douglas-fir (*Pseudotsuga menziesii*) caused marked changes in bird species composition in California (Hagar 1960). Species of birds using different stages of forest succession following timber harvest in coniferous forests of Finland changed as habitat structure of the forest stands changed (Haapanen 1965). In northern Maine spruce-fir (*Picea-Abies*) stands, the distribution of breeding songbirds was determined by habitat structure in each of 5 seral stages following clearcutting (Titterington et al. 1979). Crawford and Jennings (1982) hypothesized that natural predation on forest insects can be enhanced by habitat manipulation, which increases numbers and variety of birds.

Three intrinsic habitat factors determine woodland bird populations in the northern spruce-fir stands we have studied: (1) the degree of hardwood admixture with softwoods, (2) vertical and horizontal stand structure, and (3) the degree of spruce budworm infestation (Crawford and Titterington 1979). Bird populations also can fluctuate because of factors such as winter mortality, migration loss, etc. The intrinsic factors vary from stand to stand. Hardwood-softwood mixture and stand structure depend on geographic location, microclimate, site characteristics, past cutting, and within-stand silviculture. Spruce budworm populations appear cyclic and are affected by weather and the amount, age, and distribution of balsam fir in the stand.

Crawford and Titterington (1979) found that stands composed primarily of balsam fir contained an impoverished avifauna with an average of only 128 breeding pairs/40 ha and 20 bird species (Table 1). Stands of mixed spruce and fir averaged 190 pairs/40 ha with 26 species. An admixture of hardwoods and conifer in the overstory increased the bird

population to 231 pairs/40 ha with 24 species. Reproducing spruce stands with saplings and poles and mature spruce stands supported 249 and 264 breeding pairs/40 ha with 17 and 23 species, respectively.

Table 1. -- Bird Density and Composition by Forest Type

Forest type	40 ha Pair	No. of species	Multiple
Balsam fir	128	20	1.0
Spruce fir	190	26	1.5
Mixed growth	231	24	1.8
Young spruce	249	17	2.0
Mature spruce	264	23	2.1

Bird populations in seral spruce-fir stands followed a predictable pattern in northern Maine (Titterington et al. 1979). The earliest seral stage was characterized by dense slash and open ground that dominated the site for 2 years following commercial clearcutting. The dark-eyed junco (*Junco hyemalis*), white-throated sparrow, and winter wren (*Troglodytes troglodytes*) commonly occupied these areas. A dense raspberry stratum generally occupied the site 3 to 5 years after cutting and favored populations of the common yellow- throat (*Geothlypis trichas*), mourning warbler (*Oporornis philadelphia*), chestnut-sided warbler (*Dendroica pensylvanica*), and white-throated sparrow. Hardwood regeneration taller than 2 m and a slow-growing softwood stratum characterized the next seral stage that lasted from 7 to 12 years after cutting. Dominant bird species in this stage were the magnolia warbler, American redstart (*Setophaga ruticilla*), red-eyed vireo (*Vireo olivaceus*), black and white warbler (*Mniotilta varia*) and white-throated sparrow. The fourth seral stage is characterized by increased densities of hardwood regeneration taller than 4.5 m with a dbh of 10-15 cm and scattered hardwood residuals. Attendant birds included the ovenbird (*Seiurus aurocapillus*), black-throated blue warbler (*D. caerulescens*), black-throated green warbler (*D. virens*), Canada warbler (*Wilsonia canadensis*), Swainson's thrush (*Catharus ustulatus*), rose-breasted grosbeak (*Pheucticus ludovicianus*), and Tennessee warbler (*Vermivora peregrina*). Mature spruce-fir stands with a dense softwood overstory and an open forest floor represented the fifth seral stage. The blackburnian warbler, golden-crowned kinglet, bay-breasted warbler (*D. castanea*), yellow-rumped warbler, and Cape May warbler (*D. tigrina*) dominated the avifauna.

Enhancing Predators Through Silvicultural Practices

Spruce and fir along the northern border of their transcontinental distribution often are found in almost pure stands. Intolerant hardwoods such as the birches (*Betula* spp.) and aspens (*Populus* spp.) increase toward the central latitudinal portion of this distributional belt. Along the southern border, mid-tolerant and tolerant hardwoods such as beech (*Fagus grandifolia*) and maples (*Acer* spp.) compete with spruce and fir for favorable sites.

Although hardwoods are naturally more abundant in the southern portion of the upland spruce-fir type, site characteristics substantially influence their distribution and abundance. Spruce and fir on thin, infertile soils in the moist eastern portion of the range generally grow in dense stands with closed canopies and little hardwood admixture. In an undisturbed state these stands are single-storied with sparse undergrowth. More fertile soils allow more hardwood growth and increased canopy layering. In the more continental climate to the west, hardwoods are better competitors for limited soil moisture, and moisture stress increases the mixture of hardwoods in spruce-fir stand (Westveld 1953).

Thus, fir stands in those parts of northern New England and the Maritimes with shallow, infertile soils have dense, shallow canopies with little admixture of hardwoods and sparse understory growth. Such stands represent some of the poorest bird habitat in eastern North America. Silvicultural practices that create greater plant diversity will enhance bird habitat.

Silviculture, when left to the spruce budworm, will favor the spruce budworm. Poor-site, dense fir stands often are underlain by deep organic mats. The long hypocotyl of fir seedlings penetrates the deep organic mat to reach mineral soil. Primary roots of other competitors are not as effective and may desiccate during dry

periods. Thus, when the overstory is defoliated by spruce budworm, small fir regeneration is released and soon fully occupies the site, producing another dense fir stand which provides food for the budworm and unfavorable habitat for birds.

Large clearcuts simulate the silviculture practiced by spruce budworm. Dense stands of fir result from copious preharvest regeneration unless the site is altered by burning or is intensively prepared, planted, and cultured after harvesting. These practices are not used extensively by forest managers. Thus, the usual large clearcut on poor sites produces another fir stand favorable for budworm and unfavorable for birds. Hardwoods occur naturally with fir on better sites but often are discriminated against in management programs. Regenerating stands that contain a large proportion of spruce will provide substantially better bird habitat than fir stands because they support high populations of magnolia warblers and other effective budworm predators.

Four effective budworm predators--blackburnian warbler, golden-crowned kinglet, yellow-rumped warbler, and red-breasted nuthatch--are associated with mature conifers, especially a mixture of conifer species. Other effective budworm predators--Nashville warbler, white-throated sparrow, and black-capped chickadee--are associated with brushy openings and the edge between openings and spruce-fir or mixed growth. The magnolia warbler and solitary vireo, also effective predators, favor immature, open conifer stands and dense stands of hardwood stems, conditions typical of regenerating forests. Thus, a mature coniferous forest with a mixture of overstory species, managed for well-distributed, small openings containing regeneration of different ages, should provide habitat to favor the best population of budworm predators. We do not have data to confirm the most effective size of opening but small patches would be necessary because territory size of most of these predators generally is less than 1/2 ha.

Of the alternatives for silvicultural practice, group selection comes closest to creating these ideal conditions. Considering only even-age alternatives, three-stage shelterwood could provide suitable habitat if the operating units are small, perhaps 10 ha and of different ages.

We find one alternative for uneven-age and one for even-age management to produce the best populations of predaceous birds. Either alternative involves a change in the scale of harvest activities that we practice today. Either system would require more maneuverable harvesting equipment. Changes in costs of harvesting will have to be compared to change in costs of insect control. If more effective insect control at lessened costs offsets increased harvesting costs, then bird management, in concert with other insect control measures, could present a viable management strategy.

We are now conducting research to quantify the effects of bird predation and evaluate its contribution to integrated pest management.

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EFFECTS OF STAND CONDITIONS ON PARASITOID DYNAMICS

Patricia M. Hanson

Research Assistant, Plant and Soil Science Department, University of Vermont, Burlington, VT 05405

The success of parasitoids in spruce budworm suppression rests on their ability to find and parasitize hosts in numbers proportional to host levels. Different ways of managing forest stands to decrease their vulnerability to spruce budworm are discussed in light of their inevitable influences on parasitoid ecology.

The goal of the silvicultural management of the spruce budworm is to create stand conditions which make life difficult for this forest defoliator while maximizing other objectives, e.g., economic and recreational. Effective management includes the regulation of all ecological factors impinging on the spruce budworm's welfare, except perhaps climate and weather. From disease, predation, and parasitism to soil chemistry, these influences interact in an ever-changing network, probably always somewhat out of balance. This paper focuses on one connection in this network: the dependence of parasitoid activity on conditions within forest stands.

Searching Capacity

The ability to find and parasitize hosts, especially at low host density, has significant bearing on the long-term success of parasitoids (Graham and Knight 1965; Debach 1974; Coppel and Mertins 1977). Some of the factors contributing to searching efficiency are systematic searching, avoidance of presearched areas, discrimination against hosts already attacked, and emigration (DeBach and Smith 1941; Burnett 1951; Wylie 1970; Price 1972).

When female parasitoids emerge in preparation for egg laying, they must locate their hosts. Random searching or the chance location of a host are assumed in many parasitoid-host models and may suffice for some species, but such activities do not appear to be advantageous where host densities are low (Vinson 1975).

Forest trees of different sizes and species provide a number of microhabitats for host insects. Effective parasitoids are able to recognize the few microhabitats frequented by their preferred hosts out of the wide range of conditions which any forest has to offer.

A hypothetical parasitoid, starting from scratch, might begin with broad categories of host habitat preference to reduce its search time. The parasitoid pursues the search by making finer and finer discriminations, with the object of maximizing its search time in the microhabitat in which the host is most likely to occur. Chemical cues originating from the host, its food source, or the feeding process can aid parasitoids in their searching behavior. Thus the search can result in biochemical coevolution between parasitoids and their hosts (Vinson 1975). For example, the leaf damage caused by feeding of the tobacco budworm Heliothus virescens (F.) results in increased frequency of landing and increased length of time spent on the plant by the parasitoid Cardiochiles nigriceps Viereck while mechanical damage does not (Vinson 1975).

Parasitoids may attack hosts more readily on some host plants than on others. Miller (1959) showed that female Apanteles fumiferanae Viereck prefer the odor of white spruce Picea glauca (Moench) over balsam fir Abies balsamea (L.) Mill. Parasitoids may reduce or limit their search area to microhabitats associated with their host food plant (Weseloh 1976). Trees differ in the strength of their stimulus to the olfactory responses of the spruce budworm as well, and this can cause host clumping (Morris and Mott 1963).

Theoretically, parasitoids may respond to host pheromones, but we have few reports of such cases (Weseloh 1976). Vinson (1975) suggests that "the utilization of a volatile compound liberated by a potential host as a cue to host location by a parasitoid may be expected in situations where the stage releasing the compound either is attacked or is present along with the potential host stage." The egg parasitoid Trichogramma minutum (Riley) of the spruce budworm or the first and second instar parasitoids A. fumiferanae and Glypta fumiferanae (Vier.) may find the female sex pheromone of the budworm useful in host location because eggs are laid soon after mating, and they hatch in about a week. Since the spruce budworm overwinters as a second instar larva, parasitoids which attack later instars have to depend on other cues for host location.

Forest parasitoids find hosts from a distance by responding to sound, temperature differences, movement, and colors associated with hosts (Weseloh 1976). After a potential host is located, female parasitoids may or may not accept it. Host acceptance and stimulation of egg release depends on host characteristics such as size, shape, surface texture, or motion (Doutt 1959). Arthur et al. (1969) found that a factor in the hemolymph of the host stimulated Itoplectis conquisitor (Say) to lay eggs, and that egg laying could be elicited by serine, arginine, leucine, and $MgCl_2$ (Arthur et al. 1972).

There is growing evidence that many parasitoids are able to avoid presearched areas. For example, in a confined area, Griffiths and Holling (1969) found density-dependent interference in oviposition. This suggests that, if unconfined, parasitoids would space themselves so that interference would be reduced. Price (1970) showed that some parasitoid species will avoid areas already searched by others, and that even within a species a female can recognize areas that she and others have searched. At least two common parasitoids of the spruce budworm, A. fumiferanae and Apechthis ontario (Cress.), discriminate between parasitized and non-parasitized hosts (Miller 1959; Ryan 1971). This behavior may result from the recognition of repellent trail odors left by searching females. Price (1972) noted further that in an effort to reduce their exposure to presearched areas, the females will try to disperse. This strategy avoids wasting eggs by discriminating against hosts already attacked by a parasitoid (Ullyett 1950; Burnett 1951; Wylie 1970; May 1978).

Rarely has the occurrence of two or more parasitoids of a solitary species developing in a single host been reported (Brown 1946a; 1946b). By dissecting spruce budworm larvae, McLeod (1977) found that multiple parasitism by A. fumiferanae and G. fumiferanae occurred less than one-third as often as expected by statistical chance.

Lewis (1960) and McLeod (1977) have studied the ovipositional behavior and interaction of A. fumiferanae and G. fumiferanae. A. fumiferanae more readily attacks freely-moving larvae, while G. fumiferanae prefers immobilized immatures in hibernacula. The ovipositor of G. fumiferanae is longer than that of A. fumiferanae and it is easier for the former to pierce hibernacula webbing and deposit eggs in the immature located inside.

The ability of a female to leave viable progeny depends on the compromise between remaining in a host population where exploitation by parasitoids is reaching saturation, and emigration into areas of unknown host resources. This emigration stage would be reached before the host resource is fully utilized because unparasitized hosts become harder to find, and the chances of progeny being hyperparasitized are greater. This demonstrates that density-dependent emigration caused by mutual interaction can be adaptive. Hosts can reach high population densities while interaction between parasitoid females is likely to become severe before this high density is reached (Price 1971). Therefore the capacity of the habitat to support a parasitoid complex may be dictated by the level of interaction between individual parasitoids rather than host supply. The result would be the inability of parasitoid populations to exploit fully hosts at high population levels. This could account for the decreased efficiency of A. fumiferanae at high host population densities.

Physical factors like humidity, temperature, and light may be partially responsible for the spatial distribution of parasitoids in the forest. For instance, reduced light intensities in cages have been shown to inhibit activity of A. ontario (Ryan and Medley 1972). Flight activity of G. fumiferanae is greatly reduced by rain (Miller 1960; Nyrop and Simmons 1982). Chalcids have one level of activity throughout the day, but braconids increase their activity during the day and ichneumonids are more active in the early morning and evening hours (Juillet 1970). The incidence of A. fumiferanae differs according to tree-crown depth, while parasitization by G. fumiferanae is randomly distributed in budworm larvae at all crown heights (Jaynes 1954; Miller 1958; Dodge 1961.

The effects of host density on parasitism are reflected in the differences in the abundance and diversity of parasitoids attacking epidemic and endemic populations of the spruce budworm (Miller and Renault 1976). Different species of parasitoids respond to changing host densities in different ways. McGugan and Blais (1959) have noted that the parasitoid complex associated with epidemic populations in one area is apt to resemble that in another area. When budworm populations are low, however, the species complex is less predictable (Hanson 1982). Some data suggest that parasitism may be relatively high during the endemic phase, although the species complex is considerably different from that found during an outbreak (Miller 1963; Fye 1963; Miller and Renault 1976).

Those parasitoids of the spruce budworm which have been studied most closely have subtle and complex behavioral characteristics which help explain their presence and abundance (McGugan 1955; McLeod 1977). Nyrop and Simmons (1982) observed that "each parasitoid must be considered individually, even those which attack the same host".

Silvicultural Practices Fostering Parasitoid Success

Should silvicultural planning for regulation of natural enemies take for granted the apparent cycle of epidemics, or rather cater to the possibility that an endemic spruce budworm population will be present during the majority of the stand life? Since the probability of a severe spruce budworm infestation occurring once in the rotation of spruce-fir forest is high (Blum 1984), forest management may be an economically viable means of reducing future budworm impact, though it

may never be a means of controlling budworm outbreaks (Flexner et al. 1983). Budworm and parasitoid populations respond to biological and meteorological factors that are often independent of stand condition.

Recently, Flexner et al. (1983) recommended the following for decreasing the vulnerability of forest stands to spruce budworm:

(1) Shorten the rotation age of fir to 50 years or less.
(2) Break up the continuity of extensive areas of mature forests.
(3) Remove fir from the stand.
(4) Maintain a mixed-species composition whenever feasible.
(5) Convert the stand to less susceptible species.
(6) On a regional basis, optimize the spatial diversity of different even-aged stands.

Most of the silvicultural procedures recommended to reduce the risk of budworm damage are appropriate to an intensive silvicultural program for optimum growth and yield (Blum 1984). How compatible are these recommendations with the creation of favorable habitats for natural enemies? What are the possible influences of changes in the forest environment on the parasitoids' searching behavior?

Few researchers have endeavored to quantify relationships of environmental variables influencing net parasitism (Simmons et al. 1975). Therefore, the effects of stand conditions on parasitoid dynamics that I will be discussing should be seen as possibilities only. Quantitative reports of these effects will only be possible when the results of silvicultural practices now being tried are available.

