PERSPECTIVES ON USING PRESCRIBED FIRE TO ACHIEVE DESIRED ECOSYSTEM CONDITIONS

James M. Vose
U.S. Department of Agriculture, Forest Service, Southern Research Station, Coweeta Hydrologic Laboratory, 3160 Coweeta Lab Road, Otto, NC 28763

ABSTRACT

Fire is a potentially powerful tool for achieving desired conditions of forest ecosystems. From an ecological perspective, the use of fire requires affirmative answers to either of the following questions: (1) Does it increase ecosystem health and sustainability? and (2) Does it preserve or restore unique species or habitats? Health and sustainability can be measured and defined in terms of: (1) rates and pool size of water, carbon, and nutrient cycling, (2) resistance and resilience to low-intensity and -severity disturbance, and (3) minimizing the likelihood of catastrophic disturbances. The departure of current ecosystem conditions from desired ecosystem conditions (defined by structural and functional characteristics) depends on the history of land use and disturbance. The disturbance history also influences the rate of attainment of desired conditions and the magnitude of ecosystem process response to burning. Hence, from an ecosystem perspective, managers must understand the interactions among land use history, current conditions, and desired conditions. These issues are examined using a case study for using prescribed fires in the southern Appalachian Mountains.

keywords: desired ecosystem condition, ecosystem analysis, prescribed fire, resistance-resilience model.

Citation: Vose, J.M. 2000. Perspectives on using prescribed fire to achieve desired ecosystem conditions. Pages 12-17 *in* W. Keith Moser and Cynthia F. Moser (eds.). Fire and forest ecology: innovative silviculture and vegetation management. Tall Timbers Fire Ecology Conference Proceedings, No. 21. Tall Timbers Research Station, Tallahassee, FL.

INTRODUCTION

Prescribed fire is a powerful management tool for altering the structure and function of forest ecosystems. The effects of prescribed fire depend on its intensity and severity. At the extremes, fires of high intensity and severity can have a greater effect on ecosystem structure and function than clear-cutting or other intensive management practices. For example, site preparation burning can result in nitrogen (N) losses comparable to whole-tree harvesting (Vose and Swank 1993). Momentum has been building for increased use of fire on public lands for fuel load reduction and ecosystem restoration. It appears that fire will play an increasingly important role in forest management for both silvicultural and ecological objectives on public land, and perhaps on private land as well. To be successful, managers will need to understand both short- and long-term effects on the whole system, not just narrowly defined silvicultural objectives, and consider the role of fire in ecosystem health and sustainability.

A large body of knowledge exists on the ecological effects of fire in ecosystems with a long history of prescribed burning (e.g., southern pines) or those with a well recognized fire regime (e.g., ponderosa pine). In some cases, however, fire is or will be reintroduced into ecosystems that have not been burned for a century (due to fire exclusion). Little research has been conducted on these ecosystems, and we lack knowledge and guidelines for their management. The challenge in these less well-understood systems will be to integrate our understanding of historical disturbance regimes, current ecosystem conditions, and the use of fire to achieve desired ecosystem conditions. This paper provides an ecosystem-based framework for evaluating the use of fire for either silvicultural or ecological objectives.

EVALUATING THE USE OF FIRE FROM AN ECOSYSTEM PERSPECTIVE

The application of a prescribed fire is driven by the goal to obtain a desired outcome or future condition of the forest. Historically, these desired future conditions have encompassed only such silvicultural goals as fuel reduction, competition reduction to promote commercial species, or site preparation. More recently, desired future conditions have been expanded to include more ecologically based goals, such as restoration of fire-dependent ecosystems. In fact, fires prescribed for silvicultural goals often produce "by-product" ecological effects that may be compatible or incompatible with pre-defined short- or long-term silvicultural goals. Hence, the term "desired ecosystem condition" is a more appropriate term for describing the desired outcome from prescribed fire. Regardless of whether the desired ecosystem condition is silviculturally or ecologically based, an ecosystem perspective requires that the decision to use fire to attain desired future conditions results in affirmative answers to either of the following questions: (1) Will the result increase ecosystem health and sustainability? and (2) Will the result preserve or restore unique species and/

or habitats? Depending on the ecosystem type, answers to questions (1) and (2) can be either compatible or mutually exclusive. For example, maintaining unique species adapted to low nutrients and high light may require high-intensity and -severity fires that substantially reduce site nutrient capital.

