

What is pine decline in the southeastern United States and how widespread is it?

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Abstract. Pine decline is a relatively new forest health issue resending itself across the southeastern United States. The problem appears most severe where loblolly pine was established on sites that historically supported longleaf pine, or on highly eroded soils, or where stand density management has been absent. Pine decline has also been reported in stands atypical of these sub-optimal conditions such as planted longleaf pine forests. Observations suggest it is caused by environmental stress arising from interaction among resource availability, weather, insects and fungal pathogens, anthropogenic disturbances, and forest management. One of its signs is the pathogenic cycle of *Leptographium* spp. root disease. The current knowledge of pine decline was the topic of a recent workshop. Our purpose is to summarize this problem, and distill information gained from the workshop regarding the scope of this issue and avenues of research to counter its effect on the sustainability of southern pine forests. The scope of pine decline appears regional. But, with research that (1) evaluates the conditions predisposing stands to pine decline, (2) assesses tree mortality to determine the extent and spread of pine decline, and (3) predicts the susceptibility, spread, and impact associated with this problem, forest managers can avoid further loss and maintain an array of land management expectations.

Introduction

Observations of Pine Decline

Several reports have suggested that since 1990 there has been an increase in the occurrence of localized forest health problems in southern pine systems (Ostrosina et al. 1999, Hess et al. 1999, 2005a, 2005b, Menard et al. 2006, Eckhardt et al. 2007). These observations are referred to as “pine decline” and are characterized by sparse, chlorotic crowns, low annual stemwood production, and isolation of fungal pathogens from the root system (Brown and McDowell 1968, Ostrosina et al. 1999, Eckhardt et al. 2007). Mortality may occur within three years after symptoms are observed (Hess et al. 2005b, Eckhardt et al. 2007). Many of these reports are species- and site-specific (e.g. Fort Benning, GA; Oconee NF, GA; Talladega and Tuskegee National Forests, AL; Shaw AFB, SC; Sumter National Forest, SC; Davey Crockett National Forest, TX). However, the regional scope of these observations indicates that multiple species and locations may be at risk. The majority of these events have occurred in mature loblolly pine (*Pinus taeda* L.) and mixtures of mature loblolly and shortleaf pine (*Pinus echinata* Mill.) near the interface between the Piedmont Province and either the East Gulf Coastal Plain or the Atlantic Coastal Plain physiographic regions, and in the Fall-line Sandhills between these regions. Loblolly pine is considered “off-site” at many of these locations which historically supported longleaf pine (*Pinus palustris* Mill.) (Hess et al. 1999, 2005a, Menard et al. 2006). Recent evidence further suggests that this forest health problem affects younger forest types including planted longleaf pine (Menard et al. 2006, Menard 2007, Zanzot and Eckhardt *unpublished data*).

Evidence of a decrease in the growth rate of southern pine has been reported over the last decade by the United States Department of Agriculture, Forest Service, Forest Inventory Analysis (FIA), although no casual factors have been identified (Bechtold et al. 1991, Ward and Mistretta 2002, Gadbury et al. 2004). Other studies investigating southern pine decline have reported reductions in growth associated with abiotic and biotic stress factors (Hess et al. 1999, Ostrosina et al. 1999, 2002, Menard et al. 2006, Eckhardt et al. 2007). These studies suggest that southern pines exhibiting reduced growth may be experiencing a decrease in vigor. Observations of reduced growth and vigor have occurred simultaneously with high levels of southern pine beetle

(*Dendroctonus frontalis* Zimmermann) (SPB) infestation which is indicative of reduced vigor (Hicks et al. 1980, Blanche et al. 1983, Schultz 1997). This information indicates there may be predisposing conditions across the southeastern U.S., reducing the vigor of the southern yellow pines, and making them susceptible to insect pests and pathogenic fungi that independently colonize a tree, or are vectored by insect pests.