Shorten Rotation Age of Fir

Stand maturity is considered a major factor responsible for susceptibility of trees to spruce budworm attack (Greenbank 1963a). One of the probable conditions influencing the susceptibility of different ages of trees is the presence or absence of staminate flowers (Graham and Knight 1965). These flowers are most abundant on overmature dominant trees and those that are growing under unfavorable conditions. Also, maturity is accompanied by reduced growth and vigor of trees, and increasing crown exposure. As Mott (1963) points out, "The taller the stand and the more open and exposed the fir crowns, the greater the susceptibility, presumably because the microclimate of feeding sites is better and because females are attracted to taller trees and stands".

If the intensity of infestation and the effects of heavy budworm feeding vary with the age and vigor of the stand, what are the possible effects of these factors on parasitoid behavior?

Increased mortality caused by some parasitoids has been attributed in part to heavy production of balsam fir staminate flowers (Dowden et al. 1950). Budworm larvae feeding on pollen are parasitized more than larvae in vegetative buds. Small parasitoids may be able to reach hosts feeding within staminate flowers more easily than they can reach larvae enclosed in vegetative buds. In addition, parasitoids could improve efficiency by limiting their search area to the staminate flower microhabitat.

Blais (1952) has shown that staminate flowers promote larval development. Shortening of the larval period increases chances for survival by decreasing the length of exposure to natural enemies like parasitoids and predators (Greenbank 1963b).

Variability in phenology of spruce budworm and/or host trees can be caused by moderations in microclimate due to stand density or crown closure. Differences between stands in regard to spruce budworm developmental time and tree phenology have been reported by Hanson (1982). Bud burst of immature balsam fir trees was generally earlier than in pole-sized or mature trees. The larger, expanding buds of the young trees exhibited few signs of spruce budworm infestation. Perhaps early or rapid development of these buds caused the larvae to move directly to new needles instead of boring into developing buds. Young larvae on immature trees which are devoid of flower bracts are also known to wander more extensively in search of food (Greenbank 1963b). Bud development in trees in pole-sized and mature stands was slower and webbing at the base of the buds or entrance holes directly into the buds were apparent. Larvae were found most often in or near buds in the older age-class trees. In younger trees, the larvae were more widely distributed.

Although no significant differences in overall percent parasitism of spruce budworm collected from plots of sapling, pole-sized, or mature trees were found, there were variations in occurrences of certain parasitoids among plots and between stand types. For example, the budworm in the mature age-class plots had the lowest overall parasitism by G. fumiferanae, with 1.51% of the larvae in one plot and 0.56% of those in the other parasitized.

Shortening the rotation age of fir appears to reduce the number of more vulnerable mature and overmature stands. The effects on parasitoids vary. For example, staminate flowers of mature trees may provide a desirable

food source for budworm larvae and consequently readily locatable host material for parasitoids. On the other hand, rapid development of larvae which ingest pollen reduces the length of their availability to parasitoids. In some stands, the microclimate of the more exposed fir crowns favors budworm attack. Parasitoid response to moderations in microclimate depends on the species of parasitoid we are considering, the phenologic response of the tree, stand density, and other factors.

Break Continuity of Extensive Mature Forests and Optimize Spatial Diversity of Different Even-Aged Stands

Extended areas of balsam fir are susceptible to spruce budworm outbreaks (Graham and Knight 1965). When a balsam fir monoculture is coupled with high stand density, additional problems arise.

Survival of small larvae increases under these conditions because dispersal loss is relatively low in dense stands of preferred host trees (Morris and Mott 1963). Mott (1963) points out that survival of small larvae is a less important determinant of population trend than survival of large larvae and dispersal of adults. However, he concludes that mature fir stands that are open enough to provide lateral crown exposure (favorable for survival of large larvae) but not so open or so high in non-host content as to make small larval dispersal difficult provide optimum conditions for survival of both these age classes of spruce budworm.

The position or exposure to light of individual trees in a stand can make them unequally susceptible to attack by spruce budworm, and, as discussed earlier, can affect the spatial distribution of parasitoids. As stand density increases, vulnerability tends to increase, perhaps due to reduced vigor and poorly developed crown in dense stands. Simmons et al. (1975) reported that when tree density increases, regardless of species, parasitism rates decrease.

Parasitism increases as the diversity of tree species increases (Kemp and Simmons 1978). Simmons et al. (1975) remarked that parasitizing other insects is only one of several preoccupations of the adult parasitoid. Needs for food, water, and shelter must also be met. It is frequently the case that unbroken balsam fir forests do not help in satisfying these requirement because of lack of diversity of habitat.

Flexner et al. (1983) speculate that "attaining a regulated, sustained-yield forest with equal areas represented by the various age classes should reduce the overall level of forest damage". Providing a variety of age classes of trees enhances the availability of diverse habitat for parasitoids. Some species of parasitoids are conspicuously more frequent in one age class stand than another. Others occur irregularly in budworm throughout a stand of a uniform age. Still others show no differences in their appearance, regardless of the age of the trees. Breaking up the continuity of extensive areas of mature forest creates openings which reduce the possibility that dispersing small larvae will land in suitable sites (Mott 1963) and provide favorable and diverse habitats for natural enemies of the spruce budworm (Flexner et al. 1983).

Remove Fir from the Stand and Convert to Less Susceptible Species

The spruce budworm feeds primarily on balsam fir and white spruce, but will also attack red and black spruce (Picea rubens Sarg. and P. mariana (Mill.)), eastern hemlock Tsuga canadensis (L.) Carr., larch Larix laricina (Du Roi) Koch, and white pine Pinus strobus L. Where mortality to balsam fir has been complete or nearly complete, white spruce trees in the same stands have generally survived the budworm outbreak (Greenbank 1963c). Spruce budworm infestations in pure stands of white spruce have sometimes persisted for long periods without spreading or gaining momentum (Morris 1958). The phenologies and foliage qualities of the three species of spruce make them more resistant to the budworm (Greenbank 1963c).

Female spruce budworm moths show a strong ovipositional preference for undefoliated hosts (Greenbank 1963c). They prefer to oviposit on relatively new needles and on shoots with closely-spaced needles. As defoliation progresses, these preferred sites become increasingly scarce on balsam fir. Loss through dispersal of adults and small larvae increases as the balsam fir dies and the budworms seek new needles.

Emergence of overwintered spruce budworm and bud burst of balsam fir are closely synchronized. Peak emergence of spruce budworm precedes bud burst by only a few days. Later opening of buds on the spruces, most notably the black spruce, results in a certain amount of immunity to budworm damage (Blais 1957).

Budworm larvae are known to feed on old foliage and buds of the red and black spruce during the lag between their emergence and bud burst (Greenbank 1963c). Old foliage and unopened buds do not provide nutrients for satisfactory development of the larvae. Thus, an increased spruce component in the stand may increase the period of host availability to the parasitoids.

Because white spruce shoots grow significantly larger than balsam fir shoots and provide more food per unit of population, they

suffer less damage than balsam fir (Greenbank 1963c). Fye (1963) reported that spruce budworm prefer white spruce during periods of endemism and suggested that these trees may be major food reservoirs at this time. This low-density residual pest population provides a food source for a low-density residual parasitoid population which can rapidly expand its sphere of influence in the event of a pest population increase. Also, larger populations of predators are believed to inhabit white spruce trees than balsam fir trees and these may appreciably reduce the populations of eggs and small larvae (Fye 1965).

Maintain Mixed-Species Composition

As the proportion of non-host tree species in the stand increases, the vulnerability of spruce and fir to spruce budworm tends to decrease. Stands with balsam fir comprising at least 50 percent of the basal area are among the most vulnerable to the budworm (Flexner et al. 1983).

With the exception of A. fumiferanae, G. fumiferanae, Phaogenes hariolus (Cress.), and possibly Horogenes cacoeciae (Vier.), all spruce budworm parasitoids are suspected or known to require an alternate host to complete development (Miller 1963). If a second generation parasitoid requires a different host, the size of the parasitoid population is partly regulated by the least abundant host (Graham and Knight 1965). For a parasitoid requiring an alternate host to be abundant during an outbreak, the alternate host must also be populous (Blais 1965). Alternate host populations limit parasitoid effectiveness and partially account for the variation in parasitism noted in different spruce budworm outbreaks (Miller 1963). A collapsed spruce budworm population can act as the high limit on the parasitoid's potential.

Some parasitoids have the ability to feed on more than one host (i.e., they exploit alternative hosts). This capacity is beneficial during the collapse period, when the parasitoid can turn to other hosts and not suffer from food shortage.

Several parasitoids reared from endemic populations have also been reared from other members of the spruce-fir defoliator complex, indicating that these hosts may serve as reservoirs for spruce budworm parasitoids (Fye 1963). McGugan and Blais (1959) found that the parasitoid Sarcophaga aldrichi Parker, which is a dominant parasitoid of the forest test caterpillar Malacosoma disstria Hbn. in Ontario, was able to respond to fluctuations in tent caterpillar and spruce budworm populations by alternating between the two.

Nectar or pollen sources are frequently required to sustain adult parasitoids (Coppel and Mertins 1977). I. conquisitor is a more effective parasitoid of spruce budworm in mixed stands with lower densities of spruce and fir than in pure stands of either spruce or fir. This is attributed to a greater variety of alternate hosts and flowering vegetation which the less dense forest provides. The proximity of these food sources to suitable host insects increases the chances of parasitism by retaining the parasitoids in the stand (Simmons et al. 1975). Nyrop and Simmons (1982) found that adult G. fumiferanae feed in the forest canopy. Forest composition had no influence on this parasitoid's ability to secure food however, and there were no differences in longevity in G. fumiferana from stands that were exclusively balsam fir and those from stands that were a mixture of balsam fir and other coniferous and deciduous trees.

In periods between outbreaks, the spruce budworm appears to be extremely scarce (Greenbank 1963a). Maintenance of mixed-species composition provides, in some cases, a better habitat for a residual parasitoid population that will exhibit positive rapid density responsiveness to budworm population increases.

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APPROPRIATE SILVICULTURE

Barton M. Blum

Principal Silviculturist
NEFES, USFS
Orono, ME 04469

Silvicultural options suitable for reducing the vulnerability of spruce-fir forests to spruce budworm damage are discussed. The concepts of susceptibility and vulnerability are outlined, and a comprehensive list of selected references for further study is presented.

The subject of my talk is supposed to be appropriate silviculture. Webster defines the adjective "appropriate" as suitable, fit, or proper. Webster also defines the verb appropriate as meaning "to steal". Since most of what I have to say is far from original with me, perhaps both definitions are apropos.

The adjective appropriate, of course, has to be qualified by the questions "for what" and/or "for whom". The previous three speakers have discussed at some length the effects of forest stand conditions as factors influencing the mortality rate of spruce budworm in its various life stages. The enhancement of these factors by the manipulation of stand conditions is silviculture designed to reduce the susceptibility of forest stands to attack, and is also related to those forest attributes that support a given population level. Silviculture designed to reduce the vulnerability of forest stands calls for manipulating stand attributes or characteristics that determine the loss of tree growth and mortality that will result from attack at a given level. The concepts are interrelated insofar as susceptibility determines the severity of attack and hence the potential damage.

Silviculture designed to enhance mortality factors of budworm may or may not be compatible with that designed to reduce the probability of damage, and it is probable that neither is totally compatible with silvicultural techniques designed to optimize the production of wood products. In practice, there will be compromises influenced by the perceived or documented efficacy of the proposed silvicultural treatments, their compatibility with one another, and the ultimate objective of the land manager for a given forest stand.

In this paper I discuss silvicultural tactics designed to reduce vulnerability on a stand by stand basis rather than large scale regional strategies that might be put into play. Emphasis is on producing wood products while minimizing growth loss and mortality due to spruce budworm. A word of caution: changing the forest through silviculture will not control the insect because factors such as climate, the dynamics of the natural enemy complexes and the mobility of the insect itself also affect budworm survival.

Long-Term Silvicultural Tactics

The Eastern Spruce Budworm Research Work Conference held in Orono, Maine, this winter, included a workshop on silviculture and the spruce budworm. Invited speakers were foresters active in silvicultural pursuits for a number of large land managing companies. Many of the questions they were asked to address pertained to their "gut" feeling about silviculture as a tool to alleviate budworm damage in both the long and short term. Silvicultural practices they were involved in ranged from site preparation and planting to precommercial and commercial thinnings, and partial harvests, shelterwood harvests, and clearcut harvests. Nearly all were pessimistic about the value of intensive silviculture as a tool to alleviate the impact of budworm. For the most part, however, their experience with intensive silvicultural techniques was short term, not always perceived as part of an overall "package" of integrated pest management that includes direct control, and initiated in the teeth of a raging epidemic.

One gets the impression that researchers in budworm silviculture are optimistic about its efficacy, while foresters on the ground are the pessimists. Part of the problem is that most espoused silvicultural goals are based on working hypotheses, not proven concepts. Our experience in shaping stands and forests toward derived goals over the long term, perhaps a rotation, has been limited if not nonexistent. As a result, the expected reduction in vulnerability cannot be quantified precisely. The state of our knowledge about the dynamic interaction between the budworm and the forest is such that we can make only qualitative statements. However, it makes sense to proceed at the qualitative level using the logic of the vulnerability relationship.

Despite the previous statement, most silvicultural tactics have been proposed from efforts to relate budworm-caused tree mortality to stand characteristics both in

a qualitative and quantitative manner. In recent reviews of the many attempts to correlate vulnerability with stand characteristics, MacLean (1980, 1982) concluded that only one general association appeared to be consistent--mature or overmature stands with a high proportion of balsam fir tend to be the most vulnerable.

Both mortality and growth loss are functions of the timing and intensity of defoliation. However, predicting mortality and growth loss from stand characteristics is not a precise science. This is understandable because budworm populations respond to biological and meteorological factors that are often independent of stand condition. The intensity, duration, and protection history of budworm outbreaks are important factors.

Where extremely high populations are present, silvicultural techniques will only partially alleviate the total impact of the infestation, mainly by altering the timing and pattern of mortality and growth loss.

Although stand characteristics other than age and the proportion of balsam fir are not closely related to damage from spruce budworm, they have exhibited local importance. Factors such as stand structure, density, crown exposure, tree vigor, and the proportion of nonhost species have shown a relationship in specific instances.

With all of these caveats, one must proceed on a combination of faith and logic, a dollop of scientific evidence and conclusions drawn from experience. In our favor is the fact that most of the silvicultural procedures recommended to reduce the risk of budworm damage are the same recommendations in an intensive silvicultural program for optimum growth and yield, the possible exception being stand conversion to a nonhost species.

At the root of all silvicultural recommendations are the well-known differences in vulnerability among the various host species. Balsam fir is the species most vulnerable. Mortality of fir usually begins 5 to 7 years after the onset of a severe attack, and mortality in mature or overmature stands can reach 100 percent. Mortality in immature stands and in spruce stands is more variable, but can be as high as 70 percent. Figure 1 shows average levels of tree mortality of fir and spruce in mature stands (more than 50 to 60 years old) and immature stands. Figure 2 shows examples of actual mortality patterns over time.

White spruce usually is considered the second most vulnerable species. White spruce can support populations of budworm as high as those supported by balsam fir, but they sustain less damage because they produce more and larger shoots, thus supplying more food for feeding larvae.

Red spruce and black spruce in that order are the next most vulnerable species. Their relative resistance is due mainly to late opening buds--on the average, red and black spruce open 13 days after balsam fir and 9 days after white spruce. Black spruce foliage is also less hospitable to budworm as a source of food.

In some situations, the budworm will feed on eastern hemlock, eastern larch, and eastern white pine. Hemlock is particularly susceptible to damage, and there have been instances of topkill and mortality. Hemlock foliage also supports a sizeable number of spruce budworm egg masses.

Most studies have shown that stand vulnerability increases with increasing amounts of mature or overmature fir. Additional trends evident in various studies indicate that:

1. Vulnerability of spruce and fir decreases as the proportion of nonhost species in the stand increases. If spruce and fir are in a subordinate crown position, this trend apparently is enhanced. It is especially apparent in stands of understory or intermediate spruce and fir overtopped by aspen such as is found in the Lake States and occasionally in northern New England; a spruce-fir understory in a pioneer hardwood stand; or individual spruce or fir trees overtopped by paper or yellow birch.

2. Fast-growing, full-crown trees that reflect good site quality and growing conditions are less vulnerable to damage than trees under stress.

3. Vulnerability tends to increase as stand density increases. This higher vulnerability may be related to a lack of vigor and/or poorly developed crowns in dense stands, or to differences in larval dispersal dynamics. However, in a few recent instances where density has been reduced in spacing operations, budworm damage has been severe.

4. Individual spruce-fir trees in a subordinate crown position relative to other host trees are more vulnerable to damage primarily due to downward larval dispersal and their poorer vigor relative to overstory trees.

