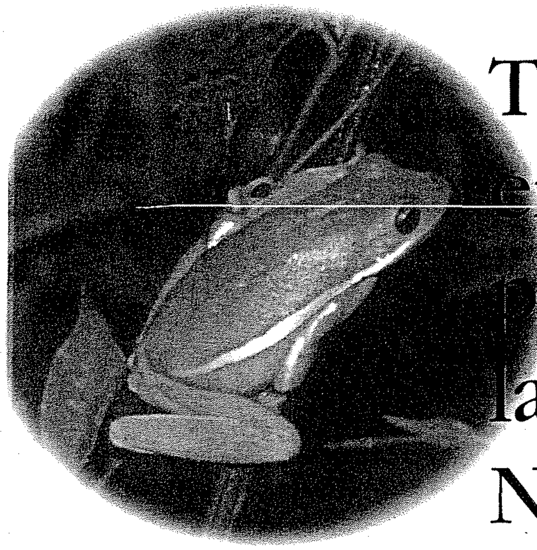

The role of herbicides for enhancing forest productivity and conserving land for biodiversity in North America

by Robert G. Wagner, Michael Newton, Elizabeth C. Cole, James H. Miller, and Barry D. Shiver

Abstract Herbicide technology has evolved with forest management in North America over the past 60 years and has become an integral part of modern forestry practice. Forest managers have prescribed herbicides to increase reforestation success and long-term timber yields. Wildlife managers and others interested in conserving biodiversity, however, have often viewed herbicide use as conflicting with their objectives. Do herbicides increase forest productivity, and are they compatible with the objectives of wildlife management and biodiversity conservation? Results from the longest-term studies (10–30 years) in North America suggest that the range of wood volume yield gains from effectively managing forest vegetation (primarily using herbicides) is 30–450% in Pacific Northwest forests, 10–150% in the southeastern forests, and 50–450% in northern forests. Most of the 23 studies examined indicated 30–300% increases in wood volume yield for major commercial tree species and that gains were relatively consistent for a wide range of site conditions. Meeting future demands for wildlife habitat and biodiversity conservation will require that society's growing demand for wood be satisfied on a shrinking forestland base. Increased fiber yields from intensively managed plantations, which include the use of herbicides, will be a crucial part of the solution. If herbicides are properly used, current research indicates that the negative effects on wildlife usually are short-term and that herbicides can be used to meet wildlife habitat objectives.

Key Words forest plantations, forest vegetation management, growth and yield, high-yield conservation, intensive silviculture

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Address for Robert G. Wagner: Department of Forest Ecosystem Science, University of Maine, Orono, ME 04469, USA; e-mail: bob_wagner@umenfa.maine.edu. Address for Michael Newton and Elizabeth C. Cole: Department of Forest Science, Oregon State University, Corvallis, OR 97331, USA. Address for James H. Miller: United States Department of Agriculture Forest Service, Southern Research Station, Auburn, AL 36849, USA. Address for Barry D. Shiver: Warnell School of Forest Resources, University of Georgia, Athens, GA 30602, USA.

Herbicide technology has evolved with forest management in North America over the past 60 years and has become an integral part of modern forestry practice. During the past few decades, herbicide use in forests also has been controversial (Wagner et al. 1998*a*,*b*). Forest managers have prescribed herbicides to increase reforestation success and long-term timber yields. Wildlife managers and others interested in conserving biodiversity, however, have often viewed herbicide use as conflicting with their objectives. Does herbicide use increase forest productivity, and is using them compatible with the objectives of wildlife management and the overall conservation of biodiversity? Substantial research has been done to address this question. The purpose of this paper is to 1) provide an overview of herbicide use in forest management, 2) review results from studies documenting the effects of managing forest vegetation (primarily using herbicides) on the growth of North American forests, and 3) describe the role that herbicides can play in helping conserve land, manage wildlife, and protect biodiversity.

Herbicides in forestry

Purpose and use

Herbicides (chemicals used to kill or control the growth of unwanted plants) come in a variety of forms and are used in forest management primarily to enhance reforestation on areas that have been recently harvested. Herbicide treatments generally fall into 1 of 3 categories: site preparation, herbaceous weed control, and release (Shepard et al. 2004). Site-preparation treatments are applied after harvest and before trees are planted (or naturally regenerated) to control woody vegetation and fast-growing herbaceous plants that can kill or suppress the growth of planted tree seedlings. Herbaceous weed control may be applied several months before or after tree seedlings have been planted to secure their early establishment. Release treatments (early- or mid-rotation) selectively remove or suppress woody or herbaceous vegetation that is reducing stand growth or could negatively influence long-term species composition of a stand.

Site preparation, herbaceous weed control, and release treatments are used to reduce competition for site resources (light, soil water, and soil nutrients) between desired trees and associated plants. These treatments help ensure that forest stands of the desired composition and structure develop within an economically feasible period of time. Desired stand attributes are determined by forest management objectives that seek to produce various combinations of timber, wildlife habitat, watershed protection, forage for grazing animals, aesthetic stands for recreation, or to achieve conservation objectives (e.g., biodiversity) on a given forest property. Recently, herbicide use also has been expanded in forest management to include control of nonnative invasive plants, especially on United States (U.S.) national forest lands (Miller 2003, Shepard et al. 2004).

Herbicides can be applied in a variety of ways, depending on management objectives and site constraints. For example, herbicides can be applied over a large area in broadcast, grid, or banded patterns, directed toward target trees and sprayed on foliage or stems, applied to spots around individual trees, or injected in small amounts into specific woody plants (Bovey 2001). The application devices used include aircraft (helicopters or airplanes), ground vehicles of various sizes (large tractors to small all-terrain vehicles), backpack sprayers, or hand-held injectors (Kidd 1987). Various herbicide formulations also are available, including liquid formulations, pellets, and granules.

Development of herbicide technology

The first reference to the use of herbicides in a North American forestry text was by Hawley (1929) in the second edition of *The Practice of Silviculture*, where he briefly described introducing "arsenical solutions" to kill unwanted trees. By the 1930s, 2 studies were cited in the fourth edition of *The Practice of Silviculture* indicating that injecting sodium arsenite was more effective for controlling unwanted trees than either traditional felling or girdling (Hawley 1937). Despite these early references in the primary silviculture textbook, the use of these early herbicides in forestry was minor before 1940.