A possible increase in the type or extent of forest health problems in southern pine systems is significant because these forests are a dominant landscape feature in the southeastern United States, and are necessary to meet regionally important ecological (e.g. wildlife recovery) and nationally important economic (e.g., timber and non-timber forest products) expectations (Prestemon and Abt 2002, Trani 2002). Potential setbacks to the former are particularly problematic because during the past 15 years, public land management in the South has emphasized longleaf pine ecosystem restoration to support the habitat needs of “at risk” species such as the red-cockaded woodpecker (*Picoides borealis* (Vieillot) (Owen 2002, Hootor et al. 2006). In the process of restoration, many areas supporting “off-site” species, or forests characterized by poor health have already been converted to more appropriate pine species that are congruent to restoration efforts (Stanturf et al. 2004).

As with any new forest health issue appearing scattered across several states, there is concern that this potential problem will be overlooked and subsequently, become a serious risk to southern pine forest health. Before research is designed to understand and counter this emerging forest health issue, an accurate and unbiased evaluation of the problem and its extent is necessary. This evaluation should include information regarding early detection and risk assessment to provide prompt guidance as management decisions are made focused on reducing the scope and impact of the problem are made.

The Pine Decline Environment

Initial reports of loblolly pine decline recognized that its occurrence was tied to unusual physiological and environmental conditions (Roth and Peacher 1971, Miller 1979). Presently, this forest health problem is associated with several abiotic and biotic stressors (Otrosina et al.

1999, Hess et al. 2005a). These include: (1) the availability of intrinsic soil resources that control the carrying capacity of a site, (2) stochastic weather events and patterns, (3) resource limitations that affect the ecology of insects and fungal pathogens, or exacerbate host susceptibility to insect damage and disease (Eckhardt et al. 2007), (4) the legacy effects of anthropogenic disturbances such as farming and military training on site quality (Otrosina et al. 1999, Menard et al. 2006), (5) impacts of rigorous forest management activities such as frequent prescribed burning on forest sustainability (Otrosina et al. 1999), and (6) root disease (Brown and McDowell 1968, Otrosina et al. 1999, Eckhardt et al. 2007).

Pine decline is primarily found in three forest settings: (1) “off-site” plantings or under-managed conditions, (2) forest ages greater than 50 years, and (3) forests characterized by high stand densities that lead to overstocking (Conner and Hartsell 2002). Information from public land managers (Conner et al. 2004, Gadbury et al. 2004, Atkinson 2006, Johnson and Wells 2006, Thomas 2006, Crawford 2007), and consensus findings from this workshop suggest pine decline is not currently a catastrophic regional forest health problem, rather, it is a localized problem arising from two themes. First, pine decline appears to be more prevalent when the more resource-demanding of the southern pines (i.e., loblolly and shortleaf pine) are planted on sites that originally supported the less resource demanding of the southern pines (i.e., longleaf pine) (Hess et al. 1990, 2005b). Second, this phenomenon is observed on sites characterized by soil resource limitations inherent to a site or resulting from past land-use decisions (Otrosina et al. 1999, Menard *et al.* 2006).

Clearly, there is some indication that the function and productivity of southern yellow pine forests, including those planted and naturally established, may be at risk from pine decline. At broader scales, such a problem would have serious landscape and watershed implications as well as an effect on local economies that depended on the forest products industry. Based on current forest pathology work, the problem appears to be due to: (1) the combined effects of multiple stressors rising from site quality, climate variation, and past and current land uses, (2) opportunistic root pathogens that worsen tree physiological responses to multiple stressors, (3) a higher susceptibility of mature or maturing plantations compared to seedling and sapling stands, and (4) in some situations, imbalances in populations of insect pests, and root infesting fungi.