ECOSYSTEM HEALTH AND SUSTAINABILITY

Ecosystem health and sustainability are terms whose definitions have been subject to debate, but they can be defined and measured in terms of carbon, nutrient, and water cycling rates and pool sizes; resistance and resilience to low-intensity and -severity disturbance; and resistance to catastrophic disturbances. It is beyond the scope of this paper to describe the effects of fire and fire exclusion for each of these terms, but a few general examples are described below.

One of the consequences of fire exclusion is a change in the amount, distribution, and availability of ecosystem carbon and nutrient pools. For the purposes of this discussion, N will be the primary focus because it most often limits ecosystem productivity (Raison 1980, Vitousek et al. 1982), has a low volatilization temperature (i.e., N is converted to gas phase and lost from the site at lower temperatures than most nutrients) (Boerner 1982), and has a strong biological control on its availability and mobility. Although most ecosystems contain considerably more N than is required for plant growth most of that N is in unavailable organic forms. The N-cycle provides a continual supply of N for ecosystem productivity through mineralization of organic N and symbiotic and non-symbiotic N-fixation of atmospheric N. Fire exclusion increases the amount of N in unavailable forms (i.e., greater aboveground organic matter) and reduces the abundance of N-fixers. In many ecosystems, burning provides an immediate pulse of available soil N (Covington and Sackett 1986), increases N-mineralization (Knoepp and Swank 1993), and increases N-fixation (Jorgensen and Wells 1971). Hence in the case of N, burning increases ecosystem health and sustainability because "natural fire regime" components of the N-cycle are reestablished.

These responses are not always consistent, however. Variations in response patterns are most likely a function of differences in the initial condition of the ecosystem and fire characteristics (e.g., season of burn, fire severity and intensity). In some cases, repeated fires may be required to reestablish fire-mediated components of the N-cycle. It should be noted, however, that prescribed fire may not always have a positive effect on the N-cycle. For example, in situations where extremely severe fires consume large amounts of the aboveground N pool, N losses can be large and may have long-term negative consequences for ecosystem health and sustainability.

Resistance and resilience (Waide 1988) to low-intensity and low-severity disturbance, and resistance to catastrophic disturbances, are components of ecosystem health and stability that encompass both ecological and societal concerns. Ecosystems that have been repeatedly burned have evolved mechanisms to (1) resist the overall impacts of burning (e.g., thick bark, sprouting, serotiny), and (2) recover quickly (i.e., resilience) so that ecosystem processes, such as nutrient cycling or plant population dynamics, equal or exceed pretreatment rates shortly after burning (Gilliam 199 1, Keeley 1991). One of the impacts of fire exclusion is to reduce both resistance and resilience characteristics of forest ecosystems. For example, heavy fuel accumulation may result in fire intensity and severity levels mat exceed the lethal threshold in thick-barked species. Similarly, species directly or indirectly dependent upon fire for regeneration (e.g., buried seed, serotinous cones, mineral soil conditions) may be lost from the ecosystem in the interval between burning. While some ecosystems are dependent upon high-intensity and -severity or catastrophic fires for succession (e.g., lodgepole pine), fire exclusion has increased the likelihood of catastrophic fires in forest ecosystems more adapted to low-severity and -intensity fire. Fuel accumulation, vertical distribution of fuels (i.e., fuel ladders), and human encroachment into the wildland-urban interface have heightened political awareness of the societal consequences of continued fire suppression in fire-evolved ecosystems.