After successes in the development and use of phenoxy herbicides in agriculture during the 1940s, herbicides began to be used during the early 1950s to control woody plants on non-agricultural land (Klingman 1961). Some of the first broadcast herbicide applications on wild landscapes were by range and wildlife managers seeking to improve forage conditions for grazing animals (Krefting et al. 1956, Mueggler 1966, Bovey 2001). Forest managers soon followed, seeking in the 1950s to control undesirable woody plants to promote successful regeneration of desired tree species. In the sixth edition of *The Practice of Silviculture*, Hawley and Smith (1954) devoted 5 pages to the use of herbicides or silvicides (primarily 2,4-D and 2,4,5-T) for cleaning treatments in young forest stands. By the 1960s using herbicides to prepare sites for tree planting, seeding, or natural regeneration, or to selectively control vegetation in young stands, was a common forestry practice (Smith 1962, Walstad and Kuch 1987). The first symposia synthesizing the technology and principles of managing forest vegetation also were organized at this time (Barnes 1961, Newton 1967).

Since the relatively widespread use of phenoxy herbicides (2,4-D and 2,4,5-T) in the 1960s, the herbicide products available for forestry use have steadily evolved. Amitrole and organic arsenicals (MSMA, cacodylic acid) began to be used in the early 1960s (Smith 1962); the organic arsenicals were the only means available at the time for reducing bark beetle (*Dendroctonus* spp.) populations during precommercial thinning. By the late 1960s and 1970s, picloram, dalapon, and the triazine herbicides (simazine, atrazine, and later hexazinone) were introduced, with dalapon and the triazines providing foresters with the first opportunity to effectively control herbaceous vegetation competing with young trees (Smith 1986). During the late 1970s and 80s, glyphosate (Roundup®) (Monsanto Corporation, St. Louis, Mo.) and triclopyr (Garlon®) (Dow Chemical Company, Midland, Mich.) gained prominence in forestry (Newton and Knight 1981, Smith 1986, Walstad et al. 1987*b*) and began replacing phenoxy herbicides due to greater efficacy and the controversy surrounding 2,4,5-T (Walstad and Dost 1986). When hexazinone (Velpar®) (E. I. du Pont de Nemours and Company, Wilmington, Del.) entered the market, options for controlling herbaceous vegetation were greatly improved, especially in southeastern U.S. pine (*Pinus* spp.) plantations, where intensive silviculture was taking hold (Fitzgerald and Fortson 1979, Nelson et al. 1981, Gjerstad and Barber 1987). During the late 1980s and 1990s, several new chemicals were added to the list of herbicide options for forest managers (Smith et al. 1997). Imazapyr (Arsenal®) (American Cyanamid Co., Princeton, N.J.) and the sulfonylurea herbicides, primarily sulfometuron (Oust®) (E. I. du Pont de Nemours and Company, Wilmington, Del.) and metsulfuron (Escort®) (E. I. du Pont de Nemours and Company, Wilmington, Del.), were introduced to fill niche uses or as additions to mixtures with other herbicides to increase the spectrum of plant species controlled.

There is currently no national tracking system to identify the extent of herbicide use in U.S. forestry; therefore, it is difficult to identify which herbicides are used most often, the rates of application, or the specific purpose. A 1999 survey of primarily southeastern U.S. forest owners found that 6 active ingredients accounted for 90% of total use (Shepard et al. 2004), including imazapyr (Arsenal) (BASF Corporation, Research Triangle Park, N.C.), sulfometuron (Oust), hexazinone (Velpar), glyphosate (Accord® and generic products) (Dow AgroSciences, Indianapolis, Ind. and others), metsulfuron (Escort), and triclopyr (Garlon) (Dow AgroSciences, Indianapolis, Ind.). Although the same herbicides are available for use in Pacific Northwest, Lake States, and northeastern regions of the U.S., the relative use of each likely is different from that of southeastern forests. Glyphosate, triclopyr, imazapyr, 2,4-D, atrazine, and sulfometuron probably are used most often in the Pacific Northwest. Herbicide use in Canadian forests is substantially different from patterns in the U.S. because fewer herbicide products are registered for forestry use. The Canadian Council of Forest Ministers (2002) indicated that the herbicides used in Canadian forests from 1988–2001 were glyphosate, 2,4-D, triclopyr, hexazinone, and simazine. Glyphosate, however, was the dominant herbicide; it was used on 94.7% of the treated area during this period.

In 1997 forestry made up <1.5% of total herbicide sales in the U.S. compared with agriculture (87%), turf and ornamental (5%), rights-of-way (3%), and home (3%) uses (M. Cyr, Kline and Company, personal communication). As a result of this small market, registration of new or existing chemicals for forestry uses is generally sought from the U.S. Environmental Protection Agency only when a herbicide also has a broad market in agriculture or other nonforestry uses. Herbicides are used in small amounts in forestry relative to other uses and may be used only once or twice on a particular hectare in 30–100 years (in contrast to annual applications to each hectare in agriculture). Although herbicides are used on only a relatively small percentage of all forestlands, they are essential for successful regeneration and enhanced yields on most managed forests across North America, especially if minimum legal reforestation standards must be met or high-yield silviculture is to be practiced.

Along with the evolution of herbicide technology, the management context for using herbicides in forestry also has changed. What had been referred to as forest weed control during the 1950s and 1960s began to rapidly change in the 1970s (Walstad 1981). The new field of forest vegetation management (FVM) was developed in response to the increasing complexity of herbicide use, the need to select among a wider variety of methods of vegetation control, the need to integrate vegetation con-

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trol practices into overall forest management planning, the desire to provide a more substantial scientific foundation for the practice, and increasing public concerns around the use of herbicides (Holt and Fischer 1981). Walstad and Gjerstad (1984, as cited in Walstad and Kuch 1987: 4) defined FVM as "the practice of efficiently channeling limited site resources into usable forest products rather than into noncommercial plant species." Several years later, Walstad and Kuch (1987) produced the first textbook describing the principles and practice of FVM for conifer production. More recently, the evolution of integrated pest management concepts and a greater emphasis on ecological and social concerns in forestry have expanded the concept of FVM to include a broader management context (Wagner 1994).