If such a forest health problem exists and effective remedial actions are needed, several questions must be answered: (1) first and foremost, what is its scope and impact, (2) what are the direct and indirect causes of the problem, (3) have past land uses or current forest management activities contributed to the problem, and if so, how, (4) are there forest management activities that reduce, or mitigate the problem, and lastly, (5) across disciplines, what are the short- and long-term implications if southern yellow pine forest types are compromised by pine decline. With information from the workshop previously mentioned, our objective is to summarize the information needed to determine the extent of pine decline, what causes it, and how forest management can be adapted to temper its negative effects on the health of southern yellow pine forests.

Background on Pine Decline Established at the Workshop

Regional Land-use and Forest Health Setting

Most of the Atlantic and East Gulf Coastal Plains, lower Piedmont Province, and Fall-line Sandhills have similar land-use histories (USDA 1988, Barrett 1995, Jose et al. 2005), though the timing and duration of land-use may vary from east to west (Jose et al. 2005). Prior to European settlement, native American communities were found along major rivers and on floodplains (Frost 2006). The upland areas were burned periodically by residents or were ignited naturally by lightning (Komarek 1968, Frost 1993, 1998, 2006). Because of frequent burning, vegetation was fire-tolerant consisting of woodlands and sparsely-treed savannas with canopies consisting of pines and some oaks (*Quercus* spp.). During the 18th and 19th centuries, European settlers cleared most of the arable land for subsistence agriculture. Erosion and nutrient depletion quickly reduced crop yields in many areas and agriculture was abandoned. Following abandonment, some areas were naturally seeded to loblolly pine and other early successional forest types but most of the landscape became severely eroded by lack of cover.

It quickly became apparent that some areas of the region were more susceptible to erosion than others. During the early and mid-20th century, federal and state agencies took action to

rehabilitate eroded areas, and many of these efforts involved planting loblolly pine (USDA 1988). To their credit, much of the erosion ceased and natural mitigation had begun. In some situations, however, these forests have been unhealthy and unproductive (Conner and Hartsell 2002, Ward and Mistretta 2002, Gadbury et al. 2004). Furthermore, since planting these loblolly pine-dominated forests, other variables acting as potential stressors have advanced and include increased variability in year-to-year weather patterns (Jentsch et al. 2007), increased pest occurrence (Ward and Mistretta 2002), decreased air quality (e.g., ozone) (Moore et al. 2002), reduced stand-level genetic heterogeneity (Ward and Mistretta 2002), reintroduction of fire onto the landscape (Brockway and Lewis 1997, Boyer 2000, LeJeunesse et al. 2006), and an increase in mechanized forest management practices that may cause root damage (Ward and Mistretta 2002). Today, much of the mature southern pine-forested landscape established from the 1920s to the 1950s is experiencing an increased occurrence of forest health problems. However, increases in local forest health problems cannot be solely attributed to the combined influence of legacy land-uses.

Root Disease

Increases in both insect pest populations and the isolation of fungal pathogens from roots often coincide with disturbance. Continuous stress caused by unfavorable edaphic, physiographic, or climatic conditions supports the development of a favorable habitat for southern yellow pine root disease. Furthermore, a single disturbance can create a favorable southern yellow pine host condition for root-feeding beetles and their associated pathogenic fungi (Eckhardt et al. 2004a). Three root pathogens have been implicated as factors contributing to pine decline: *Phytophthora cinnamomi* (Fr.) Bref., *Heterobasidion annosum* (Fr.) Bref., and *Leptographium* spp. Although the symptoms of littleleaf disease, caused by *P. cinnamomi*, are similar to those of pine decline, several attempts to isolate *P. cinnamomi* from the soil and roots of declining shortleaf and loblolly pine have resulted in only a weak relationship between this pathogen and pine decline (Roth and Peacher 1971, Miller 1979, Mistretta and Starkey 1982, Hess et al. 2005b, Eckhardt et al. 2007). One exception to this trend was found by Hess et al. (1999) who, in 1998, reassessed the causal factors of pine decline on the Oakmulgee Ranger District of the Talladega National Forest in Alabama. They concluded that pine decline was caused by a combination of edaphic disturbances and root disease attributed to *P. cinnamomi* and *Pythium* spp. Although