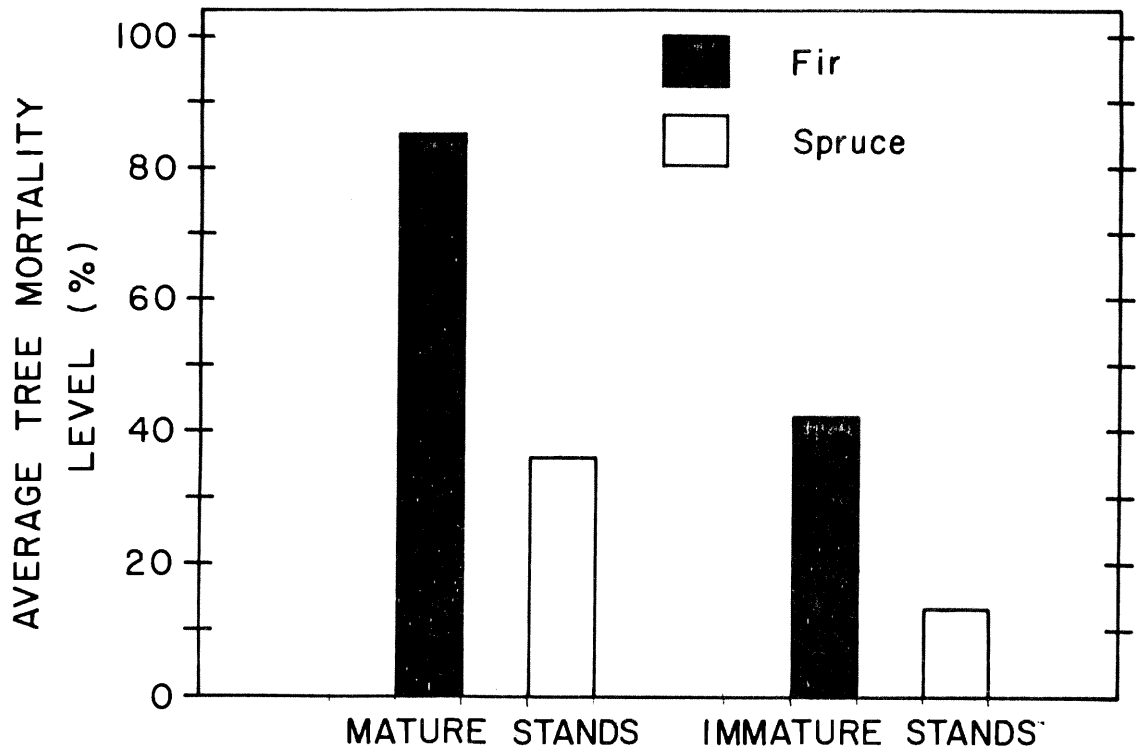

Figure 1.--Average levels of mortality of balsam fir and spruce in mature and immature stands (From MacLean 1980).

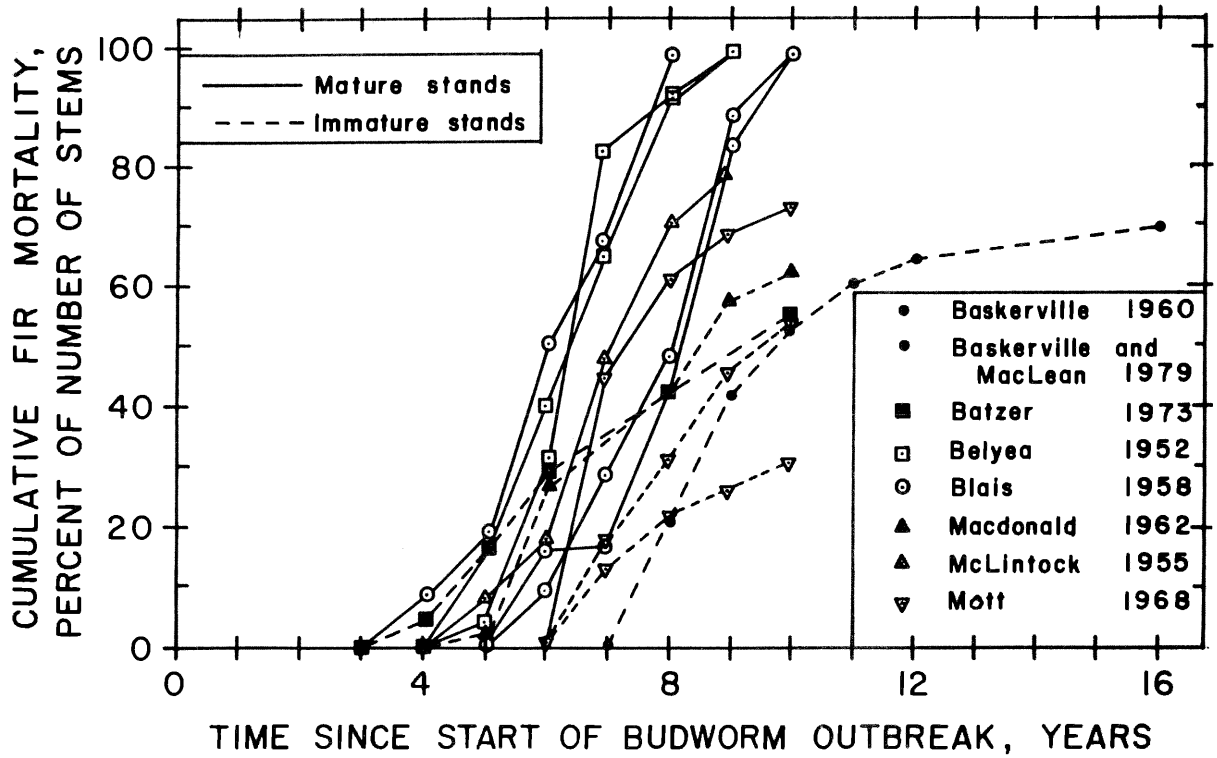

Figure 2.--Cumulative fir mortality in relation to time during various spruce budworm outbreaks (MacLean 1980).

Silvicultural Goals

These relationships between stand characteristics and vulnerability to budworm damage, while quite general in nature, suggest the following silvicultural goals: 1) maintaining a vigorous stand with rapid growth rates, 2) increasing the spruce and/or nonhost component in the stand, and 3) reducing the fir component in the stand at an early age. Achieving these goals should provide a general reduction in stand vulnerability, particularly for future infestations.

In the absence of budworm damage, the end result of such stand manipulation is the production of high-value wood products and the maintenance of a vigorous forest cover. But we know that there is a high probability of a severe infestation occurring at least once in the rotation of a spruce-fir forest regardless of an intensive silvicultural program, and it is natural to ask what additional benefits might be derived from reducing vulnerability.

Well-managed stands should respond better to protection efforts as they usually are well spaced and vigorous. Species compositions should be favorable. Having a sizeable proportion of land in a relatively invulnerable condition should allow more time between direct control efforts, should decrease the need for direct control in the early stages of an infestation, and should allow more time for shifting salvage operations to the most vulnerable stands as mortality commences. Also, the glut of salvaged wood that occurs at the height of an infestation should be reduced somewhat.

Silvicultural Treatments To Meet These Goals

How can managers reduce vulnerability? From a regional standpoint the magnitude of the undertaking is overwhelming. Nevertheless, silvicultural treatment of selected stands is a viable and important weapon in the integrated pest management arsenal. Given both sufficient time and intensity of treatment before a severe infestation, managers can achieve significant reduction in vulnerability, and any silvicultural treatment of forest stands should be considered in light of its long-term effects on vulnerability to the budworm.

When evaluating intensive silvicultural options a number of factors must be considered. Site productivity, accessibility, and present stand condition probably are the most important factors common throughout the range of spruce budworm. Differences in marketing, economics, and social factors throughout the budworm range also should be considered. Obviously, the availability of information sources such as inventory data, type maps, and data on site productivity are important aids for identifying stands worthy of intensive silvicultural input. The greatest opportunity for manipulating species composition of existing stands is a high-quality, accessible site. Fully mature or overmature stands with a good proportion of spruce or nonhost species probably require the least investment because of marketable products removed, but sapling and pole stands offer the best opportunity because of a greater number of stems to choose from, generally greater vigor, and somewhat greater resistance to windthrow.

Because of the relative tolerance to shade of the spruces and balsam fir, both uneven-age and even-age management is appropriate, depending on the circumstances (Table 1). However, even-age management is the most common practice in use today throughout the range of spruce and fir.

Table 1.--Summary of even-age and uneven-age forest management systems to reduce vulernability to spruce budworm damage

Even-Aged Management Systems	
	Clearcut harvesting in blocks or patches
	Clearcut harvesting in strips
	Shelterwood harvesting
Components of system	
	Species conversion--natural conversion to less vulnerable species or site preparation and planting to nonhost or low-vulnerability species.
	Thinning and partial cutting--heavy discrimination against fir where possible to encourage increases in spruce content.
Uneven-Aged Management Systems	
	Individual tree selection harvesting
	Group selection harvesting

Even-age silvicultural systems.--Clearcut harvesting in blocks, patches, or strips is recommended for mature, overmature, or insect- and disease-ridden stands where partial harvesting could result in mortality or damage to residual trees. Clearcutting is an efficient system of harvesting, especially with highly mechanized equipment.

Natural regeneration often can be used to restock a clearcut area. However, success is critically dependent on the presence of advance regeneration. Biologically, a clearcut harvest with advance regeneration present is a shelterwood, but there is no attempt to manipulate the size or species composition of the regeneration by means of preparatory harvests as there usually is in the case of the shelterwood system of silviculture. In smaller clearcut blocks, patches, or narrow strips, where adequate advance regeneration is absent, seed dispersal from adjacent stands may suffice, but in many cases will require site preparation and planting. Residual overstory trees of spruce budworm host species must be removed to prevent budworm larvae from dispersing downward to the new regeneration.

In many areas, clearcut harvesting encourages undesirable vegetation such as hardwoods and raspberries that may inhibit growth and development of softwood regeneration. Herbicide treatment of these areas will be necessary if normal growth and development is expected.

Clearcut harvesting in narrow strips or small patches often is termed strip or patch shelterwood. As mentioned previously, it is used where regeneration is lacking, but it also is a valuable technique when excessive losses of regeneration to exposure or mechanical damage are anticipated. Both methods leave nearby border trees that provide a seed source for regeneration and partial shade. However, these same border trees are a potential source of spruce budworm larvae that may disperse to young seedlings. Harvesting in strips or patches increases the species diversity of plants and may encourage natural enemies of the spruce budworm.

The shelterwood system is applicable to spruce-fir stands that lack adequate advance regeneration. It is especially suitable for stands on good sites where vigorous growth can be expected, windthrow potential is minimal, and there are no insect or disease problems of immediate concern. With the shelterwood system, the overstory is removed gradually in two or three stages, thus stimulating seed production and providing light and moisture conditions conducive to seedling development. Gradually opening the stand may improve windfirmness, and the partial shade will reduce the development of herbaceous growth such as raspberries.

The shelterwood system allows good control over species composition of the developing regeneration so long as desired species are represented in sufficient numbers in the overstory. An additional benefit of the system is the good growing conditions provided the residual overstory, which should be high quality, vigorous trees. However, if high populations of spruce budworm are present in the overstory, direct suppression of the insect will be required to ensure seed production and to protect developing regeneration.

Stand conversion.--The economic and biological ramifications of stand conversion and the creation of monocultures are many and vary considerably across the range of the spruce budworm. Throughout most of the spruce-fir region there have been numerous recent advances in site preparation, planting techniques, improved planting stock, and techniques for controlling competing vegetation. Although relatively expensive, planting to a nonhost or relatively invulnerable host on the best sites certainly will decrease vulnerability and susceptibility to spruce budworm and improve long-term yield potential. Of the host species, black spruce is the most promising.

Uneven-age silvicultural systems.--The individual tree and group selection systems of silviculture have been recommended for reducing vulnerability to spruce budworm damage. Repeated light harvests create stand openings that favor the establishment of regeneration. Because these harvests take place in all merchantable size classes, they can be an effective tool in altering species composition. The main disadvantage of the selection system is that a continuous, open canopy consisting of mature or nearly mature trees that are both relatively vulnerable and susceptible to spruce budworm is maintained. Once infested, the overstory serves as a reservoir of larvae that disperse downward, exposing trees in smaller size classes to damage. The selection system also is more complicated than most even-age systems because of the mixture of age and size classes and the need to maintain this mixture at specified levels. Harvesting must cover a larger area to meet a given allowable cut, damage to residual trees is a greater risk, marking trees in advance usually is

necessary, and detailed record keeping is desirable. However, the selection system is the only way that owners of small properties can get a consistant return over time; in some areas such as streamsides and roadsides where esthetics are important, the selection system is the only viable alternative.

Thinning or partial cutting.--If the regeneration process has resulted in maintaining or increasing spruce (particularly red and black spruce) or nonhost species, the key to reducing vulnerability is a program of frequent, relatively light partial harvests or thinnings. This will allow the alteration of species composition to the detriment of fir. A precommercial thinning when the stand reaches the sapling or small pole stage can cause a dramatic change in the species composition of the residual stand. Even a small proportion of well-distributed spruce may be sufficient in absolute numbers to generate acceptable stocking if it can be freed from the fir competition.

Besides removing fir, the primary goals of partial harvests should be to: 1) provide adequate growing space for individual trees, 2) remove trees that may not survive to the next harvest, and 3) avoid creating large holes or openings in the canopy that may decrease windfirmness. Removing trees in a subordinate crown position should be the first priority, followed by improving spacing in the main canopy.

The potential for wind damage after a partial harvest varies considerably according to site and soil characteristics, the amount of overstory removed, and the past management of the stand. Harvests should be relatively light (perhaps no more than one-third of the basal area removed). If past management has kept the stand vigorous, well spaced, and fast growing, improvement in windfirmness should follow. The windthrow history of an area, if available, might provide a clue to future potential. It is possible that budworm defoliation and subsequent rootlet mortality may be a factor increasing the risk of wind damage. Of course, the possibility of an overpowering storm, regardless of stand condition, is always present.

This has been a very brief discussion of silvicultural possibilities to alleviate budworm damage. Details of each recommendation can be found in the references listed. Much is still "art" rather than science. As we are better able to quantify the reduction of vulnerability, it is hoped that we will be able to recommend specific actions, at specific levels, at specific times and for specific forests and budworm conditions, that will render future budworm outbreaks less potent by specific amounts.

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TREE IMPROVEMENT POLICY GUIDELINES FOR ONTARIO WITH SPECIAL EMPHASIS ON WHITE AND BLACK SPRUCE

R. Marie Rauter,

Forest Resources Group, Ministry of Natural Resources, Toronto, Ontario, CANADA, M7A 1W3

Currently under review is the Ministry of Natural Resources' first comprehensive document on the Policies and Strategies of Tree Improvement for the Province of Ontario. It describes the rationale for needing tree improvement, the history of the research and management programs, some basic principles, species priorities for improvement, recommended approaches for the various species, organizational responsibilities, and an example of economic costs and anticipated returns. The document is intended to serve many purposes. It outlines the various tree improvement work that is required to supply the artificial regeneration program with sufficient seed and planting material, it provides guidelines and direction to the field specialists who will be writing the tree improvement management plans, and most important it provides senior managers with sufficient information to enable them to determine the level at which they are willing to support and fund the program.

This paper will summarize parts of the document with special emphasis on white and black spruce as well as provide some background information on the Province of Ontario.

Introduction

Ontario is a forested Province. The total land area is 96.9 million hectares (374,000 square miles). Productive forest area is 42.5 million hectares (164,000 square miles) or 42 per cent of the total and commercial forest area is 33.5 million hectares (129,430 square miles) or 35 per cent of the total. The Crown (government) owns 88 percent of the land and the private sector 12 percent. However, the northern portion is very different from the southern. Ninety-two percent (28.7 million ha) of the north is Crown land compared to only 27 percent (642,000 ha) in the south. The north is composed of extensive continuous forests in the Boreal Forest Region; whereas the south, in the Great Lakes - St. Lawrence and Deciduous Forest Regions, is heavily populated, highly industrialized and the rural areas primarily farmland interspersed with small woodlots. In 1981-82, 17.5 million cubic metres (4.03 million cords) were cut, of which 14.6 million(4.03 million cords) were softwoods; but by the year 2020, the annual cut is expected to be 25 million cubic metres (6.90 million cords). Economically, forestry is the prime industry in the Province and employs approximately eight and a half per cent of the working population.

The Government of Ontario has made a commitment to maintain the productivity of the province's forests by regenerating the cut and burned productive forest areas. This commitment complements one of the purposes of the Forest Management Agreements. With the advent of these agreements, started some five years ago between the Ministry and forest industry, the areas being regenerated have increased at a dramatic rate and the number of seeds and the number of trees required annually have risen and will continue to rise exponentially until the 1990s. If the production targets are to be met and the predicted wood shortages minimized, more support is needed, not only for silvicultural managment, but also for all aspects of the tree improvement program. This latter need has been recognized by both the Ministry of Natural Resources and by several forest companies, who recently joined together to establish the Ontario Tree Improvement Council.