DESIRED ECOSYSTEM CONDITIONS

Prescribed burning is conducted to achieve short-term and/or long-term desired ecosystem condition(s). Desired ecosystem conditions can be classified into 4 general types: (1) attainment of "pristine" or natural forest ecosystem conditions approaching those existing prior to human influence (or pre-European settlement), (2) altering the structure and function (e.g., diversity, nutrient cycling rates, vertical structure) of the ecosystem to achieve a more healthy and sustainable condition, (3) creating and maintaining unique habitats and species, and (4) increasing value of commercial species (e.g., timber, wildlife). The first condition (i.e., attainment of a "pristine" or natural forest) is particularly controversial, as many argue that re-creation of natural forest conditions can never be obtained because of human influence. While this argument may be true to some extent, it is naive to ignore the evolutionary context of many fire-evolved ecosystems in North America. The biota and functional attributes of every ecosystem have evolved in response to environmental oscillations of certain types, magnitudes, and periodicities (Waide 1988). For example, thousands of years of periodic burning has generated species adaptations (e.g., serotinous cones, buried seed strategies) to burning that a few hundred years of fire exclusion have not altered. Hence, creation of ecosystems approaching "pristine" or natural forest conditions is an achievable goal, although research will be required to determine the best techniques and attainment metrics. Several tools are available to use as guides to historical and prehistorical conditions of forest ecosystems. For ex-

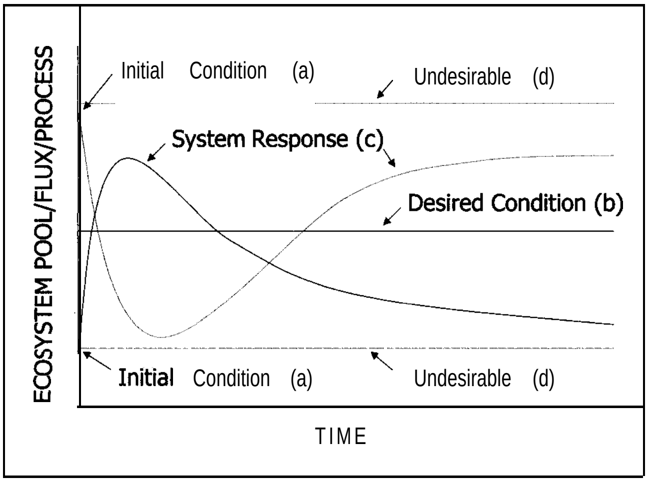

Fig. 1. Conceptual diagram depicting initial ecosystem condition (a) and ecosystem response (c) to burning relative to undesirable (d) and desired future condition (b).

ample, vegetation composition and fire frequency can be re-created from analyses of charcoal and pollen in lake and bog sediments (Clark and Royal1 1996, Clark et al. 1996) or soil organic matter analysis (Krioepp et al. 1998). In addition, historical accounts by early explorers often provide anecdotal evidence of the structure of presettlement forests. Although it is unrealistic and perhaps undesirable on a large scale, restoring portions of contemporary forests to presettlement conditions is a management goal for many fire-dependent ecosystems in the United States (e.g., southwestern ponderosa pine, southeastern longleaf pine, southern Appalachian pine/hardwood, southern Appalachian balds).

It can be argued that prescribed fire provides a reasonable approach to achieve these general conditions; and at a landscape scale, it will be necessary to attain all of them in order to produce multiple ecosystem benefits. The challenge for land managers is to identify and apply the correct combination of current ecosystem conditions, prescribed fire techniques, and monitoring (short- and long-term) of key ecosystem parameters to determine whether desired ecosystem conditions are attained, without compromising ecosystem health and sustainability.

CURRENT ECOSYSTEM CONDITION

The structure and function of an ecosystem is the net result of the complex interactions among environment, species, and historical and contemporary disturbances (i.e., the disturbance legacy). The importance of disturbance varies geographically, but in the eastern United States, disturbance is probably the single most important factor determining current ecosystem condition. The disturbance legacy of an ecosystem has the following effects; it (1) determines the magnitude of departure of current conditions from desired ecosystem conditions, (2) influences the rate of attainment of desired ecosystem conditions, and (3) influences the magnitude of response to burning. Figure 1 illustrates these points using a hypothetical ecosystem described in terms of resistance (i.e., the magnitude of departure along the Y-axis) and resilience (i.e., the rate of return to desired conditions along the X-axis) to disturbance (Waide 1988). The resistance-resilience model has provided a theoretical basis for understanding ecosystem responses to disturbance for >20 years (Webster et al. 1975, Waide and Swank 1976). In its original formulation, organic matter pool sizes and turnover rates were key indices. For example, ecosystems with large organic matter or nutrient pools were hypothesized to be most resistant to disturbance, while small organic matter or nutrient pools with rapid turnover rates were indices of resilient ecosystems (Webster et al. 1975).