Leptographium spp. was isolated from roots at this location, its pathogenicity was considered secondary to that of *P. cinnamomi* and *Pythium* spp. Evaluations of pine decline on the Talladega National Forest were expanded in 2000 through 2002, and results indicated that *Leptographium* spp. rather than *P. cinnamomi* and *Pythium* spp. was the primary root pathogen associated with pine decline (Hess *et al.* 2005b). Inconsistency among the root pathogens isolated from declining pine trees at this location suggests that year-to-year variation in agents such as climate contribute to pine decline. Generally, accounts of *H. annosum* (i.e., sporophores, root isolations) occurring in association with loblolly and shortleaf pine decline are either absent or negligible (Roth and Peacher 1971, Miller 1979, Hess *et al.* 2005b, Eckhardt *et al.* 2007). One exception to this generalization, however, was reported by Mistretta and Starkey (1982) who found healthy sporophores on several stumps and dead loblolly pine trees in two of three Alabama Ranger Districts surveyed in the early 1980s. Otrosina *et al.* (1999) found both *Leptographium* spp. and *H. annosum* in declining stands of longleaf pine but suggested that the presence of *H. annosum* did not necessarily indicate that the trees were experiencing annosum root disease.

At present, *Leptographium* spp. and the vectoring of these pathogens by root-feeding beetles of the subfamily, Scolytinae, appear to be a fairly consistent component of pine decline in the southeastern United States (Brown and McDowell 1968, Otrosina *et al.* 1999, Eckhardt *et al.* 2007). The root-feeding Scolytids are attracted by stress-altered allelochemical profiles (Hodges *et al.* 1979, Lorio and Hodges 1985), and aggressively feed on pine roots producing these chemicals. The pathogenicity of the *Leptographium* spp. vectored by the Scolytids may increase as beetles begin to feed due to changes in oleoresins that favor the fungus (Paine *et al.* 1997). Growth assays demonstrate that *L. serpens* and *L. terebrantis* grow more vigorously in pine oleoresin than does *L. procerum* (Shrimpton and Whitney 1967, Cobb *et al.* 1968, Bridges 1987, Paine *et al.* 1987, Paine and Hanlon 1994, Payne *et al.* 2001, Eckhardt *unpublished manuscript*). Furthermore, *Leptographium* spp. growth is significantly reduced in the presence of some oleoresin constituents, notably 4-allylanisole (4AA) and p-cymene (Paine and Hanlon 1994, Eckhardt *unpublished manuscript*). Successful colonization by these pathogens appear to be beneficial to the development of insect brood (Jacobs and Wingfield 2001, Eckhardt *et al.* 2004b,). The insect-fungus relationship increases the extent of root disease, and the insects are indispensable in vectoring fungal spores from infected to healthy roots, but the fungus alone may

be the key contributor to pine decline because it interacts with tree root vascular tissue (Eckhardt *et al.* 2004a).

The healthy, dying, and dead roots of southern yellow pine support both saprophytic and parasitic cycles of *Leptographium* root disease. In the saprophytic cycle, roots that are dying or nearly dead provide substrate for *Leptographium* spp. to sporulate, and areas for the Scolytids to feed, lay eggs, and develop a brood. In the parasitic cycle, healthy roots are exposed to a suite of pathogenic *Leptographium* spp. vectored by aggressively feeding Scolytids. The fungi colonize the healthy root tissue and cause staining, lesions, resinosis, and root death. This process is repeated and accelerated as one or more disturbances continue to favor an increase in the root-feeding beetle population. In stands of increased disturbance and occurrence of root-feeding beetles, the isolation of *Leptographium* spp. from roots increases and decline symptomology becomes more severe. In the absence of disturbance where tree chemical defenses disrupt the pathogenic cycle of root disease, the population of root-feeding beetles is low and little evidence of root disease or decline symptomology is observed.