Herbicide influences on forest productivity

Over the past few decades, there has been substantial research quantifying the enhancements in forest productivity (primarily for conifer species) associated with control of competing vegetation, especially through the use of herbicides. Stewart et al. (1984) completed the first comprehensive review of the scientific literature (260 studies) documenting the effects of competing vegetation in forest stands before the early 1980s. A review of these studies by Stewart (1987) indicated that 40–100% increases in wood volume growth were common following vegetation control, most using herbicides. The responses in increased tree survival and growth also were remarkably consistent over a wide range of forest types and environmental conditions.

A major limitation of these studies documenting forest productivity enhancement was that nearly all reported responses were documented for only a short period of time (i.e., only several years after treatment). Actual enhancements in forest productivity from vegetation control or herbicide use should be measured over enough time (i.e., a significant portion of a stand rotation) to document the long-term growth and yield effects associated with the treatment.

Even though formal reviews of yield enhancements have been documented in forest vegetation management literature since the early 1980s, a substantial amount of long-term research in this area has been initiated and maintained during the past two decades. Results from many of these studies have been reported in the Proceedings of the International Conference on Forest Vegetation Management (see Canadian Journal of Forest Research 23[10] 1993, New Zealand Journal of Forestry Science 26[1/2] 1996, Canadian Journal of Forest Research 29[7] 1999, and Annals of Forest Science 60[7] 2003). Although much of the newer research also has been of a relatively short-term nature, a growing body of longer-term studies from southeastern, northern, and Pacific Northwest forests of North America is beginning to document growth and yield changes over a significant portion of the forest rotation following herbicide treatment (Table 1).

Pacific Northwest forests

In the Pacific Northwest region (including coastal British Columbia, Washington, Oregon, northern California, and the northern Rocky Mountains), a wide variety of hardwood, shrub, and herbaceous plants present an obstacle to reforestation efforts (Walstad et al. 1987*a*; Newton and Comeau 1990; Tappeiner et al. 1992, 2002). Some of the first long-term projections of yield enhancements associated with herbicide treatments were presented in a series of 4 case studies involving Douglas-fir (*Pseudotsuga menziesii*) plantations in Oregon (Brodie and Walstad 1987). Growth and yield model projections from herbicide-treated and untreated sites indicated that early differences in stand development would translate into 60% increases in merchantable volume at the end of a typical Douglas-fir rotation (60–75 years) for 3 of 4 cases. The increase in merchantable volume at 60 years for the fourth case was projected to be 15% greater than for untreated sites.

A 10-year study of Douglas-fir response to various herbicide and manual methods of competition release on 6 sites in the Coast Range of Oregon and Washington (Harrington et al. 1995) revealed that when herbicides effectively controlled all competing vegetation around saplings, stem volume was double that of untreated plots 10 years after treatment (12–13 years after planting). Monleon et al. (1999) also demonstrated a doubling of Douglas-fir stem volumes at year 10 in western Oregon from the early control of shrub densities with herbicides. Another study in the Oregon Coast Range recently demonstrated that complete vegetation removal for the first 5 years of stand development increased Douglas-fir volume per hectare after 15 years by 454% relative to plots that received no vegetation control (Yildiz 2000). Stein (1995) found that site preparation using herbicides on 5 sites in the Oregon Coast Range resulted in an 85% increase in the stem volume of individual Douglas-fir after 10 years and a 165% increase in volume per hectare over untreated areas after survival was taken into account. A 12-year study using a mixed-species Nelder design with various combinations of western hemlock (*Tsuga heterophylla*), red alder (*Alnus rubra*), and

Table 1. Percentage increases in wood volume yields from managing competing vegetation in the longest-term studies from Pacific northwestern, southeastern, and northern forests of North America. Dates covered: 1980–2004.

Region-tree species	% wood volume yield increase	Units reported	Length of study after treatment (years)	No. sites-location(s)	Source
Pacific Northwest					
Ponderosa pine	89	Total volume per area	20	1 site, CA	Oliver 1990
Douglas-fir	15-60	Merchantable volume per area	11 & 27, projected to end of rotation	4 case studies, OR	Brodie and Walstad 1987
Douglas-fir	454	Total volume per area	15	4 sites, OR	Yildiz 2000
Douglas-fir	~200 & ~240	Total volume per tree	12 & 14	3 sites, OR	Hanson 1997
Ponderosa pine	~460	Total volume per tree	14	1 sites, OR	Hanson 1997
Western hemlock	~100	Total volume per tree	12	3 sites, OR	Newton and Cole 2000
Douglas-fir	~140	Total volume per area	10	6 sites, OR & WA	Harrington et al. 1995
Douglas-fir	165	Total volume per area	10	5 sites, OR	Stein 1995
Douglas-fir	~120	Total volume per tree	10	1 site, OR	Monleon et al. 1999
Southeast					
Loblolly pine	17	Total volume per area	30	1 site, LA	Clason 1989
Loblolly pine	5,800	Total volume per area	27	1 site, AL	Glover and Zutter 1993
Slash pine	65	Total volume per area	23	15 sites, GA & FL	Shiver (unpublished data)
Longleaf pine	40	Merchantable volume per area	20	3 sites, AL	Michael 1980
Loblolly pine	30-148	Merchantable volume per area	15	13 sites across seven states	Miller et al. 2003b
Loblolly pine	53	Merchantable volume per area	12	25 sites across SC, GA, & AL	Shiver and Martin 2002
Loblolly pine	33-131	Merchantable volume per area	12	3 sites, AR & MS	Glover et al. 1989
Loblolly pine	37-122	Merchantable volume per area	10-12	6 sites, GA	Borders and Bailey 2001
Loblolly pine	14	Total volume per area	11	1 site, LA	Haywood and Tiarks 1990
Loblolly pine	11	Total volume per area	10	1 site, LA	Haywood 1994
Northern					
White spruce	57-96	Total volume per tree	30	3 sites, ON	Sutton 1995
Balsam fir	157-265	Total volume per area	28	1 site, NB	MacLean and Morgan 1983
Balsam fir and red spruce	264	Merchantable volume per area	22	1 site, ME	Daggett 2003
Black spruce	111 & 477	Total volume per tree	10	2 sites, ON	Pitt et al. 2004
Jack pine	116	Total volume per area	10	1 site, ON	Wagner 2003
Red pine	212	Total volume per area	10	1 site, ON	Wagner 2003
Eastern white pine	219	Total volume per area	10	1 site, ON	Wagner 2003
Black spruce	349	Total volume per area	10	1 site, ON	Wagner 2003