The resistance-resilience model is useful for evaluating ecosystem responses to fire, but a modification of the key concept of high organic matter and nutrient pools and resistance must be made. One of the primary effects of fire exclusion is a considerable accumulation of organic matter and nutrient pools in both living and dead biomass. In contrast to resistance-resilience theory, ecosystems with high aboveground organic matter pools (i.e., fuels) are considerably less resistant to high-intensity and -severity fires than ecosystems with low organic matter pools. In application of the resistance-resilience model to the reintroduction of fire to fire-evolved forest ecosystems, the "Initial Condition (a)" represents the current state of the ecosystem relative to the "Desired Ecosystem Condition (b)." As noted in Figure 1, this initial condition can be evaluated based on pool sizes or process rates. Burning causes the ecosystem to respond ("c" in Figure 1) (e.g., changes in pool size and cycling rate), and the magnitude and duration of the response vary with the initial condition and the burning technique. In fact, combinations of initial conditions and various burning techniques may result in "Undesirable (d)" short- or long-term responses. These combinations are represented as thresholds beyond which changes in pool sizes or processes result in responses that reduce ecosystem health and sustainability. After the initial effects of burning, the ecosystem reaches a new, though rarely static, condition. Attainment of the desired ecosystem condition may occur several years after the burn and may be transient. Understanding the timing and duration of attainment of desired ecosystem conditions is important for determining the necessary return interval for additional prescribed bums.

The information presented above provides a conceptual framework for evaluating the application and effects of prescribed fire from an ecological perspective. The resistance-resilience model provides a tool for evaluating ecosystem response based on departure from desired conditions and the ability to converge to desired ecosystem conditions after prescribed fire. The following case study provides an example of how these concepts can be applied in a "real world" situation.

CASE STUDY APPLICATION OF ECOSYSTEMS APPROACH

The disturbance legacy of southern Appalachian ecosystems is dominated by anthropogenic influences.

Like many areas in the eastern United States, forests in the southern Appalachian region evolved under a fire regime of low intensity and high return interval. Fires were primarily set by Native Americans, who used fire to improve agriculture and hunting for lO,OOO-12,000 years (DeVivo 1991). Beginning in the mid-1800's European settlers also used fire, in combination with land clearing; nearly the entire southern Appalachian region was logged at the turn of the century (Stephenson et al. 1993). Smaller-scale logging, chestnut blight, woodland grazing, reversion of agricultural lands to forest, and fire exclusion have further shaped these ecosystems.

While the structure and function of all forest ecosystems in the southern Appalachians have been influenced by historic and contemporary disturbance, one of the most severely impacted forest types is the pitch pine-mixed hardwood ecosystem. These ecosystems typically occupy the most xeric sites (south- or west-facing ridges) and comprise primarily scattered dry site hardwoods (e.g., scarlet oak [*Quercus coccinea*], chestnut oak [Q. *prinus*], red maple [*Acer rubrum*]) and pines (pitch pine [*Pinus rigida*], shortleaf pine [*P. echinata*], and Virginia pine [*P. virginiana*]). A combination of past land use, fire exclusion, drought, and southern pine beetle infestation has caused substantial pine mortality (Smith 1991) and a lack of regeneration of all overstory species as mountain laurel (*Kalmia latifolia*) increases in the shrub layer. The maintenance of pine-hardwood ecosystems is hypothesized to depend on intense fire (Barden and Woods 1976). In fact, pitch pine has a combination of serotinous and non-serotinuous cones, indicating an evolutionary adaptation to intense fires. Because of the abundance of flammable understory species (primarily *K. latifolia*) and dry fuels (due to exposure), these sites were probably subjected to more intense fires than most other forest types under both anthropogenic and natural fire regimes.