Given the size of Ontario's artificial regeneration program and the investment in stock production, site preparation, and planting, it is advantageous to use only genetically improved material. To obtain the greatest possible return from the money invested, tree improvement must be integrated with silvicultural management. In well-managed stands grown from seed produced in a tested and rogued first-generation seed orchard, volume gains of 10 to 15 percent are easily attainable. Substantial and impressive volume gains can also be obtained from accurate site selection and good stand management, but once obtained, these gains cannot be increased; whereas continual gains are possible through progressive breeding, testing, and selection for advanced-generation orchards. To maximize any return on tree improvement and silviculture; time, money, and manpower should first be concentrated on the best sites.

Several economic analyses, including one later in this paper, have shown that major tree improvement programs can be justified by increases in volume growth as low as 3 or 4 percent. The projected gains for the proposed strategies in this paper far exceed three percent. Moreover, through planning and through the use of new technology, the time from initial investment to the initial return on investment can be shortened. For example,genetic gain can be captured more rapidly and efficiently for those species that can be propagated through the rooting of cuttings rather than by using conventional production seed orchards. Breeding halls can reduce the time from the establishment of an orchard to the onset of flowering, thereby significantly reducing the time needed to establish progeny trials and to obtain parent donor material for the cutting programs.

In order to improve the quality of wood and to increase the yield through tree improvement, it is important to have both short-range and long-range goals. In the short term, some genetic gain can be obtained relatively quickly and economically. Such gains are significant when there is a large artificial regeneration program. But to get the maximum benefit from genetics, there must be a continuing program with long-range goals. To reach these goals, much planning and forethought are necessary, especially since the plant material initially selected for the program will constitute the foundation for future generations of trees.

Tree improvement within any organization is a continuous, long-term venture that requires continuity of support, funding and staffing. Goals must be decided at the outset, the necessary funds committed, and the program started as rapidly as possible. Delays in getting started mean delays in reaping the benefits as well as a depletion of the gene pool with which to work.

History and Current Status of Tree Improvement in Ontario

Research on tree improvement by the provincial government was pioneered by the then Department of Lands and Forests in 1946 with Dr. Carl Heimburger. The early studies dealt with aspen, white pine, and hard pines; spruce studies were started in the mid-1960s with Dr. Don Fowler. The spruce work at first concentrated on interspecific hybridization, but in the early 1970s there was a shift towards intraspecific hybridization to evaluate the plus-tree selections. Through these years there was also much experimental work on the rooting of the spruces.

During the late 1970s and into the 1980s, the work expanded to include physiological and quantitative genetics and shifted away from the conventional "tree breeding". Various projects examined the genetics of frost resistance and drought tolerance, identified and evaluated genetic variation through isoenzyme analysis, studied methods of flower induction, and determined the most effective and efficient mating and test designs.

Operational tree improvement started about ten years after the research. During the late 1950s modest programs for the selection of plus-trees were started for several species including white and black spruce. Scions were collected and grafted for the establishment of clonal production orchards. Unfortunately, the success rate of much of the early grafting was very low. In addition poor site selection and inadequate management of the first seed orchards led to high mortality in the outplanted stock. Not until the mid-to late 1970s was a concerted effort made to improve the results. The slow development of the grafted orchard program was one of the reasons for switching to seedling seed orchards for the first generation of black spruce work.

Since 1980, there have been some important changes in emphasis. These have included specific strategies for each of our important species, a major thrust in establishing all production and

breeding orchards within a few years, publishing of operational guidelines for all aspects of the tree improvement program, and intensive training for field staff culminating in the tree improvement policy document.

Species Priorities

The choice of species for a tree improvement program is based on a number of factors. The primary one is the commercial importance of a species as this determines the size of the areas harvested, and in turn plays a major role in the size of the artificial regeneration program needed. Two other important factors are the genetic variability of the species and the heritability of the characteristics for which improvement is desired.

The priorities differ from one portion of the Province to another. The overall Provincial priorities, in order of importance, are black spruce, jack pine, white pine, white spruce and hybrid poplar. Lower on the priority list, but still significant enough to merit intensive tree improvement strategies, are tamarack, black walnut, European x Japanese larch, Norway spruce and blister rust-resistant hybrid white pines.

Other hardwoods such as the aspens, maples and yellow birch are not considered priority species for improvement as regeneration is primarily by natural means. For this reason, the emphasis should be on good stand management to ensure high quality regeneration, optimal stocking, and the maintenance of a satisfactory gene pool. Only small quantities of this group of species are planted and survival in many of the plantations is very poor. Until good silvicultural management can be practised and until the planting program warrants, tree improvement cannot be economically justified.

Although red pine still plays a large role in Ontario's artificial regeneration program, there is no strategy proposed because the amount of genetic variation is minimal. Any attempt to improve the species would not be cost-effective.

Over the past thirty years there has been a significant shift in the demand for white and black spruce. Figure 1 shows the change in numbers of seedlings grown over time for these two species. Figure 2 shows the percent change for the same time period. There are several reasons for the decreased interest in planting white spruce, not the least of which is the occurrence of spruce budworm and the damage caused by this insect. Two other common problems associated with white spruce are damage from late spring frosts and retarded growth due to "planting check". The ease of raising black spruce, both as container and bare-root stock; in addition to high degrees of success in plantation establishment, especially since black spruce is a pioneer species, has led to large numbers being established throughout its commercial range. Conversely, white spruce normally grows in mixed-wood stands, is better known as a climax species and does not lend itself to being planted on large cut-overs as pure species plantations.

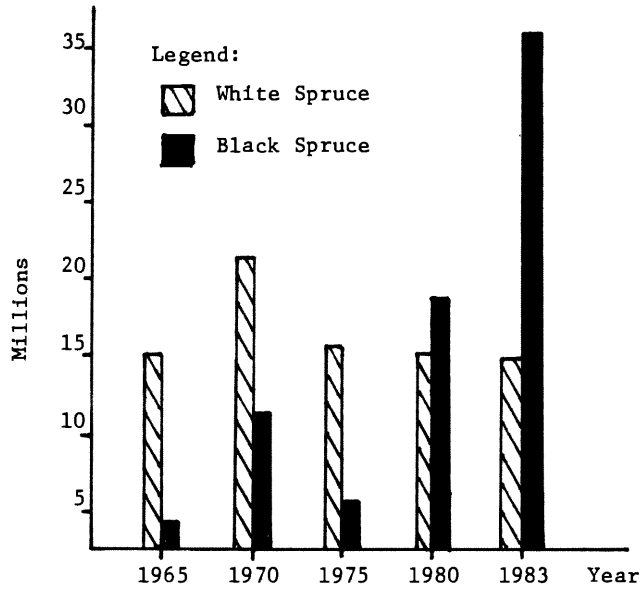

Figure 1: Numbers of black and white spruce trees planted through time.

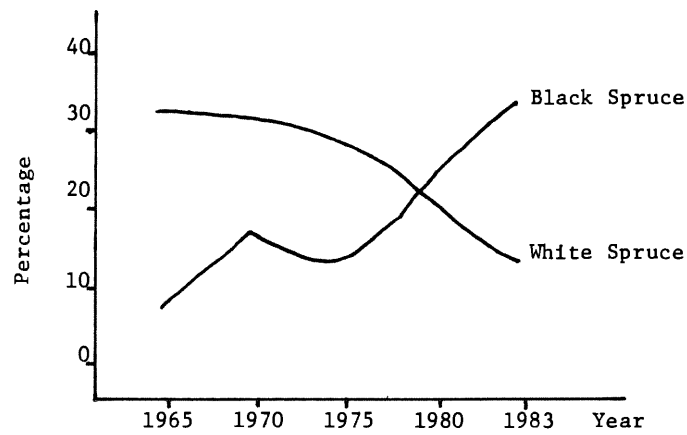

Figure 2: White and black spruce seedling production as a percentage of all seedlings produced.

Tree Improvement Strategies

Through the concerted efforts of quantitative forest geneticists throughout the world, more breeding options are available to the forest manager than ever before. These have been examined and three intensive breeding strategies have been developed for Ontario species. The strategies for

each species depend on a number of factors, including ease of reproduction, either sexually or asexually; ease of scion or seed collection for seed orchards; time from establishing an orchard to the onset of flowering; and ease of cutting production from either hedge orchards or serial propagation. A base program is also proposed for all species artificially regenerated. Only policy guidelines are outlined rather than operational details. The latter will be found in a series of publications that are either published, in press or in the draft stage.

Strategy I - The Base Program

This base program is the minimum work required for all native species that are regenerated artificially, including those that do not merit an intensive tree breeding strategy, either because there is not enough variation in the species or because the regeneration program is too small to justify the establishment of production seed orchards. It will also provide material to the regeneration program for the priority species until seed or cuttings are available from the more advanced breeding programs.

A summary of points in the Base Program follows:

1) Seed for all species will come from an identified source;
2) Enough seed (or rooted cuttings) will be available for each planting zone so that no material will have to be moved far from its place of origin;
3) Neither seeds nor seedlings will be moved from one planting zone to another without permission from the Administrative Region and the Main Office Tree Seed and Forest Genetics Unit.
4) Seed will not be collected from plantations unless its seed source is known. If the source is unknown, the plantation must be one-third rotation age before any seed is collected from it;
5) All seed-collection and seed-production areas will be in natural stands or plantations whose seed source is known. If the source is unknown, the plantation must be one-third rotation age before being designated as a collection or production area;
6) All gene pool reserves and seed-collection and seed-production areas will be regenerated with their own seed source.

Strategy II - The Seedling Seed Orchard

This approach is proposed for species that have characteristics such as poor success in grafting of scions from mature trees, difficulty in selecting phenotypically superior trees in natural stands, and a precocious flowering habit. Black spruce is amenable to this approach for the first generation of selection and improvement.

In the seedling seed orchard approach, superior trees are selected from natural stands in each seed zone. Open-pollinated seeds are collected from each tree, identified by family and germinated; the resultant seedlings are planted in a production seed orchard and at least two family test plantations. In addition to seed, a few scions are collected from each parent tree, grafted and placed in a clonal breeding orchard. Performance measurements such as height, diameter, and form are taken in the family tests and are used to eliminate the poor representatives in the production orchard, thus improving the quality of seed produced. Some trees from the family test may also be used to establish the second-generation orchard. As the breeding orchard matures and starts to flower, controlled pollinations are made according to a predetermined mating design. The progeny produced are planted in field trials. Although the trials are also used to evaluate the production orchard, their primary purpose is to provide the foundation stock for the second-generation orchards. Figure 3 outlines the steps in this program.

A summary of the points for this approach follows:

1) By the year 2000, all seed required for the production of bareroot and container stock will come from first-generation seed orchards;
2) The first-generation production orchards will be established with seedlings according to a predetermined layout;
3) A minimum of 450 selections will be made in order to obtain the 400 families required for the orchard;
4) A minimum of two family tests will be established to evaluate the material in each seedling seed orchard;
5) A breeding orchard will be established for all superior trees selected;
6) Selective breeding will be done after the first evaluation of the family tests according to a specific mating design;
7) A minimum of three progeny tests will be established for each pedigreed family according to a predetermined layout;
8) Selections from the family tests and the progeny tests will form the foundation for the second-generation orchards;
9) The clonal approach which uses rooted cuttings will be followed whenever economically and biologically feasible, especially in the early stages of seed production in the orchards in order to use the genetically improved seed more efficiently.

Strategy III - The Clonal Orchard Approach

This approach is proposed for species that characteristically occur in mixed-wood, uneven-aged stands necessitating a more expensive, time-consuming superior tree selection method, have good graft compatability, and a non-precocious flowering habit.

Superior trees are selected primarily from natural stands (occasionally from plantations if not enough natural selections are available)

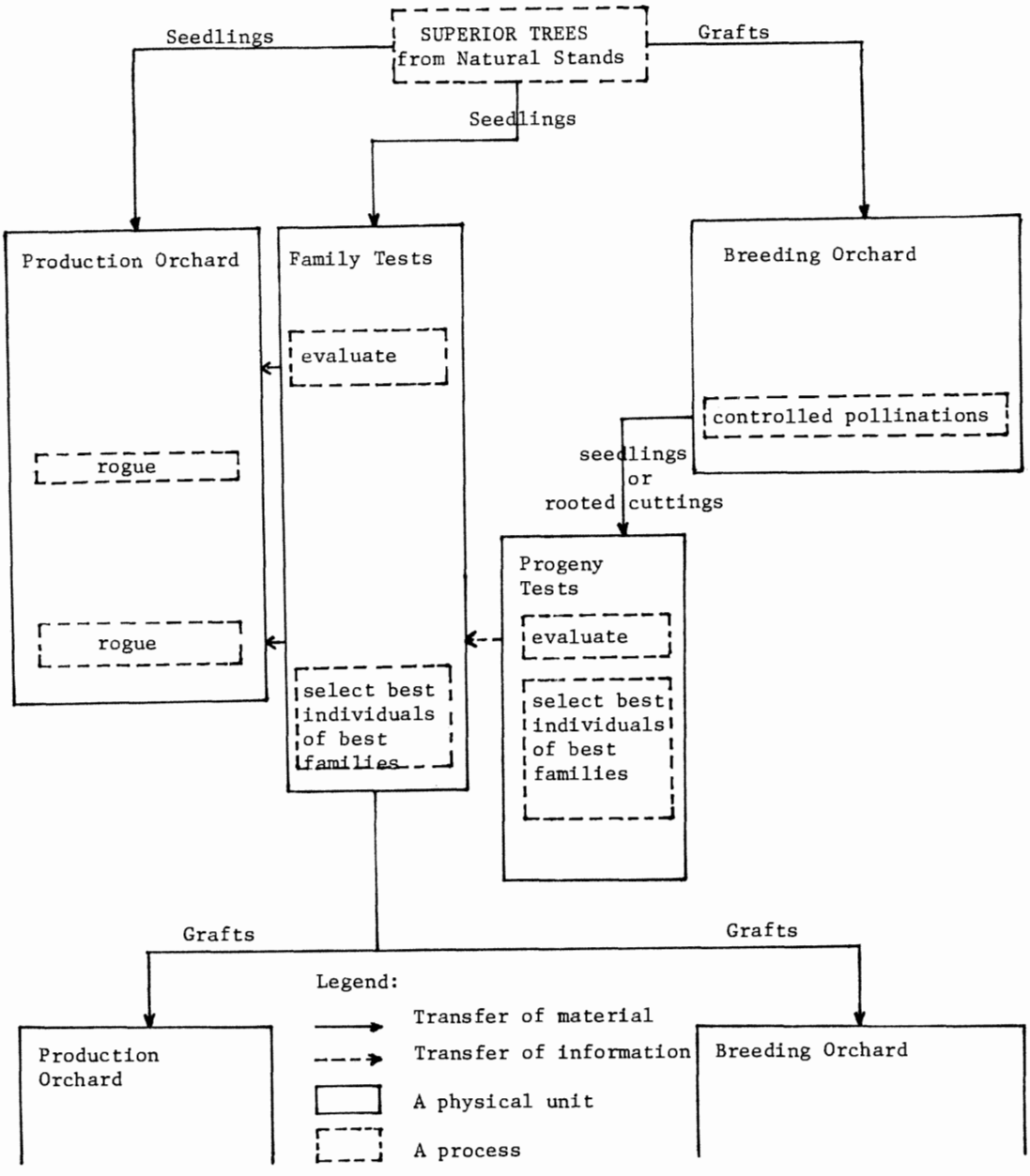

Figure 3: Strategy II - The Seedling Seed Orchard Approach.

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in each seed zone. Scions are collected from these trees, grafted and placed both in production orchards and breeding orchards. As the breeding orchard starts to flower, controlled pollinations are made according to a specific mating design. The trials are used first to evaluate the first-generation production orchard and then to provide foundation stock for the second-generation orchard. Figure 4 outlines the steps in this program.