salmonberry (*Rubus spectabilis*) in the Oregon Coast Range also showed a doubling of stem volume yields for western hemlock grown without shrub and herbaceous vegetation (Newton and Cole 2000).

In one of the longest-monitored studies in the Pacific Northwest, Oliver (1990) followed the 20-year growth and development of planted ponderosa pine (*Pinus ponderosa*) in northern California in 2,4,5-T herbicide-treated and untreated plots of various planting densities. Regardless of planting density, the total volume per hectare was 189% greater for pine stands treated with herbicide. Using 14-year measurements from a southwestern Oregon study, Hanson (1997) found that the stem volume of individual ponderosa pines was about 460% higher on plots without vegetation than when shrubs and hardwoods were maintained at a high density.

In 2 experiments in southwestern Oregon, 12- and 14-year measurements of Douglas-fir growth showed that the mean volume per tree was about 200 and 240% higher, respectively, when hardwoods and herbaceous vegetation were controlled using herbicides (Hanson 1997). In addition, the early negative influence of competing vegetation led to significant underestimations of the growth potential for managed forests. Significant upward corrections of 50-year site index curves were needed if herbicides were used to control vegetation early in stand development. The ability of modern herbicides to selectively control a wide variety of competing plants has initiated a re-evaluation of the metrics traditionally used to measure productivity of forest sites and for modeling long-term wood supplies for large forest areas.

Southeastern forests

Plantation forests, primarily of loblolly pine (*Pinus taeda*) and slash pine (*P. elliottii*), are most abundant in the southeastern U.S. states and make up about 17% (14.6 million hectares) of the region's forest (Smith et al. 2001). Southeastern pine forests account for about 40% of all U.S. commercial timberlands (Wear and Greis 2002), and successful establishment and growth of pine plantations is dependent upon managing competing woody and herbaceous vegetation (Gjerstad and Barber 1987, Minogue et al. 1991). The potential yield gains associated with intensive management of competing forest vegetation in North America were documented first by forest researchers and managers in the southeastern states (Elwell 1967, Grano 1970, Smith and Schmidtling 1970). Michael (1980) provided one of the first reports of long-term gains 20 years after 2,4,5-T aerial release of longleaf pine (*P. palustris*) that resulted in 40% more wood volume.

In one of the oldest studies in the Southeast, Glover and Zutter (1993) measured the 27-year yields for loblolly pine that were planted following no treatment in plots with dense residual understory hardwoods and in plots following herbicide, mechanical, and manual methods of site preparation. Variable levels of hardwood control among the study plots provided a unique opportunity to quantify how various densities of unwanted hardwoods influenced the yield of loblolly pine. Herbicide treatments and scarification with a bulldozer provided the best control of hardwood vegetation. Total pine volume at age 27 was 59-fold more on herbicide-treated than untreated plots. A very strong negative relationship ($R^2 = 0.95$) was found between the basal area of loblolly pine at year 27 (the end of the rotation) and number of hardwood stems 3 years after site preparation. Therefore, vegetation dynamics established early in stand development by herbicide or other vegetation control treatments were found to have a long-term influence on yield and species composition of stands through the entire rotation.

Probably the earliest region-wide study of intensive vegetation control treatments in the Southeast was a site-preparation study established in 1980 with slash pine (B. D. Shiver, University of Georgia, unpublished data). After 23 years, controlling all herbaceous and woody vegetation resulted in total volume gains of about 65%. Gains in volume were evident at 5 years and were maintained over the rotation. While the age of peak mean annual increment in total stand volume was not changed from that exhibited by less intensively managed plantations, the total wood volumes produced were substantially higher. As in the Pacific Northwest, traditional site-index curves were inadequate for projecting the growth of pine stands under intensive management regimes.

Another region-wide site-preparation study with loblolly pine (Shiver and Martin 2002) included 25 locations across South Carolina, Georgia, and Alabama. The treatments included total vegetation (woody and herbaceous) control with herbicides, a typical site-preparation treatment including herbicides, and 2 other mechanical treatments. After 12 years there was a 32% increase in area pine volume with herbicide and burn treatments over chop-and-burn site preparation. Two years of herbaceous control resulted in an added 42% gain in volume (74% total gain).

One of the most comprehensive studies examining yield enhancements and succession alterations from herbicide use has been conducted by Miller et al. (1991; 1995*a*, *b*, *c*; 2003*a*, *b*), Zutter and Miller (1998), and Zutter et al. (1999). The same experimental design was replicated in 13 loblolly pine plantations across 7 states and 4 physiographic provinces of the region. As of 1998 the plantations had been monitored for 15 years (or over 60%) of the typical 24-year pulpwood rotation. The study is using a factorial combination of 2 woody control treatments (no woody control vs. complete woody plant control) and 2 herbaceous control treatments (no herbaceous control vs. complete herbaceous plant control). Herbicides were used before planting and annually through crown closure (3–5 years after planting) to establish and maintain the treatments. Pine yields at year 15 were strongly influenced by herbicide treatments applied during the first 3–5 years after planting. Controlling both woody and herbaceous vegetation increased merchantable wood volumes at year 15 from 30–148% above that on untreated plots. Control of only woody vegetation increased merchantable pine volume on 11 sites by 14–118% (main effects), and gains on treated plots increased as the abundance of hardwoods and shrubs increased on the check plots. Gains from early control of only herbaceous vegetation (leaving woody vegetation) were somewhat less, increasing only 17–50% on 10 sites (Miller et al. 2003*b*). No gains and some losses occurred when control of one component released severe competition from an enhanced remaining component; otherwise gains were generally additive for control of both vegetation components.