Due to the combined effects of historic and contemporary disturbances and fire exclusion, the current condition of most pine-hardwood ecosystems in the southern Appalachians is generally characterized by:

1. high overstory mortality and slow growth rates,
2. inhibited regeneration of overstory species,
3. increased density and biomass of ***K. latifolia*** in the shrub layer,
4. heavy fuel loads (i.e., large nutrient and carbon pools) in the forest floor and shrub layer,
5. decreased herbaceous abundance and diversity, and
6. increased susceptibility to insect infestations.

All of the guidelines for determining desired future conditions could be applicable to degraded pine-hardwood ecosystems. For example, prescribed fire could be used to (1) re-create ecosystem conditions expected under the pre-European settlement fire regime (i.e., occasional high-intensity fires), (2) change the current structure and function of the ecosystem to a new set of ecologically based conditions (i.e., increase N cycling, increase pine regeneration), (3) preserve current conditions of the pine-hardwood mixture, or (4)

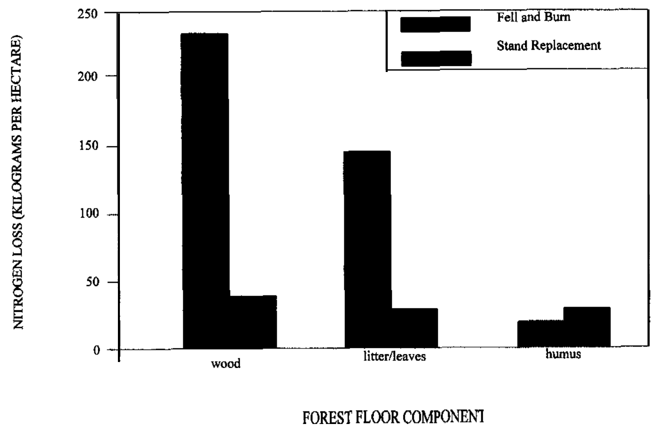

Fig. 2. Comparison of aboveground nitrogen losses between Fell and Burn and Stand-Replacement fires by forest floor component (wood, litter, humus).

change the current structure and function of the ecosystem to achieve silviculturally based objectives. As noted previously, these guidelines are not mutually exclusive and often overlap.

For the past 15-20 years, prescribed fire has been applied as a management tool in pine-hardwood ecosystems using an approach called the "fell and burn" technique. After merchantable products are removed, all standing vegetation is chainsaw-felled in the early summer. Fuels are allowed to cure and cut stumps to resprout. In late summer or early fall, the site is burned with a high-intensity (but low-severity) fire and planted to white pine (*P. strobus*) on a wide spacing. The silvicultural objective is to increase overall productivity of commercial species and reduce susceptibility to insect damage (i.e., "[4] change the current structure and function of the ecosystem to achieve silviculturally based objectives"). Recent ecosystem studies (Swift et al. 1993) of this burning technique have shown that the treatment satisfies, at least in the short term, the silvicultural objectives of increased productivity and insect resistance of commercial species (i.e., ***P. strobus***) (Clinton et al. 1993). In addition, the technique has a positive effect on many other ecosystem attributes, such as regeneration of other pine species native to the site (Clinton et al. 1993, Vose et al. 1994), increased soil N availability (Knoepp and Swank 1993), and increased diversity (Clinton and Vose, ***this volume***). However, the large fuel loading resulting from long-term fire exclusion, the felling and curing of existing vegetation, and high-intensity burning interact to cause large losses of total site N (Figure 2), which equal or exceed N losses expected from whole-tree harvest. These losses need to be evaluated in the context of other N-cycle components, such as N-fixation and atmospheric deposition, which add N to the ecosystem. For example, in the southern Appalachians about 26 kilograms N per hectare are added annually in atmospheric deposition and symbiotic and asymbiotic fixation (Swank and Vose 1988, Swank and Vose 1997). Nitrogen lost as a result of this prescription would require roughly 10–15 years to be replaced.

Using the ecosystem-based approach to evaluate the "fell and burn" technique in pine-hardwood ecosystems, the following conclusions can be reached:

1. Site disturbance history resulted in large carbon and nutrient pools in aboveground material.
2. Felling and curing the aboveground material caused substantial fuel consumption and subsequent losses of site N.
3. While the treatment resulted in short-term achievement of desired ecosystem conditions, long-term improvement may not be achieved due to large losses of site N.
4. Treatments used to obtain specific silvicultural objectives also resulted in other positive effects, such as increased herbaceous abundance and diversity.