A summary of the points for this approach follows:

1) By the year 2000, all seed required for the production of bareroot and container stock will come from first-generation seed orchards;
2) The first-generation production orchards will be established with grafts according to a predetermined layout;
3) A minimum of 240 selections will be made to obtain the 216 clones required for the orchard;
4) A breeding orchard will be established for all superior trees selected;
5) Breeding will start with the onset of flowering in the breeding orchard;

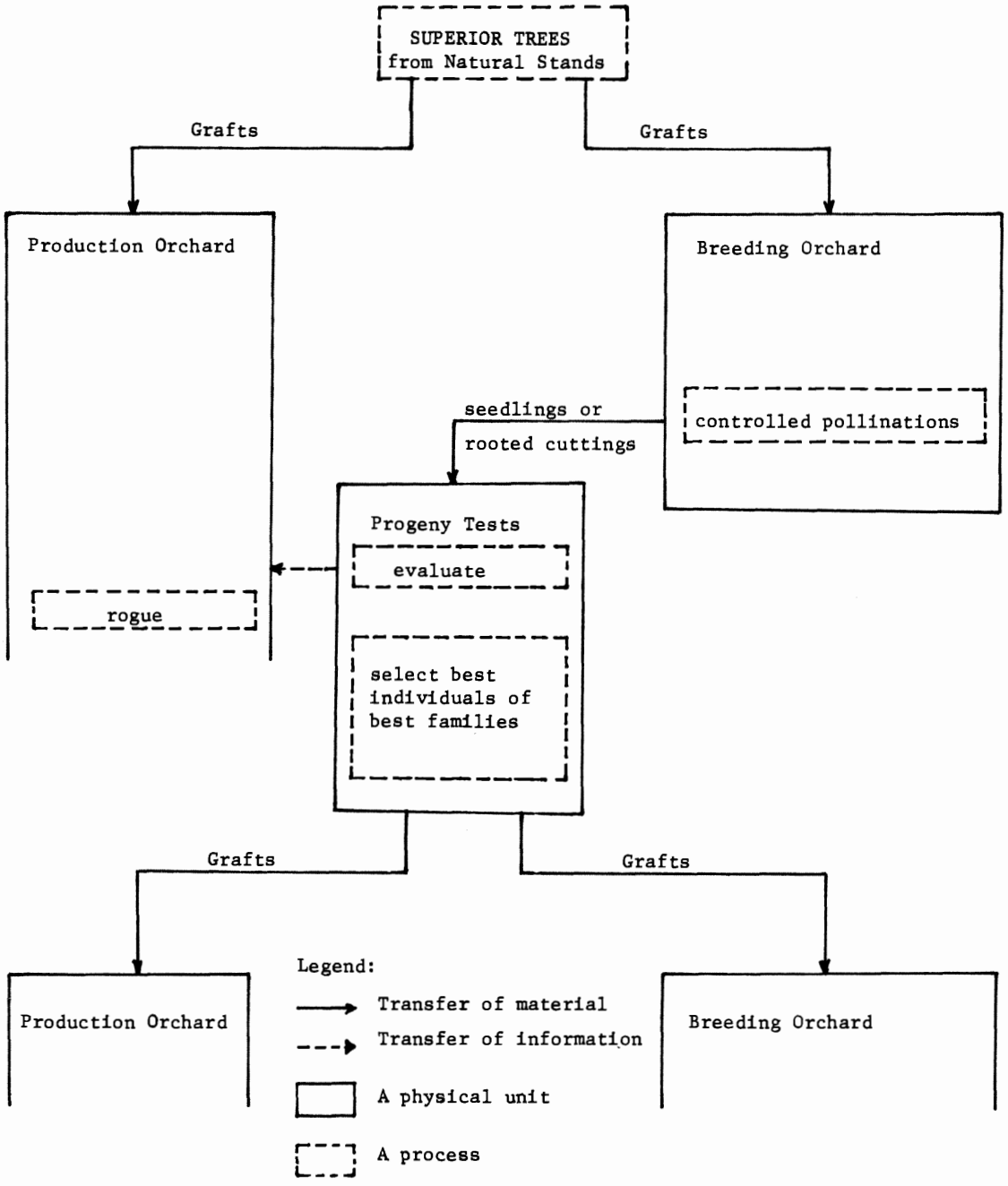

Figure 4: Strategy III - The Clonal Seed Orchard

6) A minimum of three progeny trials will be established for each set of pedigreed families according to a predetermined layout;
7) Information from the progeny trials will be the basis for roguing the production orchards;
8) Selections from the progeny trials will form the foundation stock for the second-generation orchards;
9) The clonal approach using rooted cuttings will be used whenever it is economically and biologically feasible, especially in the early stages of seed production in the orchards in order to use the genetically improved seed more efficiently.

Strategy IV - Clonal Forestry

This approach is proposed not only as a source of improved material through the first generation but also as a source of material for all subsequent generations. Clonal forestry is recommended for species that have several characteristics such as ease of rooting, difficulty in being reproduced by seed, insufficient quantities of seed required to fulfil the needs of an artificial regeneration program, too small an artificial regeneration target to merit a conventional production orchard program, or a need to produce specialty stock (eg. blister-rust resistant white pine hybrids).

In the clonal forestry approach for most species other than poplars, superior trees are selected from natural stands, plantations and local or external improvement programs. Scions are collected from these trees, grafted and placed in a breeding orchard. As the breeding orchard starts to flower, controlled pollinations are made according to a specific mating design. The resultant seeds are germinated and the juvenile seedlings are used as parent donor stock for the production of rooted cuttings. Some material is placed in field test plantations and the rest is used for production plantations. After several years of field testing, the best families are identified and their parents are used for selective breeding to produce donor stock for clonal production plantations. The best clones are also selected in these test plantations and put into hedge orchards and in the next-generation breeding orchard. The hedge orchard supplies donor material for production plantations; the breeding orchard is used to make additional crosses for future generation testing and selections. Figure 5 illustrates the steps in the program.

The above approach is modified to accommodate the specific characteristics of poplar.

A summary of the points for this approach follows:

1) The number of trees selected for any particular clonal forestry program will depend upon the source of material and the purpose for which the cutting will be used;
2) Breeding orchards will be established for all selections made;
3) One breeding orchard can contain several breeding zones for each species, several species and several species-hybrids of each species;
4) Breeding will start with the onset of flowering in the breeding orchard;
5) A minimum of three clonal-progeny trials will be established for each set of pedigreed families according to a predetermined layout;
6) Information from the clonal trials will determine which parents will be used for production of additional seed for the donor stock that will supply cuttings for production plantations;
7) The best clones will be selected from the clonal-progeny trials for the establishment of hedge orchards and advanced-generation breeding orchards;
8) Material for production plantations will be mass-produced either from cuttings obtained in an hedge orchard or by the serial propagation of rooted cuttings;
9) Standards for clonal forestry will be established by the end of 1984.

The above four strategies form the basic policy guidelines. The Base Program is used for the priority species until seed is available from the production or breeding orchards, and continues to be used for all other species artificially regenerated within the Province. Strategy II is proposed for the first generation of selection for black spruce and jack pine; strategy III for the first generation of selection for white pine, white spruce and black walnut; a modification of III for tamarack; strategy IV for Norway spruce, European and Japanese larch, blister-rust resistant white pine hybrids, and a modification of IV for hybrid poplars. Strategy IV would also be used with the species mentioned in strategy II and III to supplement the seedling requirement with rooted cuttings.

Strategy for Black Spruce

A summary of the Ontario approach for this species is as follows:

1) Strategy I - the Base Program will be in effect until material is available from the seed orchards;
2) Strategy II - The seedling seed orchard approach will be used for black spruce;
3) All future first-generation production orchards will be seedling seed orchards;
4) The collection of cones and scions for all spruce orchards will be under way by 1985;
5) The establishment of all production and breeding orchards will be completed by 1990;
6) All planting stock (either seedlings or vegetative propagules) will originate from orchard material by 1995;
7) Considerable effort should be devoted to developing the clonal forestry strategy;
8) Clonal stock should form 30 to 50 percent of the planting requirements by 2000.

To fulfil the planting needs for black spruce, a total of 350 hectares of seedling seed orchards are required for 24 different breeding zones. The projected annual production per hectare oforchard is 0.5 million viable seed at 15 years, 1.0 million at 20 years and 1.5 million at 30 years of age. The anticipated volume gain in seedlings produced from orchard seed is approximately 8 percent from a 15-year old orchard, 11 percent from a 20-year old and 14 percent from a 30-year old one.

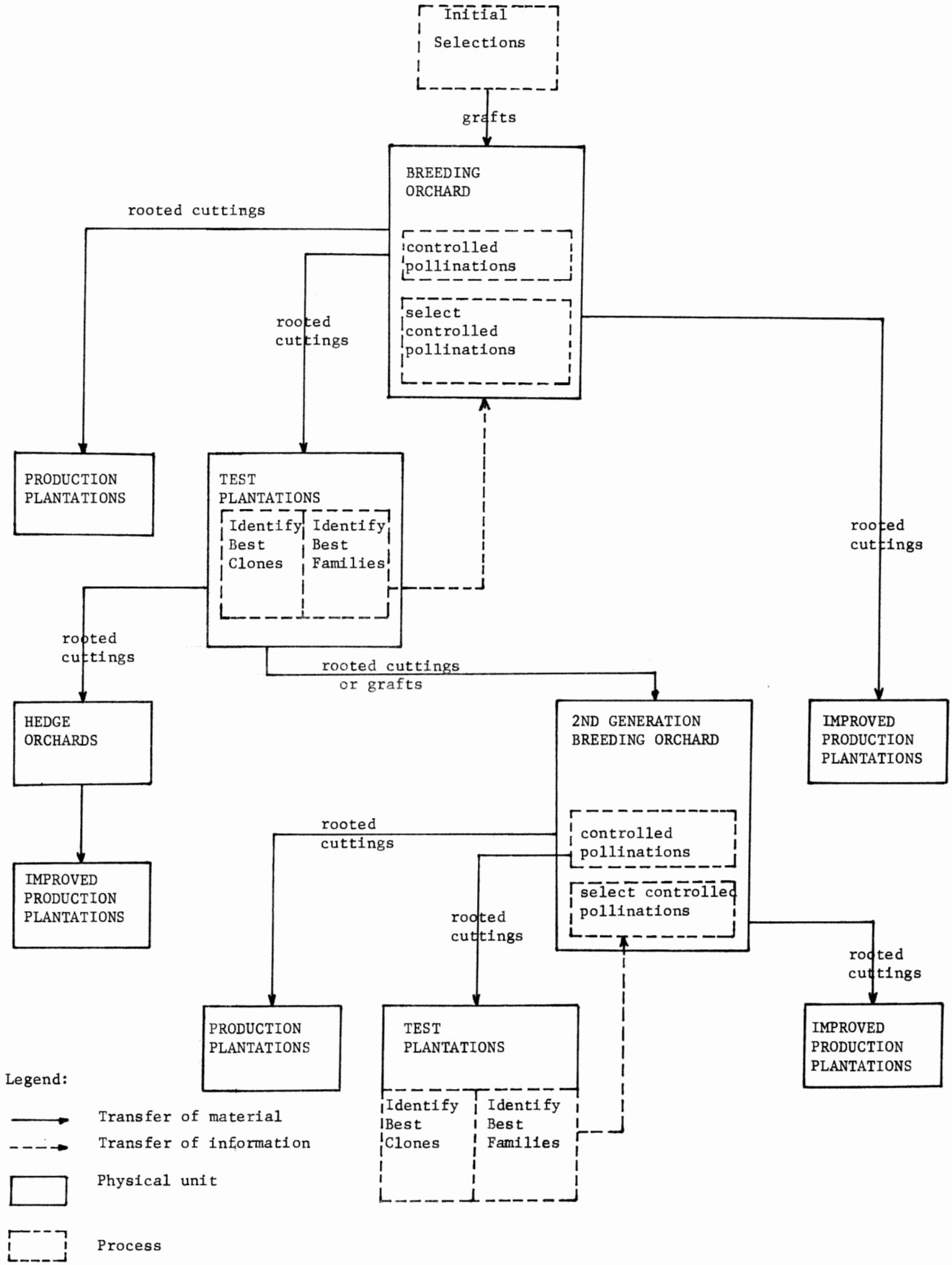

Figure 5: Breeding and Production Strategy for Clonal Forestry (Except Poplar)

Strategy for White Spruce

A summary of the Ontario approach for this species is:

1) Strategy I - The Base Program will be in effect until material is available from the seed orchards;
2) Strategy III - The clonal orchard approach will be followed for white spruce;
3) All first-generation production orchards will be clonal orchards;
4) Programs for all orchards will be under way by 1985;
5) All production and breeding orchards will be established by 1993;
6) By the year 2000, all planting stock (either seedlings or vegetative propagules) will originate from orchard material;
7) Research into ways of overcoming the problems with donor stock will continue in an attempt to make the clonal forestry option more viable.

To fulfil the planting needs for white spruce, a total of 250 hectares of clonal seed orchards are required for 21 different breeding zones. The projected annual production per hectare of orchard is 0.2 million viable seed at 15 years, 0.3 million at 20 years and 0.5 million at 30 years of age. The anticipated volume gain in seedlings produced from orchard seed is approximately 4 percent from a 15-year old orchard, 6 percent from a 20-year old orchard and 14 percent from a 30-year old one. Additional gains will be obtained in stem and crown form.

Economics of Tree Improvement

Several factors affect the profitability of seed orchard programs. Interest rates and real prices are the main determinants for long-rotation species and will outweigh any particular program design. However, the shorter the rotation, the more important is the program design and the less the improvement needed to economically justify the program. Many of the costs in the seed orchard program are fixed. Selection costs and tests costs are constant; only orchard establishment and management costs are variable. Thus, the larger the orchard required to supply the seed needs, the less the genetic improvement required for the program to be financially solvent. If planting and intensive silvicultural management of improved stock are restricted to the best sites, the necessary improvement is easier to attain.

The costs of establishing an 8-hectare seed orchard, associated testing and data evaluation were calculated. These costs were used as a basis for an elementary economic analysis of a seedling seed orchard program for black spruce. A number of points resulting from this analysis are highlighted in Table 1. A sub-table 1a shows the number of seedlings and the area that can be regenerated at different seed utilization rates using all of the seed produced during the life of this orchard. Sub-table 1b shows the reduction in area to be planted with improved stock, having different amounts of genetic gain, in order to maintain a given volume production. Sub-table 1c shows the present value savings or loss calculated at a 7 percent discount rate. The figures in sub-table 1c are derived by subtracting all costs

Table 1. Present Value Calculations for an 8-hectare Black Spruce Production Orchard with a 40-Year Life Span (Total Seed Production = 270.4 M Seed)

Sub-table 1a

Seed to seedling ratio	Seedlings produced (M)	Area regenerated (@2500 trees) (M ha)
2:1	135.200	54.080
5:1	54.080	21.632
10:1	27.040	10.816
20:1	13.520	5.408
50:1	5.408	2.163

Sub-table 1b

Reduction in areas to be planted to maintain same volume production (ha)

Seed to seedling ratio	Genetic Gain = 4%	8%	12%	16%	20%
2:1	2080	4006	5794	7459	9013
5:1	132	1602	2318	2984	3605
10:1	416	801	1159	1492	1803
20:1	208	401	579	746	901
50:1	83	160	232	298	361

Sub-table 1c

Present value using 7% discount (M$)

Seed to seedling ratio	Genetic Gain = 4%	8%	12%	16%	20%
2:1	+0.392	+0.990	+1.547	+2.065	+2.549
5:1	-0.040	+0.160	+0.346	+0.518	+0.680
10:1	-0.147	-0.048	+0.046	+0.132	+0.213
20:1	-0.201	-0.151	-0.103	-0.061	-0.021
50:1	-0.233	-0.213	-0.195	-0.178	-0.162

for establishing a seed orchard program from the savings accrued by planting fewer hectares of plantation. It shows that if 2 seeds are used to produce 1 shippable seedling, the seed orchard program is profitable with a 4 percent genetic gain in volume production, whereas if twenty seeds are used to produce 1 shippable seedling, the program is operated at a loss even if a twenty percent genetic gain were available. Since seed utilization plays such a large role in the profitability of the seed orchard program, it is essential to have good greenhouse and nursery practices.

This financial analysis concentrated on avoiding costs that occurred in re-establishing the forest with unimproved stock. There was no attempt to estimate anticipated benefits from improving the quality of the lumber, fibre, or the reduction in harvesting and milling costs that would result from the improvements. Such analyses are beyond the scope of this document, but if done, would reveal even greater benefits from a properly developed tree improvement program.

Summary Statement

The policy document has been just completed and sent to field foresters and forest geneticists for critical review. Once the comments have been received and incorporated, the policy will be submitted to senior management. If it is approved and satisfactorily funded, Ontario will once more have the opportunity to take the lead in tree improvement in Canada.

INFORMATION NEEDS FOR PEST MANAGEMENT IN AGRICULTURE

Dean L. Haynes

Professor, Department of Entomology, Michigan State University, East Lansing, MI 48824-1115.
Michigan State University Experiment Station Journal Article 11392.

The use of modern computer technology in pest management has so far not justified its cost. Systems models and on-line pest management systems have not resulted in control beyond the increased efficiency of pesticide applications. Research evaluating entire ecosystem "design" as a variable in pest control reveals that current designs often require pesticide use for stabilization, but that structural modifications can reduce these requirements and provide a new role for computer technology, as yet undefined.

Pest management has placed new demands on information requirements for effective pest control decision making. We must analyze these needs independently from hardware and software limitation. To use modern computer technology for networking to process more efficiently control recommendations as currently practiced does not justify the cost of information system development. In this talk I will briefly trace the history of computer use in IPM at Michigan State University. I will project some alternate potential futures utilizing computer technology to evaluate ecosystem design characteristics.

The development of effective pest management must rely on basic biological knowledge about the pest species and its environment. To this end a great deal of research effort has been expended to quantitatively describe population changes of pest insects. At present, it is clear that the acquisition of detailed biological parameters is not sufficient, even with the aid of models, to bring about effective pest control. This conclusion has not been easy for me to accept even though I have been involved with four major pest research programs, each dedicated to disproving this distasteful conclusion.