Borders and Bailey (2001) studied intensive treatments for loblolly pine plantation management at 6 sites in Georgia (including high-density shrub sites). After intensive mechanical site preparation and planting high-performance half-sib seedlings, continuous vegetation control increased merchantable volume through ages 10–12 years by 37–122%; adding repeated fertilization further enhanced yields from -1 to 207%. Borders and Bailey concluded that growth rates were comparable to those obtained at other high-biomass production areas for loblolly pine throughout the world (e.g., South Africa, Brazil, and Australia).

Glover et al. (1989) found that regularly controlling herbaceous vegetation using herbicides from planting to crown closure in young loblolly pine stands increased merchantable volume after 12 years by 33, 96, and 131% on 3 sites in Arkansas and Mississippi. Other long-term studies of intensive competition control have come from Louisiana's nutrient-deficient Coastal Plain and have documented loblolly pine volume increases of 11–17% over 10–30 years (Clason 1989, Haywood and Tiarks 1990, Haywood 1994). In the longest-term study, volume gains remained constant from years 20–30 (Clason 1989), an indication of the persistence of volume enhancements with herbicide use.

Northern forests

Competition from vegetation also can be a substantial deterrent to successful regeneration in young forest stands in the northeastern states, Lake States, and eastern Canada (Newton et al. 1987, Wagner et al. 2001). Although there has been relatively less research activity documenting the effects of vegetation management on long-term yields than in the Pacific Northwest and Southeast, several key studies in the region characterize the role that herbicides can play in enhancing productivity of northern forests.

MacLean and Morgan (1983) published results from one of the earliest studies on the effect of herbicide release in northern forests. Plots where phenoxy herbicides were used to release young balsam fir (*Abies balsamea*) in northern New Brunswick were compared to those that were manually cleared and to those that received no treatment. The herbicide treatments were applied in 1953 and the plots remeasured in 1981, 28 years after treatment. The total stem volume of balsam fir was 157–265% greater in herbicide-treated plots than in untreated control plots. Fir volumes on the manually released plots were 64% greater than on untreated controls.

In another early Canadian study, Sutton (1995) reported the combined influence of fertilization, irrigation, and vegetation control (using herbicides and mechanical methods) on the 30-year response of planted white spruce (*Picea glauca*) in eastern Ontario. Results from 3 sites indicated that spruce stem volume was from 57–96% greater with vegetation control than without treatment. Vegetation control was the only treatment among the 3 producing statistically significant differences in tree growth after 30 years.

In a recent study of spruce–fir (red spruce [*Picea rubens*] and balsam fir) in Maine, Daggett (2003) examined the effects of aerial herbicide application and precommercial thinning (PCT) on long-term stand development. This study, initiated in 1977, is the longest examination of the newer and most commonly used herbicides (glyphosate and triclopyr) in North America. Although total wood volumes (with hardwoods included) were not increased by herbicide or PCT treatments 22 and 13 years after treatment, respectively, the proportion of wood volume in 29-year-old balsam fir and red spruce was substantially increased by herbicide treatment. Among 14 treatments tested, softwood composition was 74% in herbicide-treated plots compared to 23% in untreated plots. Daggett (2003) also compared the influence of herbicide and PCT treatments on the merchantable volume of softwoods using several standards. Using the lowest standard (i.e., the smallest merchantable top diameters), softwood volume was increased by 171% in herbicide-only plots relative to untreated plots. When including only the newer herbicides (glyphosate and triclopyr), merchantable softwood volume increased 264% above untreated plots. The effect of the herbicides was enhanced further if the stands were later subjected to PCT and previous herbicide application enhanced the later effectiveness of PCT. When herbicides and PCT were used in combination, merchantable softwood volume at 29 years was 411% greater than the untreated controls.

In one of the few studies examining the effects of herbicide use on a state's wood supply, Wagner et al. (2003) examined the long-term effect of herbicide treatments on Maine's sustainable harvest level. Using U.S. Forest Service Forest Inventory and Analysis data for the state, they analyzed the role that silvicultural investments (primarily tree planting, herbicide treatment, and PCT) could potentially have on the annual level of sustainable timber harvest in the state. The effect of herbicide release alone was studied, but herbicide technology also was assumed to be an integral part of the gains associated with both tree planting and PCT. Under an optimum future treatment scenario, annual sustainable harvest levels were

31% higher than if no further planting, herbicide, or PCT treatments were applied in the state. If current annual levels of tree planting, herbicide application, and PCT continue to be applied over the next century, the harvest level would be 8.5% higher than if those treatments were no longer applied to Maine's forest. So, differences in stand-level growth associated with early herbicide treatments described above also can influence harvest levels on large forest properties, states, and regions.

Pitt et al. (2004) studied the 10-year growth responses of planted black spruce (*Picea mariana*) and associated vegetation for 10 years following several competition release treatments on 2 sites in northeastern Ontario. Five growing seasons of annual vegetation removal using repeat applications of glyphosate herbicide produced nearly complete domination by spruce with 111% and 477% increases in individual tree-stem volume relative to that of untreated plots. The degree of stem volume gain among treatments was positively correlated with the level of vegetation control during the first few years after treatment. Despite effective vegetation control on annual removal plots, dominant species of deciduous trees, tall shrubs, low shrubs, forbs, ferns, and grasses or sedges were well represented after 10 years.

In a recent Ontario study examining responses of young northern forest plantations to various timings and durations of vegetation control, Wagner et al. (1999) found that nearly all of the potential productivity in early stand development could be obtained if vegetation was controlled with herbicides for a short time after planting jack pine (*Pinus banksiana*), red pine (*P. resinosa*), eastern white pine (*P. strobus*), and black spruce. Ten-year measurements from this study indicate that these earlier patterns are maintained for the first decade of stand development (Wagner 2003). Stem volume production for jack pine, red pine, eastern white pine, and black spruce increased by 116, 212, 219, and 349%, respectively, during the first 10 years if surrounding vegetation was controlled for the first 2–3 years after planting. Tenth-year data for ponderosa pine and California white fir (*Abies concolor*) in northern California suggest similar benefits from controlling vegetation for only the first few years after tree planting (McDonald and Fiddler 2001*a*,*b*).