Did this treatment alter the health and sustainability of the ecosystem? Overall, prescribed burning increased the health and sustainability of the ecosystem by increasing diversity and productivity (Clinton et al. 1993, Elliott and Vose 1993, Clinton and Vose, *this* volume), stimulating N cycling (Knoepp and Swank 1993), and reducing fuel loading (Vose and Swank 1993). The only potential negative impact is large losses of site N, which may impact long-term site productivity. These losses could be detected only by using an ecosystem approach to evaluating the use of prescribed fire. In application, this knowledge was used to modify burning prescriptions to minimize N losses but still improve the condition of degraded pine-hardwood stands (Vose et al. 1997).

CONCLUSIONS

The concepts and application described above provide a whole-system context for using prescribed fire in forests. While it is unrealistic to expect monitoring of all ecosystem components, it is clear that certain ecosystem components are key "indices of ecosystem health and sustainability." Four of the most important indicators are: (1) maintenance or enhancement of site nutrient capital and cycling rates, (2) enhanced productivity and regeneration of keystone species, (3) increased resistance to insect and disease, and (4) risk reduction from catastrophic disturbance. Short- and long-term monitoring of these components will be particularly critical as managers reintroduce fire into less well-studied ecosystem types.

LITERATURE CITED

Barden, L.S., and F.W. Woods. 1976. Effects of fire on pine and pine-hardwood forests in the southern Appalachians. Forest Science 22:399–403.

Boemer, R.E.J. 1982. Fire and nutrient cycling in temperate ecosystems. Bioscience 32: 187-192.

Clark, J.S., and PD. Royall. 1996. Local and regional sediment charcoal evidence for fire regimes in presettlement in northeastern North America. Journal of Ecology 84:365–382.

Clark, J.S., T. Hussey, and PD. Royall. 1996. Presettlement analogs for quatemary fire regimes in eastern North America. Journal of Paleolimnology 16:76–96.

Clinton, B.D., J.M. Vose, and W.T. Swank. 1993. Site preparation to improve southern Appalachian pine-hardwood stands: vegetation composition and diversity of 13-year-old stands. Canadian Journal of Forest Research 23:2271–2277.

Clinton, B.D., and J.M. Vose. In press. Plant succession and community restoration following felling and burning in the southern Appalachians. *In* W.K. Moser (ed.). Fire and forest ecology: innovative silviculture and vegetation management. Tall Timbers Fire Ecology Conference Proceedings 21.

Covington, W.W., and S.S. Sackett. 1986. Effect of periodic burning on soil nitrogen concentrations in ponderosa pine. Soil Science Society of America Proceedings 50:452–457.

DeVivo, M.S. 1991. Indian use of fire and land clearance in the southern Appalachians. Pages 306-312 *in* S.C. Nodvin and T.A. Waldrop (eds.). Fire and the environment: ecological and cultural perspectives. Proceedings of an international symposium. General Technical Report SE-69, U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station, Asheville, NC.

Elliott, K.J., and J.M. Vose. 1993. Site preparation burning to improve southern Appalachian pine-hardwood stands: photosynthesis, water relations, and growth of planted *Pinus strobus* during establishment. Canadian Journal of Forest Research 23:2278–2285.

Gilliam, ES. 1991. The significance of fire in an oligotrophic forest ecosystem. Pages 113-122 *in* S.C. Nodvin and T.A. Waldrop (eds.). Fire and the environment: ecological and cultural perspectives. Proceedings of an international symposium. General Technical Report SE-69, U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station, Asheville, NC.

Jorgensen, J.R., and C.G. Wells. 1971. Apparent nitrogen fixation in soils influenced by prescribed burning. Soil Science Society of America Proceedings 35:806–810.

Keeley, J.E. 1991. Fire management for maximum diversity of California chaparral. Pages 11-15 *in* S.C. Nodvin and T.A. Waldrop (eds.). Fire and the environment: ecological and cultural perspectives. Proceedings of an international symposium. General Technical Report SE-69, U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station, Asheville, NC.