First there was the work I was involved within the late fifties and early sixties on the European pine shoot moth. Other forest entomologists (like George Green, Phil Pointing, William E. Miller and Bill Drooze) were all involved in population studies concerning this pest. The economics of the problem diminished but our research did not impact its reduced pest status on pine. The published reports are indirectly useful for management consideration but no definitive management approach was recognized. I thought at the time our resources were too limited and sampling was too ineffective to show the fine differences necessary for detailed parameterization.

During the early sixties, I worked on the spruce budworm in the Green River Project. Neither resources or historical data were limiting factors with this project. During the period of time I was directly involved with the spruce budworm, quantification of population parameters was the specific intended goal of most of the work. Modeling was limited to least square analysis in a search for specific associations. It appears that this work and much of the work that followed did not lead to spruce budworm control.

By 1966 I had left Fredericton and had become involved with a new pest, the cereal leaf beetle. Many others continued spruce budworm research that ultimately lead to the "Canusa" Project and this meeting in Burlington. From my perspective the cereal leaf beetle project followed a much different route than the spruce budworm program since 1966, but at this point in time may be similar. We have had little or no direct impact on control. Most of you are aware of the spruce budworm research but let me for comparative purposes familiarize you with the approach utilized with the cereal leaf beetle and briefly summarize the intensive research conducted on this pest (see Battenfield et al. 1982).

Field work on the cereal leaf beetle included an extensive survey which measured regional population change, and intensive studies in three locations. The intensive studies utilized a life table approach for both the pest and plant development. By 1970 information was available to undertake regression analysis of individual components. However, it became apparent that the coupling of these models into a more complete model would require more than conventional analytical techniques. Fortunately the project was able to enlist the cooperation of systems engineers in the Dept. of Electrical Engineering at Michigan State University. The engineering concepts of systems and the associated analytical techniques have become an integral part of pest management research in Michigan. Haynes and Gage (1981) summarize the development of component models for the cereal leaf beetle life system in a review article tracing the cereal leaf beetle project's 16-year history. Population models and simulations were developed by Ruesink, Tummala, Lee and Gutierrez. The models of Ruesink and Tummala were based on difference equations but were capable of simulating several generations of the cereal leaf beetle and parasites. Most models, however, were site specific and restricted to within-generation dynamics of the pest. These models were very good and lead to additional insight into the interactions of populations but the resulting simulations did not lead to control. Models associated with dispersal had a similar fate.

Sawyer tested the hypothesis that beetles moved at random between fields. The number of beetles in a field at any particular time was a net result of immigration and emigration rates. The rate on entering a field was a function of the spatial distribution and nature of both overwintering sites and other nearby fields and the relative length of the field's boundary. The rate of departure depended on the suitability of conditions within the field. The spatial distribution of beetles among fields related to general features of the region, such as relative acreages and developmental synchronies of the different host crops.

Currently, three different models are associated with the dispersal of cereal leaf beetle adults through a region: (a) in which the population moves from grass to wheat to oats, (b) in which the population moves to wheat or oats and remains in the field, and (c) Sawyer's model mentioned above. At present it is not known which of these models are correct for cereal leaf beetle movement. Each model can describe observed events but each would lead to different strategies for potential regional cereal leaf beetle management. This fundamental question of how the adult beetles disperse and move between fields has been defined and modeled, but the models have been of no direct use.

A series of simulation models were developed for specific purposes. For example, a model to assess the feasibility of strip spraying for the cereal leaf beetle was developed to simulate a variety of strip configurations, insecticide concentrations, and cereal leaf beetle adult movement rates. A model describing oat growth in the presence of cereal leaf beetle populations was developed to simulate the interaction between oat growth and cereal leaf beetle feeding. This model simulates a single cereal leaf beetle field under different environmental factors, fertilizer treatments, and cereal leaf beetle densities and can be used to screen temporal synchrony between the beetle and the plant.

A quantitative model was developed for improved density estimates of cereal leaf beetle larvae taken in a sweepnet. Fulton developed a model to evaluate the influence of cereal leaf beetle population maturity with respect to developing monitoring techniques. These models were used to estimate seasonal incidence of cereal leaf beetle larvae from a single population density estimate by incorporating weather and developmental rates estimated for cereal leaf beetle larvae. Casagrande and Haynes developed a model to evaluate overwintering mortality of adult beetles exposed to subfreezing temperatures. Sawyer and Haynes used an analytical approach to optimize the allocation of limited sampling resources in order to estimate regional cereal leaf beetle populations.

These models with specific, limited objectives appear to be the most effective, but by themselves do not lead to control. Three different simulation models of the cereal leaf beetle life system have been developed but were also of little direct use in control.

However the availability of this systems model lead to the on-line control paradigm for pest management programs (Haynes et al. 1973). It was felt that if this model could be synchronized with the environment it could be used directly in an on-line interactive manner.

The components of on-line pest management include (a) environmental monitoring, which provides information on weather in relation to biological activity of the life stages of the cereal leaf beetle, its parasitoids, and host plants; (b) biological monitoring, which comprises a regional survey of cereal leaf beetle density and measures the proportion of the population parasitizd by each species of parasitoid, the host conditon, and the relative proportion of host species; (c) cereal leaf beetle ecosystem modeling, which brings together each of the above components in addition to allowing mathematical experimentation with the system; and (d) a computer-based delivery system, which provides access to the information for remote terminals.

This process has been useful in identifying priorities for cereal leaf beetle research and attempts to implement models. A diagram of the conceptual framework for each component in the system is given in Figure 1. Tummala and Haynes (1977) described the general features of an on-line pest management system.

Many of the biological investigations of the cereal leaf beetle under field conditions indicated that weather played a major role in factors such as cereal leaf beetle adult overwintering survival and emergence from overwintering sites, transition of adult cereal leaf beetle from winter wheat to spring oats, synchrony of larval feeding on different ages of host crops, synchrony of parasitoid attack on cereal leaf beetle larvae and eggs, overwintering parasitoid survival in the soil,

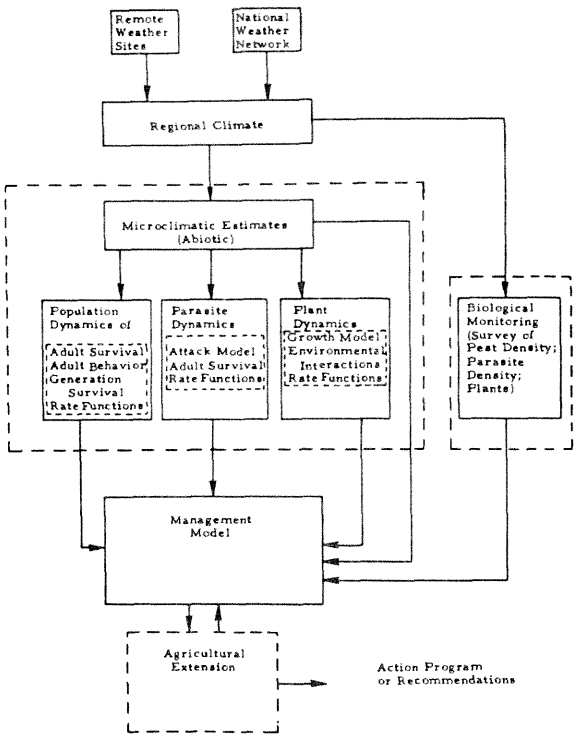

Figure 1. Environmental monitoring network for pest management systems, from Haynes, D. L., Brandenburg, R. K., Fisher, P. D. 1973. Environmental monitoring networks for pest management systems. Environ. Entomol. 2:889-899.

and survival of cereal leaf beetle pupae prior to emergence of summer cereal leaf beetle adults. In addition to the effect of weather on cereal leaf beetle and its introduced parasitoids, weather also affects host growth and development. Survival of cereal leaf beetle populations depends on the condition of the host crop, which in turn depends on nutrients and available moisture in the soil. Growth dynamics of small grains can rapidly change during the growing season; therefore modification of conventional economic threshold levels assigned for recommendation of management efforts is necessary.

The regional nature of cereal leaf beetle populations, the necessity of estimating when different life stages of the population occurred within a region, and the variability of weather in Michigan led to an investigation into the needs and kinds of developments necessary for a statewide weather monitoring network. Since current weather data were required to develop the on-line management paradigm, various network configurations were examined, as well as documentation of weather information requirements. These studies not only identified weather needs for cereal leaf beetle decision making but also generalized these needs to include a weather information delivery system for pest management. During the early 1970's, hourly weather data was available, via the Aviation Weather Network, from 14 weather stations located at airports.

To determine the use and applicability of regional weather data, historical weather data were obtained to

assess the value of cereal leaf beetle life stage prediction. A method to correlate real time and historical weather data to increase the usefulness of historical data for on-line pest management was developed. Weather data were used to predict the occurrence of cereal leaf beetle life states in order to accurately determine when to survey (using computer-mapping) for cereal leaf beetle in Michigan. Weather data and computer mapping were used to develop the concept of the "biological window" (Fig. 2).

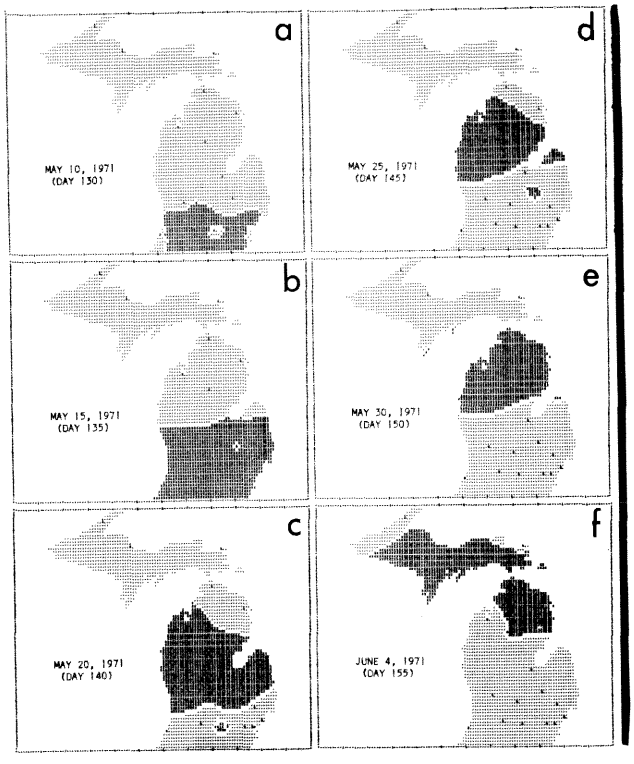

Fig. 2. Illustration of the concept of a biological window where the dark portions (x) indicate regions in Michigan in 1971 where control of adult cereal leaf beetles could be initiated using a short-lived pesticide (e.g., malathion) without killing the parasite T. julis.

Although temperature and precipitation data are useful for input into general regional models of cereal leaf beetle occurrence, weather stations located at airports and in other nonagricultural sites did not provide the level of accuracy required for prediction in agricultural sites where cereal leaf beetle populations occur. This problem prompted investigation of cereal leaf beetle microhabitat weather to define the variability of weather between standard weather stations and cereal leaf beetle microhabitat weather. Satellites and other modes of weather data transmission from remote sites were used to determine the optimal location of automated weather stations in Michigan. These and other activities relating weather to pest biology have led to an operational weather delivery system in Michigan. The system consists of 61 weather stations. Information users can access current daily weather for any or each of these weather stations.

Out of the research on the cereal leaf beetle came a regionally oriented pest management program. This system utilized models, computers and extension personnel in a highly interactive communications system. However, it appears to me (this is not generally accepted) that the principle use of the computer based information system was to accurately and efficiently time the application of pesticides. We had what I eventually came to call a "dynamic spray calendar". How do you control the spruce budworm after 37 years of relatively intensive ecological research?

The question came to mind again, "Is the only solution for pest outbreaks the use of pesticides? Will all detailed studies of pest systems finally revolve around the use of pesticides for control?

These programs, the European pine shoot moth, the spruce budworm and the cereal leaf beetle, in my opinion were and are all excellent studies. They have not lead to solutions. We have excellent analytical tools, access to very sophisticated computers and adequate if not opulent budgets to conduct this field research; why then is so little progress made toward non-chemical control of pest populations?

In 1976 we initiated a new program where we examined this question in the context of the entire ecosystem. We intended to evaluate ecosystem "design" as a variable in pest control. Successful biological control through the interaction of exotic parasites or predators is a clear example of design modification for control. The design of the ecosystem is the structural components which interact together to produce a particular ecosystem behavior. In more gross engineering jargon it could be said that: the specific objective of the design is to articulate the structural options of the ecosystem under consideration to achieve the desired behavior of the system. For example, introduction or removal of a parasite or predator component from the pest system would be a design change. Management of the ecosystem assumes the structure of the system to be fixed, while certain key parameters like time synchronies between the parasite and the pest, planting dates, fecundities, mortality rates, fertilization levels, etc., are managed to obtain the desired system performance.

When a system is being managed (tuned) to give a desired response, the underlying assumption is that the set of desired behavior (B) is a subset of all the admissible behaviors (A) exhibited by the system under varying conditions; i.e., we assume $B \leq A$. If this assumption were not true, then set B does not include the desired behavior. In this case we have to expand the behavioral space by including more components in the system under study.

In most situations the structure of a pest control problem is considered fixed even though it has evolved to its particular state slowly over time. It appears that in many problem areas the current structure requires the use of pesticides for stabilization.

If we view pest control in this light we can conclude that pest management at its best is the incremental adjustment to the current system and does not addess the problem of reducing pesticides. It simply removed the pesticides which were not needed but can not address the question of removing pesticides needed with current design. This is extremely important if the current design is unstable over a long time frame. This leads to a whole series of problems which may be answered through research if properly stated. When you have designed a particular system and it brings about pest control, what in that system brought about pest control? If you design another system,

would you have that pest control, or would you lose it? Could the design, and alterations to that design, actually be used as a management variable? Could you design a system that had more control options in it than another system?

To do this, you have to come up with a fairly clear definition of what the systems structure is. What are these things that we're working with? What are the components of this particular system? What structural modifications can be made that would bring about additional control?

In our search for a cropping system to serve as a suitable template for several university disciplines, we looked for a system that was small, manageable, rich in ecological, economic, and social principles, and representative of the energy-intensive agriculture paradox. The onion pest-crop agroecosystem of the Northeast and Lake states offers a near ideal prototype. Onions (as well as celery, lettuce, and carrots) are cropped on remnants of bogs, which were formed when receding glaciers left small pockets of perched water tables. Once drained, they provided unique soils (muck soil) where vegetable crops grow well.

The onion pest-crop agroecosystem is an ecological island because it is a closed system with definite borders (ecological, physical, economic, and social). Muck soils have a unique interface with surrounding mineral soils, so the types of crops grown, their biotic cohorts, and the indigenous ecological communities are distinct from the surrounding landscape. (In fact, the anomaly is so complete that the specialized skills required to grow these crops can be identified with a small ethnic subset of farmers. For instance, in Michigan most muck farming is done by second- and third-generation Dutch farmers, whose forefathers were familiar with intensive agricultural technology from the low countries of western Europe.)

The onion-pest crop ecosystem is also an excellent prototype because:

- The existing system is the result of energy-intensive cropping and chemical control practices.
- The organic soil ecosystem is a relatively simple one, which contains most of the basic interactions inherent in larger, more complex agroecosystems.
- The pests of this system have a long history of pesticide resistance.
- Crop losses due to pestilence range from 10 to 40% of the estimated annual crop value.
- Despite heavy reliance on pesticides to ensure high annual yields, 10-30% of the crop is discarded due to unstable and restrictive markets.
- Amortization of capital investment is slow.
- The crop protection strategy of insurance spraying is threatened with the accelerated premature displacement of pesticides.

Due to the specialized nature of the crop (nonessential for subsistence) coupled with the high cost of pesticide registration and the lack of economic incentives, pesticide companies are reluctant to develop new materials. As a result, this cropping system and many others like it are unstable and have difficulty adapting to changing conditions.

Onion production is intensive agriculture. In Michigan, we've reported more than 51 compounds put on one crop of onions. We're now down to very few chemicals available for even marginal control. Like the house fly, it is resistant to most pesticides.

Figure 3 shows the structural features of the onion ecosystem. We have an object of control and a monitored environment. In our plan the object of control was to be studied and modeled. The monitored environment were things to be monitored as both controllable and uncontrollable variables (Tummala and Haynes 1977). If something became important, we would include it in our object of control model. There were some very important components we were just monitoring, but within the object of control, everything was quantified and measured from the reference point.

We felt that if we were going to work within an agroecosystem, it had to be tied to some biological component. In this particular case, we tied it into the onion. Everything in the ecosystem, including man's activity, or anything else, we measured as a point of interaction from the onion crop (Figure 3). First order interactions were the pests, the leaf blight, the onion maggot, the onion thrips, and the northern root-knot nematode. Those are four first-order interactions, and that's where pest control specialists have spent all their time attempting to control pests, trying to break that linkage. If you look at the second order interactions, you see that the fungus of the onion plant had a fungus disease that attacks it. The onion maggot has a nematode that attacks it, plus a fungus disease, and series of predators and parasites. You can move on up into the third order interactions, where you find that the parasite attacking the onion maggot also had a fungus disease killing it. So, if we could put up such a structure, where we could look across orders of interactions, and then set up experiments, where we could measure those flow rates, we felt we could perhaps come up with an understanding of what that whole structure looked like.