The role of herbicides in the conservation of land, wildlife habitat, and biodiversity

Herbicides in agriculture

Current levels of world food production and, in fact, the success of most forms of plant culture in the modern world are strongly dependent upon successfully managing unwanted plants or weeds. Herbicides play a vital role in this regard for U.S. agriculture. Gianessi and Sankula (2003) indicated that 85% of agricultural lands in the U.S. were treated once or more annually with herbicides and that herbicides represent 60% of total pesticide volume used in agriculture. Agricultural yield losses from 50–90% have been demonstrated for most food crops if competition from weeds is left unmanaged (Gianessi and Sankula 2003). The nonuse of herbicides on U.S. farms would require farmers to substantially increase labor inputs to control weeds, increase erosion of farm soils by 15% (resulting from increased tillage), reduce net farm income by $21 billion annually, and reduce yields from 5–67% for most crops (Gianessi and Sankula 2003).

Recent increases in agricultural yields have done more than feed a growing human population. High-yield agriculture, of which herbicides are clearly a crucial part, has substantially reduced population pressure on land, thus making more habitat available for wildlife species and the overall conservation of biodiversity. Borlaug (2000) estimated that if global cereal yields per ha in 1950 had been held constant through the end of the 20th century, 3-fold more farmland would have been needed by 1999 (i.e., 1.8 billion ha instead of the 600 million ha that was actually used worldwide). In this regard, wildlife habitat availability and biodiversity conservation have been and will continue to be influenced by successes in high-yield agriculture and therefore by herbicide use.

Shrinking forestland, increasing population, and wood demand

As with the relation between agricultural land and food production, increasing yields on a declining forestland base will be essential to meet social demands for both wood fiber and the conservation of biodiversity. The Food and Agriculture Organization of the United Nations (2001) reported that between 1990 and 2000 the net loss of global forest area was 94 million ha–an area larger than Venezuela. This rate of forest area decline is about 0.22% per year. Although North American (U.S. and Canada) forested areas, which make up about 12% of the global forest area, have remained relatively stable, the proportion of that land available for wood production has been significantly reduced (Food and Agriculture Organization of the United Nations 2001). For example, while U.S. national forests accounted for 17% of forestland and 19% of the theoretically available timber supply, as of 1996 only 5% of the U.S. timber harvest came from national forests (Food and Agriculture Organization of the United Nations 2001). This policy-driven decline in harvest has put more pressure on softwood supplies because 46% of the softwood growing stock in the U.S. is on national forest lands (Smith et al. 2001). As a result, forest harvesting to meet wood demand has shifted over the past decade from public to private lands in the U.S. (Food and Agriculture Organization of the United Nations 2001), as well as to other countries, especially Canada (Haynes 2003). The area of private forestland available for timber production in the U.S., however, is expected to decline during the coming decades. In addition, harvest demands currently being placed on Canada's largely public forestlands are not likely to be met in the future under the current system of management (Food and Agriculture Organization of the United Nations 2001).

Assuming that the annual per-capita global consumption of wood (0.6 m^3) remains constant and the human population reaches 10 billion, Sutton (1999) projected an annual 2.2 billion m^3 deficit in the global wood supply by the year 2050, based on estimated productivity outputs of natural and plantation forests. Because annual U.S. per-capita wood consumption is 3–4 times the global average and is projected to increase 40% by 2050 (Haynes 2003), North Americans will be exerting disproportionately more pressure on forestlands to produce wood fiber. Combined with increasing social pressures for recreational uses and to conserve more forestland to meet biodiversity objectives (United States Department of Agriculture 2001), it is clear that forest managers must find ways to substantially increase forest productivity on a smaller land base.

How much increase in forest productivity will be required to meet global needs? Based on the current 0.6-m^3 annual per-capita wood demand (Sutton 1999), 6 billion human population, and current 3.87-billion-ha supply of forestland (Food and Agriculture Organization of the United Nations 2001), providing a sustainable wood supply today requires an average forest productivity of only 0.93 m^3/ha/yr. By 2050, if the world's population reaches 10 billion, the 0.22% annual rate of forest area decline continues, and global per-capita consumption remains constant, the global forest will need to produce 1.74 m^3/ha/yr, or 87% higher growth rates. If the global per-capita consumption rate for wood increases with living standards in countries such as China and India, or if forest area declines accelerate above current levels, the required increases in forest productivity may be >2 fold by 2050.

Plantations and biodiversity

Sohngen et al. (1997), in modeling long-term global wood demands, indicated that most of the future increases in forest harvest will come from existing and newly established plantations and that future increases in harvests will come primarily from increased management intensity rather than from increased harvests in currently inaccessible forests. By 2050 about 60% of the softwood harvest from private lands in the U.S. will come from plantations in the Southeast and Pacific Northwest that are expected to occupy about 30% of the softwood timberland area and ≤20% of the total area of U.S. timberland (Haynes 2003). There is evidence that meeting increased global wood demands from intensified silviculture is already occurring (Sedjo 2001). Forest plantations currently produce more of the world's commercial timber (34%) than do old-growth forests (30%), managed second-growth forests (22%), or minimally managed second-growth forests (14%) (Sedjo and Botkin 1997). There also can be substantial financial returns from increasing silvicultural intensity (Sedjo 2001). Yin and Sedjo (2001) indicated that a shift to plantations and especially the control of competing vegetation have substantially increased the growth rate of southern U.S. loblolly pine, and that the financial returns increased with increasing silvicultural intensity. Berlik et al. (2002) suggested that in addition to reducing per-capita fiber consumption, the U.S. and other affluent countries need to be more environmentally responsible by locally producing more wood and reducing the export of their higher per-capita wood demand to parts of the globe where forestry practices may not be as environmentally sound.