Knoepp, J.D., and W.T. Swank. 1993. Site preparation to improve southern Appalachian pine-hardwood stands: nitrogen responses in soil, soil water, and streams. Canadian Journal of Forest Research 23:2263–2270.

Knoepp, J.D., L.L. Tieszen, and G.G. Fredlund. 1998. Assessing the vegetation history of three southern Appalachian balds through organic matter analysis. Research Paper SRS-13, U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC.

Raison, R.J. 1980. A review of the role of fire in nutrient cycling in Australian native forests, and the methodology for studying the fire-nutrient interaction. Australian Journal of Ecology 5:15–21.

Smith, R.N. 1991. Species composition, stand structure, and woody detrital dynamics associated with pine mortality in the southern Appalachians. M.S. Thesis, University of Georgia, Athens.

Stephenson, S.L., A.N. Ash, and D.F. Stauffer. 1993. Appalachian oak forests. Pages 255-303 *in* Biodiversity of the Southeastern United States: upland terrestrial communities. John Wiley and Sons, New York.

Swank, WT., and J.M. Vose. 1988. Effects of cutting practices on microenvironment in relation to hardwood regeneration. Pages 71-88 *in* H.C. Smith, A.W. Perkey, and W.E. Kidd, Jr. (eds.). Proceedings of the workshop on guidelines for regenerating Appalachian hardwood stands. West Virginia University Books, Office of Publications, Morgantown.

Swank, WT., and J.M. Vose. 1997. Long-term nitrogen dynamics of Coweeta forested watersheds in the southeastern United States of America. Global Biogeochemical Cycles 11: 657-671.

Swift, L.W., K.J. Elliott, R.D. Ottmar, and R.E. Vihnanek. 1993.

Site preparation burning to improve southern Appalachian pine-hardwood stands: fire characteristics and soil erosion, moisture, and temperature. Canadian Journal of Forest Research 23:2242–2254.

Vitousek, PM., J.R. Gosz, C.C. Grier, J.M. Melillo, and W.A. Reiners. 1982. A comparative analysis of potential nitrification and mobility in forest ecosystems. Ecological Monographs 52:155–177.

Vose, J.M., and W.T. Swank. 1993. Site preparation burning to improve southern Appalachian pine-hardwood stands: aboveground biomass, forest floor mass, and nitrogen and carbon pools. Canadian Journal of Forest Research 23: 2255-2262.

Vose, J.M., W.T. Swank, and B.D. Clinton. 1994. Fire, drought, and forest management influences on pine/hardwood ecosystems in the southern Appalachians. Pages 232-238 *in* Proceedings, 12th international conference on fire and forest meteorology. Society of American Foresters, Bethesda, MD.

Vose, J.M., W.T. Swank, B.D. Clinton, R.L. Hendrick, and A.E. Major. 1997. Using fire to restore pine/hardwood ecosystems in the southern Appalachians of North Carolina. Pages l-6 in J.M. Greenlee (ed.). Proceedings of the first conference on fire effects on rare and endangered species and habitats. International Association of Wildland Fire, Fairfield, WA.

Waide, J.B. 1988. Forest ecosystem stability: revision of the resistance-resilience model in relation to observable macroscopic properties of forest ecosystems. Pages 383-406 in W.T. Swank and D.A. Crossley (eds.). Forest hydrology and ecology at Coweeta. Ecological Studies 66. Springer-Verlag, New York.

Waide, J.B., and W.T Swank. 1976. Nutrient recycling and the stability of ecosystems: implications for forest management in the southeastern United States. Pages 404–424 *in* Proceedings of the 1975 National Convention of the Society of American Foresters. Society of American Foresters, Bethesda, MD.

Webster, J.R., J.B. Waide, and B.C. Patten. 1975. Nutrient recycling and the stability of ecosystems. Pages l-27 *in* EG. Howell, J.B. Gentry, and M.H. Smith (eds.). Mineral cycling in southeastern ecosystems. ERDA Symposium Series (CONF-7405 13), National Technical Information Service, Springfield, VA.