We did this before we went into the field. We did this by going through the literature back to the turn of the century and finding out everything we could about the relationships that existed in there before we set up the experiment. We also came to the conclusion that when you were looking at this ecosystem, the last place you're going to find those relationships will be in the conventional agricultural setting. Conventional agriculture has been driven by a set of inputs that have changed the ecological relationships that exist there. We're trying to search for ecological relationships that could survive if we modify the structure.

Therefore, the only hope we had was to develop something called a noncommercial ecosystem, where we did not grow the crop for the purpose of producing the crop. We grew the crop to produce potential interactions. We were looking at all orders of interactions. We selected two places. One of them happened to be an organic farm, the other was the MSU property at the Laingsburg Muck Farm, where we actually systematically planted onions and planted weeds and hauled in insects from other areas and tried to make something a farmer would probably call a mess—we called it an ecological soup or a "pristine" situation. Within this context interactions took place. Our intent was to take one interaction at a time and compare it to a commercial agriculture situation. This approach did not lend itself to well-designed statistical experiments. We did not know what was possible and later we concluded that the well-designed field experiment was part of the problem, not an aid to the solution.

One of the experiments looked like this (Figure 4). We utilized a three acre field near Grant, Michigan. One part was a nontreated area and received no pesticides. The other side received just the soil treatment: 10 lbs of Dyfonate® applied at the time of seeding for

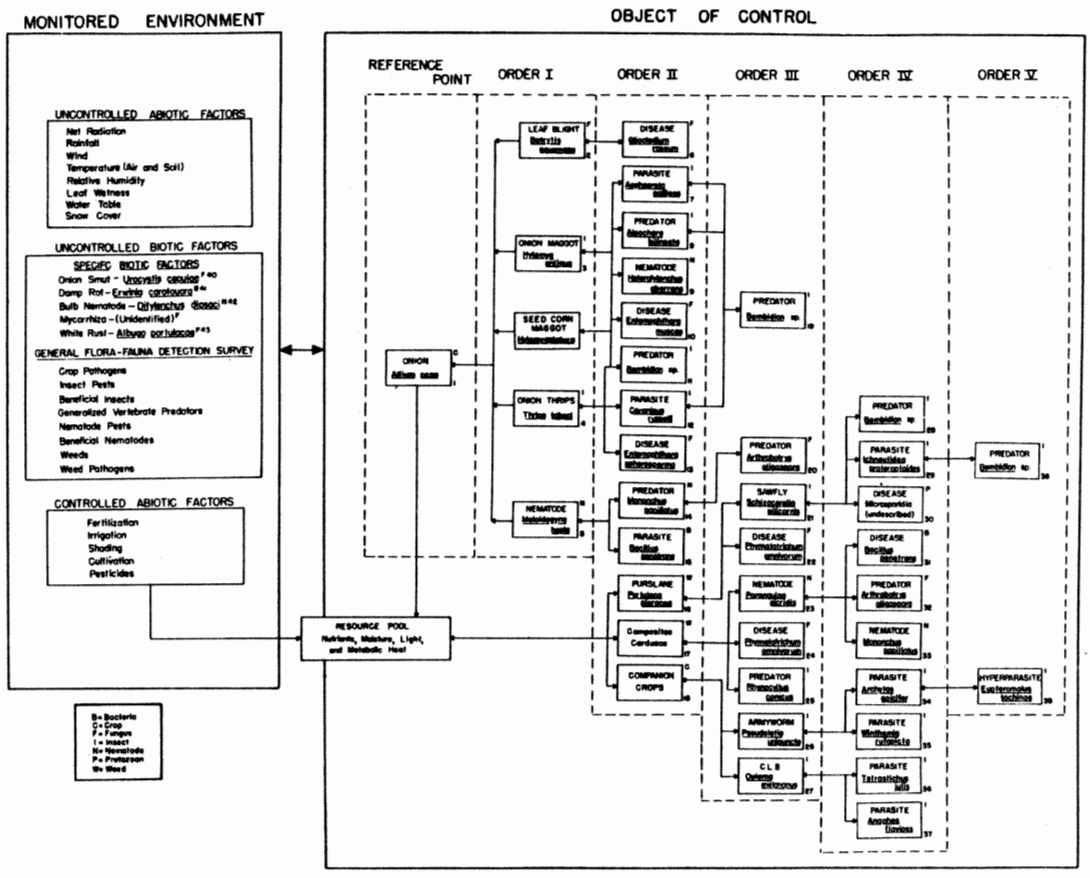

Fig. 3. Structural features showing levels of interaction within an onion agroecosystem design (object of control) and the monitored environment. Letters refer to the role of the organism.

onion maggot control. The surrounding onion field received conventional treatment, which at that time was about 10 lbs of Dyfonate at planting time, and between 12 and 17 foliar sprays for adult onion maggot. This was right in the middle of a commercial growing area. If we look at the place where we only put on Dyfonate, we had a crop with about 2-3% damage. If we look at the surrounding fields, where all the sprays went on, we had a crop that received 2-3% damage. If we look at the place where we took out the pesticides, the crop was totally destroyed, was just wiped out. So clearly we have a good IPM here. We could say, "Look, the foliar sprays are not needed. We don't know how they got in there, but they're doing no good." We followed up the following year with a 10-acre field, one side received Dyfonate and all the foliar treatments, the other side received only Dyfonate. There was no difference. The following year we put in 40 acres and demonstrated a similar thing. The sprays were not necessary. There was no more research needed in this area, although a great deal of extension needs to be done, because five years later farmers still spray.

But that wasn't the research question. If that was where the experiment stopped, we would say that this pesticide, Dyfonate, is absolutely essential or you don't grow onions. However, in the organic farming situation, we had a crop grown after 5 or 6 years of total crop failure. The farmer got to some point where he could grow onions, and there was no Dyfonate there.

Think now for a minute about the implications of alternate design. If we tested a chemical like Dyfonate, as good scientists, up in a commercial growing area, we would say it's absolutely needed--the crop cannot be grown unless you use this pesticide. If at the same time we went out to this organic farm and put out plots with Dyfonate, we would see no economic reason to use it. Now, think about how frightening that idea is—if you are in a particular system, you cannot even run an experiment that will tell you the ultimate truth about what has taken place. In one situation, Dyfonate

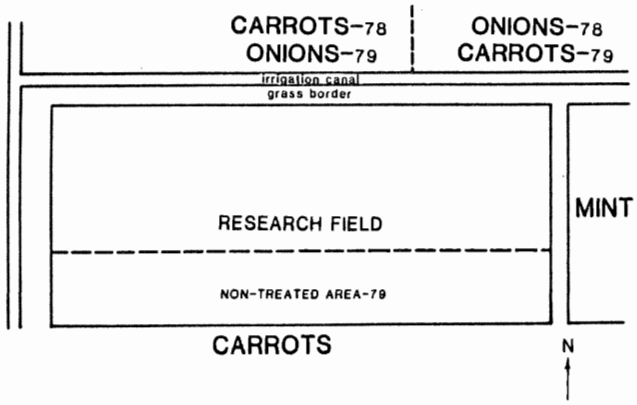

Fig. 4. Plot design of the research field in Grant, Michigan, for 1978-1979.

is needed. You can justify it with all your economic theory, however you want to look at it, and in another system you can justify it not being used. Experimental design and statistical analysis will not provide the truth, only a philosophical comparison of two structurally different systems allow the problem even to become evident. We began to look at why this was true.

One reason was because of cow pats and the face fly. Ellie Groden took bunches of onions that were infested and laid them next to a pasture, where the parasite, Aphaereta pallipes, had its alternate host available to it. Near the pasture we got 75% parasitization. Moving away from it, parasitization dropped to zero. When we began to specialize in high-energy inputs, where the cows are pulled away and specialized in one area and onions are grown in another, we ripped apart the life system of this parasite. It no longer had the two components it needed. The only way that could have taken place in the beginning is if you had pesticides to substitute for what this parasite was doing. The pesticides did not have to kill the parasite—we modified the structure and the pesticides were available to take up the lost control component.

We began to look at other pests in the same light. Entomophthora muscae is a disease of the onion fly. When we figured out its life cycle, we found that 90% of the disease inoculum that was dropping into the field was dropping in on the edge of the onion field, right at the border. As flies moved from carrots and weeds into the onions, they died and spores from the cadavers were falling down in a narrow band.

When we harvest onions, we spread the cull onions over the entire field and the behavior of the onion maggot changes—it relates to the whole field. But now all the disease is built up back there in the narrow band between those two crops. So we use high energy to spread the distribution of the adult flies that will emerge in the spring, removing them from the whole season's build-up of the disease in the narrow band. Another inadvertent structural modification.

Another one involves the tiger fly. Its immature stage is parasitic on earthworms. For years one of the compounds recommended in the onion system was benomyl, which also controls earthworms.

Another pest, a staphylinid, is parasitic on the onion fly pupae, and the adults are predaceous on the larvae. The staphylinid, however, can't live in a commercial area where herbicides are used, because the soil is black and bare to the sun. Soil temperatures rise up to over 140^{o} and kill it. You would find if you weren't going to use herbicides, you'd have to use mulch, and then these things would build up and increase in number.

What had happened to this organic farmer who successfully grew onions? He switched from commercial practices for religious reasons after he was knocked down by a chemical. He said, "I will not use any chemical no matter what." And he lost his crop, and he lost his crop and he lost his crop, because God's balance wasn't right. At some point in time, though, something began to happen. If you think for a minute, in terms of accidents, if you're a farmer and you're starving and you can't produce a crop, the first thing you do is get a cow. Even if you can't sell the milk, you have something to eat. If you have a cow, you pasture the cow, and if you pasture a cow, you make long and narrow pastures, which maximize, in scientific terms, the border/field ratios. This would build up the parasite, A. pallipes. If you weren't going to use herbicide, you'd have to use an organic mulch and that would build up the system where the staphylinid beetle could live. You would also be building up earthworms, and thus the tiger fly.

These are the kinds of structural modifications that can be experimentally defined in this system. How you go from one system to another economically is still unknown. This grower suffered total loss. There may be transitions from the way we do it now to where we want to go, with various transition costs. Some will be more viable than others.

I think this is an exciting area of research, looking at the structural implications, the population dynamics and pest management. I think a great deal of work in the future will somehow relate to this particular subject.

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INTRODUCTORY REMARKS FOR PANEL DISCUSSION; MANAGING SPRUCE BUDWORM IN VERMONT

Ted Walker
Director of Forests
Vermont Department of Forests, Parks and Recreation
State Office Building
Montpelier VT 05602

Because the spruce budworm problem is new to Vermont, Vermont is new to the budworm. Not that the budworm hasn't been around, but for some reason or reasons it remained at relatively low population levels in spite of several periodic mass flights of moths into the northeastern part of the state, until some ten years ago. Having been around a while, I have often wondered why the spruce-fir type in Vermont, apparently resistant to spruce budworm damage for so long, has become so susceptible in the last decade. It seems almost as if spruce-fir forest use patterns had changed enough to alter susceptibility to budworm over a relatively short time. Because of this, the Vermont situation perhaps affords a unique opportunity to look back a few decades and try to determine what we were doing then that we are not doing today or what we weren't doing then that we are doing today that could account for the change in susceptibility.

Considerable public interest in the budworm problem has developed in the Northeast Kingdom not only because of the importance of wood products to the local economy, but also because sizeable deer yards exist throughout the area. Opposition to the use of chemical insecticides has presented a difficult climate for carrying out direct control with anything but B.t.; but this has proved helpful in gaining support for an integrated approach to control through other pest management techniques such as species conversion, planting, encouraging polyculture, shorter rotations and silviculture. We remain hopeful that with what has been learned by others before us, together with some insight gleaned from the recent history of budworm behavior in Vermont, that a truly integrated pest management strategy can be developed, tested and demonstrated which will allow us to manage the budworm on an on-going basis through "comprehensive husbandry based on sound ecological fact and theory". (Geier and Clark, 1960). "Although greater creative effort will be necessary, (this approach) should prove to be less costly, invoke less social and ecological repercussions, and be of more lasting benefit than the continued use of present-day methods which ignore the ecological realities of pest regulation." (Stark, 1970).

To this end, the Vermont Spruce-Budworm Management Demonstration Project is dedicated as will be borne out by the various contributors to this panel.

Panel: Managing Spruce Budworm in Vermont

The panel discussions reflected the concerns and issues that shaped the Vermont Spruce Budworm Demonstration Project, a joint effort of the Vermont Department of Forests, Parks, and Recreation, and the Northeastern Area, State and Private Forestry, U.S. Forest Service. We present below the opening statements of the panelists, each of whom represents a constituency with varying but compatible resource management goals. Budworm feeding alters the environment in which normal managment processes take place. The nature of the adjustments required are what the panel is about.

Vermont Spruce Budworm Demonstration Project
Background
by
Sam T. Hudson, Jr., Project Leader
Vermont Dept. Forest, Parks and Recreation

The spruce budworm is a relatively new forest insect problem here in Vermont, first building up to noticeable levels in 1974.

During the past nine years, the outbreak has increased in size, acres infested - and intensity, damage incurred.

1983 surveys list nearly 180,000 acres of spruce-fir stands currently being damaged in Northern Vermont.

Spruce fir stands which have been repeatedly defoliated are now deteriorating rapidly and new mortality is increasing.

The total timber value of the affected five-county spruce-fir resource exceeds 50 million dollars. The value lost to budworm currently exceeds 2.5 million dollars per year. This value does not account for deer wintering areas and aesthetics. Landowners, foresters and timber operators in the affected area are concerned about the budworm problem and are asking for assistance. Recent research, specifically that sponsored by CANUSA, has made new technology available.

Advanced technology will be applied on the ground in 1984, during the landowner assistance phase, of the Vermont Spruce Budworm Demonstration Project.

The overall goal of the spruce budworm management project is to reduce the susceptibility and vulnerability of spruce-fir to the budworm. Protecting and maintaining critical deerwintering areas is receiving critical attention.

The project's short term objectives are to provide technical information and assistance to woodland owners where heavy budworm damage is impacting timber, wildlife habitat, and aesthetic values. Project objectives are achieved through training, demonstrations and technical assistance in management, utilization and protection.

These activities will serve as a model for implementing an integrated approach to budworm management. The demonstration project will serve as a practical model, statewide, for achieving diverse management objectives as outlined in the 1984 spruce budworm demonstration project annual work plan.

SPRUCE BUDWORM/DEER WINTER RANGE: A SITUATION STATEMENT

C. E. Alexander and L. E. Garland

Alexander, Wildlife Biologist, Vermont Fish and Game Department, St. Johnsbury, Vermont 05819

Garland, Chief, Habitat Section, Vermont Fish and Game Department, Montpelier, Vermont 05602

Abstract

Social and economic contributions of deer herds to the public well being make the perpetuation and improvement of winter deer range an important consideration in forest management planning. Spruce budworm infestations can lead to deterioration of winter deer range quantity and quality. The responses of deer to winter weather, winter deer range characteristics and silvicultural recommendations for managing spruce-fir winter deer range are discussed.

Introduction

The Vermont Fish & Game Department's interest in spruce budworm defoliation is centered upon an anticipated deterioration in quality and acreage of winter deer habitat. We are vitally interested in ways of lessening the damage to winter deer habitat and anxious for the development and implementation of silvicultural practices that will lessen the impact of budworm outbreaks in future years. It is our desire to maintain deer populations at the highest levels range conditions will allow in order to provide satisfactory recreational hunting opportunties. This is what Vermont hunters want from their deer herd. A remnant population may have scientific purpose, but no real social and economic values. That is not of any interest to us or to the people of this state.

Deer hunting in Vermont is a long standing, highly valued tradition. It is also a big business that generates over a million man days of recreation annually, and as a result $71,716,115 to this state's economy each year (Gilbert, A. H. Personal Communication) (Gilbert, A. H., 1977). Our Department is

financially tied to the deer herd with license and permit fees generated by deer hunting providing 76.1 percent of our operating budget annually. Anything that lessens deer numbers significantly affects hunter satisfaction levels negatively and can result in diminished levels of hunter participation bringing reduced economic benefits to all concerned.

Socially, deer hunting is important to this state. Picture a place where one in five people is a licensed deer hunter! That is regardless of the sex or age of the people in the population and studies show most Vermont hunters are males between their late teens and 60 years old (Gilbert, A. H., 1977). To a significant number of these people biological principles are totally unknown and are not appreciated. Changes in deer numbers, particularly downward changes, are automatically the Department's fault regardless of the cause. Government officials don't look forward to "good natured" grumbling from 20 percent of the population even if the blame can be placed on a worm. They aren't going to buy that in the deer camp anyway.