The key elements of successful intensive silviculture or plantation establishment include the use of genetically improved planting stock, the effective control of competing vegetation (most often using herbicides), fertilization, and thinning. These practices, together or separately, often are perceived to be incompatible with wildlife habitat management and biodiversity conservation (Hartley 2002). However, in addition to conserving land through increased yields, there is growing evidence that forest plantations, if well designed at the stand and landscape levels, are compatible with many biodiversity objectives when applied in the context of managed landscapes.

Erdle and Pollard (2002) examined whether plantations were changing the tree-species composition of eastern Canada's natural forest. They found evidence of reduced diversity evenness in plantations at the landscape level, but at the stand level few plantations were true monocultures and the abundance of high single-species dominance in plantations was similar to that of the natural forests they replaced. Erdle and Pollard also provided several recommendations for establishing plantations to minimize differences with the natural forest. In developing principles for "ecological forestry," Seymour and Hunter (1999) identified the need to increase wood production on a portion of the forest landscape to balance land withdrawals associated with establishing ecological reserves. Their triad approach balanced intensively managed, extensively managed, and ecological reserve areas on a managed forest landscape.

Hartley (2002) reviewed the world's literature on the ecological effects of forest plantations and provided recommendations for how they can be managed to both increase wood fiber needs and satisfy many of the objectives for biodiversity conservation. Carnus et al. (2003) also reviewed the role that plantation forests can play in conserving biodiversity. In many parts of the world, forest plantations are increasingly replacing other human-modified ecosystems (e.g., degraded pasture) and as a result are increasing the diversity of native species in these areas. Hence, plantations can play an important role in conserving or restoring native biodiversity in many landscapes. In addition to providing wildlife habitat, plantations can buffer remnants of native forest and increase the connectivity between areas of native ecosystems.

Herbicides and wildlife

Herbicide use in the forest has been controversial for several decades and continues to be perceived by the general public as risky and inconsistent with ecological aspects of forest management (Wagner et al. 1998*a*,*b*). Potential negative effects of herbicides on non-target organisms and biodiversity have been a key element of public concern about using herbicides in forests (Lautenschlager and Sullivan 2004, Tatum 2004). As a result, the influence of forest herbicide use on wildlife and wildlife habitat has been well researched (Lautenschlager and Sullivan 2002, 2004; Miller and Miller 2004; Tatum 2004).

Reviews of this research indicate that at recommended label rates and under normal use scenarios, herbicide use in forests poses negligible chronic or acute toxicity hazard to domestic or wildlife species, is not mutagenic or oncogenic, and is rapidly eliminated from animal systems once ingested or absorbed (Tatum 2004). The largest influence appears to be on wildlife habitat because vegetation manipulation is the purpose of herbicide use. Studies of forest habitat impacts, however, indicate that although herbicide use may be deleterious for some wildlife species, these effects occur at relatively small spatial scales and for relatively short periods of time (Lautenschlager 1993; deCalesta et al. 2002; Lautenschlager and Sullivan 2002, 2004; Miller and Miller 2004). Affected wildlife populations typically are mobile and generally recover within a short time as vegetation communities recover. It has been widely concluded that the influence of herbicides on wildlife populations must be assessed over longer time periods and in relation to the landscape mosaic and desired future forest conditions (Lautenschlager and Sullivan 2002, 2004). Predictions of long-term consequences for wildlife populations, however, must be tempered by uncertainty about the degree of intensity in vegetation control and the ultimate extent of conifer plantations across future landscapes (Miller and Miller 2004).

Because herbicides can effectively, selectively, and economically manipulate forest vegetation toward desired species composition and community structure, they can be useful tools for managing wildlife habitat. Indeed, several early wildlife habitat management studies (Krefting et al. 1956, Mueggler 1966, Bramble and Byrnes 1972) demonstrated how valuable even the most rudimentary herbicides could be for improving wildlife habitat. Lautenschlager et al. (1995) suggested that by selecting the appropriate herbicide, time, and application method, herbicide treatments can 1) reduce populations of damaging invasive exotic plants, 2) create snags and downed woody material, 3) maintain patches of early-successional vegetation within later successional communities, and 4) maintain woody and herbaceous plant communities for browsing animals. Although herbicides cannot functionally replace fire, they can be used as an alternative to fire for achieving some wildlife management objectives when prescribed burning is not feasible (Wigley et al. 2002). Wigley et al. (2002) also provide examples of studies in which a variety of wildlife habitat objectives have been achieved using herbicides.

Conclusions

Meeting the growing human demand for wood products while conserving land for wildlife management, biodiversity conservation, and other uses is one of the most significant challenges facing forest and wildlife managers. Meeting this challenge will require increasing wood yields on a shrinking forestland base. Thus, intensive silviculture will be required on a greater proportion of the forest landscape. Herbicides are a vital tool for increasing wood volume yields. Results from the longest-term studies (10–30 years) in North America suggested that the range of wood volume yield gains from effectively managing forest vegetation (primarily using herbicides) was 30–450% in Pacific northwestern forests, 10–150% in the southeastern forests, and 50–450% in northern forests (Table 1). Most of the 23 studies examined indicated 30–300% increases in wood volume yield for major commercial tree species and that gains were relatively consistent for a wide range of site conditions.

If herbicides are properly used, current research indicates that the negative effects on wildlife usually are short-term and that herbicides can be used to meet wildlife habitat objectives.

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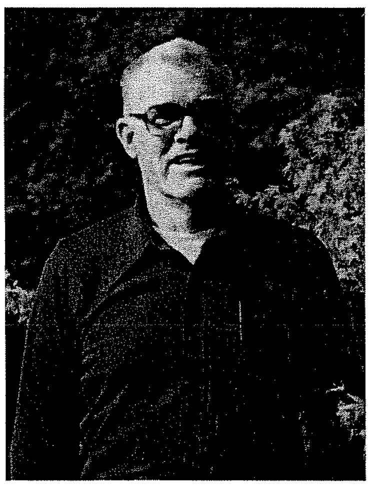
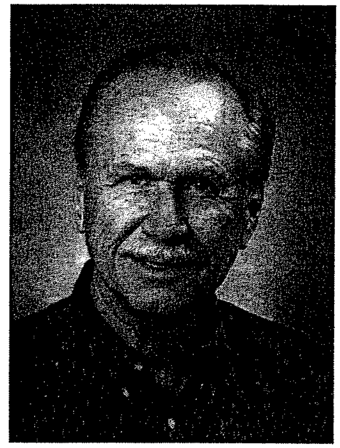
Robert G. Wagner (top left) is the Henry W. Saunders Distinguished Professor in Forestry at the University of Maine. He also serves as Director of the Cooperative Forestry Research Unit (CFRU) and Forest Ecosystem Research Program (FERP). He has over 20 years of experience in forestry research in New England, the U.S. Pacific Northwest, and Canadian boreal forest. He has authored more than 200 scientific and technical publications in the areas of silviculture, forest ecology, and vegetation management. He has a Ph.D. in silviculture from

Oregon State University, an M.S. in forest ecology from the University of Washington, and a B.S. in forest management from Utah State University. ***Michael Newton*** (below right) is Professor Emeritus at Oregon State University's Department of Forest Science, where he has led forest vegetation management, reforestation, and silviculture research programs since late 1959, and, despite retirement, continues as full-time leader of young stand management, riparian and late-successional Douglas-fir forest and habitat management and reforestation programs. He is also leader of major programs in young stand and wildlife management in interior and coastal Alaska. He was leader of biological assessment in a USDA and EPA assessment of 2,4,5-T, and was leader of biological research on behalf of the National Academy of Sciences's Committee of Effects of Herbicides in Vietnam. He has published more than 275 technical and scientific articles and three books on the above subjects. ***Elizabeth C. Cole*** (not pictured) has been a senior research assistant in the Department of Forest Science at Oregon State University since 1988. Her current research includes reforestation in interior and south-central Alaska, pre-commercial thinning in southeast Alaska, wildlife habitat management, riparian buffer management, young stand competition, and stand management in Oregon. She holds a B.S. in forest ecology from Utah State University (1981) and an M.S. in forest ecology from Oregon State University





(1984). ***James H. (Jim) Miller*** (left) is research ecologist and team leader with the USDA Forest Service's Southern Research Station, and affiliate professor of forestry, Auburn University School of Forestry and Wildlife Sciences. For the past 25 years, he has performed research in forest vegetation management, developing integrated vegetation management treatments for sustainable forestry and human land use. He has regional responsibilities and directs an internationally recognized research project at 13 sites in 7 states that has been underway for 20 years. He has published over 100 scientific and popular reports; most noteworthy is the book and CD-version entitled *Forest Plants of the Southeast and Their Wildlife Uses* (1999), coauthored with Karl Miller, University of Georgia. More recently he has authored *Nonnative Invasive Plants of Southern Forests: A Field Guide for Identification and Control*. ***Barry D. Shiver*** (right) is professor of timber management and silviculture at the Warnell School of Forest Resources at the University of Georgia in Athens. Dr. Shiver is the Director of the Plantation Management Research Cooperative, which has conducted research for 30 years on improving southern pine plantation management through better understanding of silvicultural responses and incorporating those responses into growth and yield models

Special Section Associate Editor: *Wigley*

Georgia losing millions of acres of forest, timberland to resident commercial development

A new study by forest economists at the University of Georgia and the U.S. Forest Service portends a loss of millions of acres of forestla coming decade, along with the economic, aesthetic and watershed protection it provides.

"Land markets, manifested through timber taxes, are changing rapidly," said UGA forest economist David Newman, co-author of the st other states, Georgia has few incentives in place to stop or even slow this conversion."

The study shows low-density residential and suburban growth is having a greater than expected impact on land prices–and the sustain supplies in the South. Spurred by rising land values and higher property taxes, several large forest products companies sold off their Ge holdings in recent years.

Authored by Newman and colleague David Wear, a U.S. Forest Service scientist in Durham, North Carolina, the study was published in issue of the Journal of Forestry. In it, researchers say about 25 percent of industrial timberland in Georgia will be in a high-conversion years.

"We used Georgia as a case study for the effects of rising timberland prices because it is representative of the kinds of land-use dynamic South," said Newman.

Researchers say the biggest changes–and losses of forestland–will occur along the I-85 corridor in the Piedmont and coastal areas of th unlike some other southeastern states, which provide tax benefits based on land productivity types, Georgia has no such "brakes" in pla conversion. Rising property taxes cut profits for timberland companies but often force individual timberland owners to sell as well, reir

"The Georgia study helps us see the situation from the perspective of the landowners," said Wear, "especially those in the urban fringe, occurring so quickly." Wear was co-leader of the 2002 Southern Forest Resource Assessment, an effort by multiple state and federal ag factors influencing forests in the southeastern U.S.

Researchers used spatial patterns of assessed forestland prices in Georgia to make predictions about the future use of lands in quickly c study, they viewed land valued at $800 per acre and above in a high-conversion class; that is, land that is likely to be sold and converte land to other uses in the next five years. Using price and other predictors such as population density, household income and farm earni that by 2010 another 5.6 million forested acres in the state across 33 counties will convert to subdivisions, roads and other commercial

"And these estimates of the potential impact of development on timberland prices are conservative," said Newman, "because our resear counties that have five or more industry-owned timberland tracts. As a result, we did not even look at counties in the northern most co about 25 percent of the state."

The researchers point out that forest land isn't necessarily "lost" when sold. Many large tracts, divided and sold to as "woodlets," remai bought by owners to use for aesthetic and lifestyle purposes. Still, the trend creates a system in which a major portion of timberland wil with little or no knowledge or experience in forest management.

"The real strength of the Georgia study is that it uses specific land values, and price is the strongest evidence of where future growth is l Wear. "It also shows that development pressure is going to have a significant effect not just in Georgia, but on timberland across the So

Contact: David Newman, dnewman@arches.uga.edu 706-542-7649
Contact: Dave Wear, dwear@fs.fedus 919-549-4011