States and Provinces to the east have faced this particular problem chronologically before Vermont. Their experiences tell us that budworm defoliation frequently leads to a high intensity softwood logging cycle as the forest products industries attempt to minimize their losses, both actual and anticipated. New Hampshire biologists tell us that the three northern counties of that state produced 60 percent of their state's deer kill during the 1960's and now produce less than 30 percent of the annual kill. Much of the decline in kill can be laid to heavy softwood cuts in old, even-aged deer yards that were infested with budworms (Joe Wiley, Personal Communication). Residual softwood stands left after cutting are frequently marginal in terms of cover quality. The few remaining wintering deer are subjected to additional stress when severe weather conditions occur (Karl Strong, Person Communication).

Concerned? That's not a strong enough word. Paranoid is more appropriate. Even though our turn has come, we don't look forward to adding budworm infested deer winter habitat to our list of problems needing solutions.

Deer Responses to Winter Weather

For backqround purposes a highlighting of the interactions of deer and winter weather is necessary. In order to inhabit northern United States and Canada, deer have had to develop adaptations, both behavioral and physical, to cope with stressful winter weather. Some of these adaptations are well known and others have only begun to be understood after two decades of sophisticated research. Essentially the problem for deer boils down to survival to spring. Deer must maintain a positive energy balance with their environment. Arrayed against the deer in their struggle are:

1. Cold temperatures that cause high rates of body heat loss. This radiant energy loss is accelerated when windy conditions occur (Moen, 1980).

2. Snow accumulations that cause increased energy loss from day to day deer movements (Mattfeld, 1973). Snow texture and the length of winter can become critical particularly if there is a marked deviation from regional weather norms. Long drawn out winters with late springs can be costly in terms of deer survival and in reduced fawn production rates (Verme, 1977).

3. Low quantity and poor quality winter foods. The well known relationship between deer numbers and winter food supplies is a corner stone in the case for deer population management. Less well known is the reduction in food quality faced by wintering deer. Even the best hardwood browses are poorer energy sources than the green leaves, grasses, herbs, nuts and fruits fed upon at other seasons (Mautz, 1978). Quantities of food are influenced by deer numbers, forest management and snow depths.

4. Disturbance of deer in winter by roaming dogs, snowmobile harassment and man contribute to deer survival problems by accelerating energy drains when deer are forced into preventable flight (Moen, 1982). Movement takes energy.

Deer respond in a variety of ways to offset winter stress.

1. Insulated winter hair coats aid in conserving energy by retarding radiant heat losses. (Moen, 1980), (Silver et al, 1969).

2. Physical activity levels are reduced. Deer are reluctant to run in winter unless pushed. Slower movements cost less. This is important when the expenditures cannot be balanced by income from increased feeding. (Moen, 1976) (Moen, 1978).

3. The deer physiologically shut down in winter. Their basal metabolism is markedly lowered. Engines at idle burn less fuel (Silver et al, 1969).

4. Stored body fats and bone marrow fat reserves are major energy sources for wintering deer. (Mautz, 1978a).

5. Voluntary food intake reductions have been noted and these are often substantial. (Mautz, 1978b). A reduced need for daily food intake at a time when even on the best of winter ranges food quality and plant numbers are low makes good energy conservation sense. Recent research indicates that undisturbed penned deer can live nearly two months with no food intake. Survival rates were good when deer were exposed immediately to quality foods (DeCalesta, et al, 1975). Although wild deer aren't likely to go as long without food as penned animals this is

an important plus in their favor. Clearly, sending deer into winter with good fat reserves from quality summer and fall habitats and having good spring habitat is vital to deer management and has probably propped up the Vermont deer herd for decades (Mautz, 1978b).

6. Seeking protective cover in winter also contributes to deer survival (Ozoga and Gysel, 1972). In snow country, where spruce and fir are king, softwood vegetative protection is essential to wintering deer. Experience shows that regional snowfall norms are strong predictors of the need for softwood protection. Areas with infrequent and limited snowfalls need little if any softwood as a winter deer range component.

Winter Deer Range Characteristics

Softwood provides several benefits for wintering deer. These stands retain solar heat better and radiate less heat at night than open or hardwood sites (Moen, 1980). They have a more stable, temperature regime so deer can reach a liveable equilibrium under softwoods in terms of radiant heat loss (Ozoga, 1968). This can mean days of added life for deer and may make the difference in whether an individual animal sees spring or not.

Softwood canopies function to break up prevailing winds, lessening wind chill (Ozaga, 1968). Tree maturity and hence size enters the picture here. To have strong enough branches to hold snow requires a decent sized tree. Small softwoods with limber branches slough their snow load directly on the ground making good snowshoe hare habitat but very poor deer habitat. Ground accumulations of snow under mature softwoods is at least a third less than is found in open cover types. Deer expend less energy in foraging under these conditions. Strong, supporting snow crusts serve the same purpose.

Winter deer ranges are oriented south, west and east in order of preference. Northerly aspects are used infrequently but are known to winter deer under some circumstance. Aspect is important because the amount and duration of solar energy is best in deer ranges that face south. Not only are temperatures higher but snow melt is enhanced.

Usually, winter deer ranges are at low to moderate elevations. Sites below 1500 feet MSL are preferred in Vermont although winter ranges at higher elevations are known to occur. Again, snow accumulation appears to be the principal factor with lower elevations receiving less snowfall.

In the rugged, mountainous terrain of central and southern Vermont steep slopes that have favorable aspects frequently are key winter deer ranges due to the combined affects of slope degree and aspect upon snow accumulation and solar radiation (Dickinson, 1976). This last attribute of winter range (steepness) is not a factor in spruce-fir areas of Vermont because topographic relief is less pronounced. Under the topographic circumstances found in northeastern Vermont deer winter range relies heavily upon softwood vegetation to minimize snow accumulations.

For several years,, we have been measuring the physical characteristics of winter deer habitat. We have found regional variations that reinforce our beliefs that snow accumulations are a major factor in cover selections by deer. The cold, hard figures do not reflect the dynamic real life situations of winter habitat as well as we would like. It has become obvious to us that solid softwood stands are not necessary for wintering deer and that they may not even be optimal. While heavy to softwood, Vermont deer range is typically "patchy," with inter-connected dense blocks of softwood mixing with hardwood, mixed and even open sites. Within all areas surveyed there are islands of softwood cover with basal areas in excess of 150 square feet and frequently in excess of 200 square feet, and crown closures over 90 percent. These locales, often only a acre or two in size, are connected by lesser softwood densities sometimes down to single trees that allow a flow of deer movement. The denser cover is probably essential in cold, stormy periods but produces no food (Ozoga, 1968), (Ozoga and Gysel, 1972). Food is found in the less dense softwood and mixed sites nearby. A balance between these conditions, while difficult to quantify, exists in all our winter ranges and this needs to be considered in cut plans.

Potential for Softwood Cover Deterioration

What is the potential for cover deterioration in deer range that has spruce budworm problems? We say the possibility of problems is high. Within the spruce budworm demonstration area (Towns of Craftsbury, Eden, Greensboro, Hardwick, Hyde Park, Stannard, Walden, Wheelock, and Wolcott), eight winter ranges were examined for cover characteristics and browse production. A breakdown of softwood trees by species noted on plots (4 inches DBH and larger) shows 45.9 percent are balsam fir with an additional 23.5 percent being red and white spruce. The balance were hemlock (5.2 percent), white cedar (19.2 percent) and white pine (6.2 percent). Larch is considered a hardwood for this purpose. If high tree mortality occurs due to budworm defoliation winter deer shelter quality will be dramatically lessened and in some locales may be eliminated. Assuming New Hampshire's experience is an accurate barometer we face the likelihood of losing large acreages of winter range and reduced deer population sizes in the budworm problem areas.

We have no winter deer range to spare. The physical requirements sought by deer in winter have been discussed. Most wooded lands including most softwood sites are not usable.

They are too high in elevation, too poor in quality or have a bad aspect. Some sites that to the human eye appear adequate are rejected by deer for reasons that to date are unknown (Weber et al., 1983). You cannot will a particular area to be a deer yard no matter how hard you try. If the deer are telling you a site meets their minimum winter requirements by their presence, go with it. In this matter, deer know more than biologists and probably foresters too.

Winter Range Acreage in Demonstration Area

From mapping work to determine acreages used by deer and browse availability data a rough illustration of the carrying capacity of the demonstration area can be developed. Estimates of existing deer populations can than be compared to develop an approximation of the status of deer range in the study site.

Fish and Game Department field locations and boundary mapping of deer winter range has been going on for years. While there may be small areas we have missed, it is not likely that significant "new" acres remain undiscovered. We estimated 13,500 acres of winter range exist in the Demonstration area. Based upon knowledge of deer range we estimate that this winter range acreage serves a larger summer, fall range of 134,400 acres (210 square miles).

Browse studies of 19 winter deer ranges in the North Central physiographic region of which the Demonstration area is a part, revealed an average of 36 pounds of browse per acre (green weight). The "typical" browse species available in Vermont could sustain an average 60 percent utilization rate without loss of plant vigor. (Severinghaus, unpublished data). Multiplication of these figures leaves 22 pounds of usable browse per acre. Assuming a daily intake for the typical deer of 3 pounds of browse per day (Mautz, personal communication) and an average yarding period of 75 days we need 10 acres of winter range per deer in the Demonstration area resulting in a calculated maximum winter deer population of 1350 deer.

Winter Deer Population Estimates

Fall population estimates based upon the mean buck kills for the period 1979-1983 in this area reveal an average population density of 8 deer per square mile. There are an estimated 1685 deer on the 210 square miles of area served by the 13,500 acres of winter range in the fall. Legal hunting kills, illegal and hunt crippling losses can be expected to trim this herd an average 20 percent before the wintering period (337 deer). An additional 100 deer (5 per square mile of winter cover) are likely to die in an average winter inspite of hunt management to causes such as highway accident, domestic dog and wild predator kills, starvation, old age, disease, illegal kills and other miscellaneous difficulties. This means that the over winter herd that reaches spring will average 1250 animals. These animals will require a minimum 12,500 acres already discussed. On paper we have 1,000 acres extra range, in fact we doubt if our methods are accurate enough to leave only a 7.4 percent slush factor. We feel there is no leeway right now with the existing deer population.

Let us be the first to assure you that a deer herd of 8 animals per square mile is a very modest population. There are those who would say that it is a shabby population and would like it much larger. For example, most hunters view the present deer population size as too small. Anyone who doesn't believe that doesn't live in Vermont or has been asleep for the past 15 years. A 25 percent population increase is not an unreasonable objective and that would only give us 10 deer per square mile and would require 16,800 acres of winter range. That level of population (10) would be considered mediocre in many States.

Spruce-Fir Silviculture in Winter Deer Range

The budworm problems for Vermont's deer herd will have to be faced even if a reduced amount of deer range and smaller herd results for several years. The real goal should be to minimize present conflicts with winter range. Please take a few chances and don't "skin it all off" just because budworm is present. The future forest composition is what we need to consider so that we don't go through another emergency 50 years down the road due to following expediency in the 1980's. The Vermont Fish & Game Department and Department of Forest, Parks and Recreation have developed the following general guidelines for cutting spruce-fir winter deer range under both uneven age and even age management systems.

Management Considerations

Objectives

Commerical timber operations in a deer wintering area can easily destroy good cover. However, some types of cutting scheme are necessary in long-range planning and can provide additional browse supplies. Three main objectives in managing deer winter range are:

1. Preserve and perpetuate shelter conditions over as much of the original wintering area as possible, maintaining maximum deer mobility.

2. Improve adjacent or future softwood shelter through the regeneration or the release of understory softwood trees.

3. Provide high quality, accessible browse.

Silvicultural Systems

Spruce-fir can be managed by either the unevenaged or evenaged management systems. Unevenaged management is the preferred system to meet the above stated ojbectives, especially when managing ownerships with less than 100 contiguous softwood acres.

Evenaged systems may be a better choice in larger ownerships due to ease of timber sale layout and administration. This system is also frequently necessary in overmature stands.

Guidelines

The following guidelines should be considered when operating in deer wintering areas threatened by spruce budworm:

Unevenaged Management

1. Maintain an average crown closure of 50 to 60 percent.

2. Group selection cuts are preferred over single tree selection as denser pockets of cover remain and more browse is produced in the resultant openings. Openings should be 20 to 40 feet in diameter.

3. Favor longer-lived, more wind-firm, and budworm resistant species such as hemlock, red spruce, cedar, and white pine.

4. Enter the stand during the winter to provide browse in the form of tops and branches and to create trails.

Evenaged Management

1. Develop an age-class distribution based on a predetermined rotation age and cutting cycle. For example, a 210 acre fir stand in a 70 year rotation could have 30 acres regenerated every 10 years. Regenerate spruce-fir using a two or three cut shelterwood system or strip clearcuts.

2. Shelterwood systems are preferred because they are a more reliable regeneration method which also favor spruce over fir.

   a. Under the shelterwood system, the first cut should remove 40 percent of the basal area. Favor budworm resistant species such as red spruce, cedar, hemlock, and pine if present. Cut from below to remove low shade, leaving the larger and more vigorous trees to provide seed. Summer logging is preferred to prepare a seedbed to encourage a higher percentage of spruce regeneration. This prepatory cut should be made during a good seed year. The second cut (release cut) should occur when regeneration has reached a height of three to four feet, generally within 5 to 10 years. Winter logging is recommended to protect regeneration.

   b. If the risk of windthrow is high, a three cut shelterwood system should be used. Remove 20 percent of basal area at the first cut and another 20 percent at the second cut. Allow 5 to 10 years between cuts.

3. Strip clearcutting is sometimes necessary in decadent stands, especially those susceptible to severe windthrow.

   a. Strips should not exceed 40 feet in width to obtain adequate softwood regeneration. Orientation should be northeast-southwest to provide cool shade and protection from prevailing northwesterly winter winds.

   b. Cut one-half of the stand in alternating strips. Remove residual strips when regeneration is 3 feet tall, generally after 3 to 10 years.

4. In critical deer crossing areas, travel lanes about 200 feet wide, should be left through regenerating stands to maintain continuity of the wintering area. These lanes should be managed as unevenaged for perpetual cover.

Foliage Protection

Application of bacterial or chemical insecticides may be required to protect trees long enough for management to take effect. Heavily defoliated trees may not produce seed and shading of the seedbed will be reduced.

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COMMENTS

Dennis J. Souto
Northeastern Area State & Private Forestry
Louis C. Wyman Forestry Sciences Laboratory
PO Box 640
Durham N.H. 03824

Many residents and non-residents own the spruce-fir resource in Vermont. This landownership pattern complicates the implementing of any overall management plan. How are landowners encouraged to select silvicultural practices and management objectives consistent with with the management plan? Should the Department of Forests, Parks and Recreation encourage harvesting and managing spruce-fir if landowners cannot sell their wood? Currently, spruce and balsam fir markets are poor, and the long term outlook is not any better. The Department cannot expect landowners to finance long-term spruce-fir management at an economic loss.

The Department of Forests, Parks and Recreation must monitor silvicultural demonstration sites to determine long-term budworm, growth/regeneration and economic impacts. Only this way can landowners be convinced that long-term management pays off. Currently, we cannot predict how Vermont stands will respond to these silvicultural practices. In Maine, we now think that partial cuts can increase budworm problems and require subsequent insecticide protection.

The Department of Fish and Wildlife's deer habitat improvement program should pay to protect deer yard trees with B.t. This way, all the deer yards needing protection that year may get treated because the Department lifts the economic burden off a few landowners.

My final recommendation is to intensively survey the demonstration area's soils. With a good soil survey, sites could be accurately mapped and good sites could grow valuable hardwoods, while poor sites sustain quality deer wintering areas.

☆ U.S. GOVERNMENT PRINTING OFFICE: 1985-505-947:10543

Schmitt, Daniel, ed. Spruce-fir management and spruce budworm; 1984 April 24-26; Burlington, VT. Gen. Tech. Rep. NE-99. Broomall, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station; 1985. 217 p.

Presents a technical update of the management of spruce-fir forests. Integrated management of eastern spruce budworm is not yet a reality. The ecological, social, and economic knowledge needed to develop an integrated management system is not available. The conference was designed to move individuals to a higher level of spruce budworm management in the eastern spruce-fir forests.

Headquarters of the Northeastern Forest Experiment Station are in Broomall, Pa. Field laboratories are maintained at:

- Amherst, Massachusetts, in cooperation with the University of Massachusetts.
- Berea, Kentucky, in cooperation with Berea College.
- Burlington, Vermont, in cooperation with the University of Vermont.
- Delaware, Ohio.
- Durham, New Hampshire, in cooperation with the University of New Hampshire.
- Hamden, Connecticut, in cooperation with Yale University.
- Morgantown, West Virginia, in cooperation with West Virginia University, Morgantown.
- Orono, Maine, in cooperation with the University of Maine, Orono.
- Parsons, West Virginia.
- Princeton, West Virginia.
- Syracuse, New York, in cooperation with the State University of New York College of Environmental Sciences and Forestry at Syracuse University, Syracuse.
- University Park, Pennsylvania, in cooperation with the Pennsylvania State University.
- Warren, Pennsylvania.