Linkages Between the Southern Pines and Pine Decline

Pine decline has been observed across the southeastern United States from Alabama to South Carolina. These occurrences, however, have been restricted to three of the five physiographic regions therein, the Atlantic and East Gulf Coastal Plains and Piedmont Province, as well as the Fall-line Sandhills at the interface of these regions. It has primarily been found on public lands managed for multiple objectives that include but do not emphasize timber production (Hess *et al.* 1999, 2005a, 2005b, Menard *et al.* 2006). Pine decline has also been observed in southern pine forests owned by non-industrial private landowners or forest industries (Haley 2006, Eckhardt *et al.* 2007). These reports are less accessible than those for public lands, but their infrequency may be attributed to a void of published reports rather than an absence of observations. Three conifer forest cover types dominated by loblolly or longleaf pine, or containing mixed stands loblolly and shortleaf pine occur naturally within the physiographic area where pine decline has been observed (Barrett 1995). Thus, there may be a regional risk associated with pine decline. The scope of this problem, however, can possibly be narrowed with knowledge of species'

requirements for sustained productivity, site-specific soil resource limitations that reduce carrying capacity, and how climate conditions and forest management practices influence the problem.

Southern pine species are each characterized by a unique set of stand conditions required for sustainability. The nutrition and water requirements of loblolly and shortleaf pine are generally greater than those of longleaf pine (Walker and Oswald 2000). Furthermore, shortleaf pine dominates mixed pine stands in the northern range of the loblolly-shortleaf pine forest type, whereas, loblolly pine is the dominant pine species across the southern range of this forest type in which sub-optimal soil drainage restricts the establishment of shortleaf pine (Barrett 1995). Within the loblolly, longleaf, and loblolly-shortleaf pine forest types, mixed pine stands occur, in part, because resource availability is conducive to the health of more than one species. However, when normal climate conditions, forest management activities, or legacy land-uses constrain a species' essential requirements for growth, its health may be compromised. The inability of loblolly pine to thrive beyond early maturity is attributed, in part, to prior land-use decisions that led to the erosion of surface soils containing the bulk of a site's mineral nutrient reserves (Hess et al. 1999, 2005a, Menard et al. 2006)

Although resource stress may be experienced by pine species within their natural range, it may also arise when species are established outside this area. For example, longleaf pine was a dominant forest type across the southeastern United States in the late 1800's, but intensive logging followed by unsuccessful regeneration led to its replacement with loblolly and slash pine (*Pinus elliottii* Engelm.) (Landers et al. 1995, Outcalt 2000). The restoration of longleaf pine to its natural range is now a priority on many public and private lands as loblolly and slash pine plantations reach rotation age (Stanturf et al. 2004, Hctor et al. 2006).

Across the southeastern United States, pine productivity is frequently restricted by mineral nutrient and water availabilities (Allen 1987, Dougherty 1996). The supply of these soil resources is one of many factors implicated in pine decline. Forest industry frequently relies on fertilization to attain acceptable rates of tree growth (Fox 2000), and this positive response is primarily attributed to a nutrition-induced increase in leaf area when light is not limiting (Vose et

al. 1988, Jokela and Martin 2000, Albaugh et al. 2004, Sword Sayer et al. 2004). Although too much or too little water does increase the variability associated with this stemwood production-leaf area relationship, water deficit does not seem to directly regulate southern pine production when tree species are within their natural range (Jokela et al. 2004). On private land, short rotation ages and fertilizer application prevent or avoid leaf area limitations to growth. On public land, however, where rotation ages are long and soils are generally not amended, growth limitations caused by sub-optimal leaf area dynamics may be realized.

Although typical water deficits in the southeastern United States do not appear to directly impact pine production, several studies demonstrate that southern pines are not completely resilient toward these limitations. For example, during an effort to model the canopy transpiration of 32-year-old loblolly pine growing on an eroded clayey soil in northeast Georgia, actual and predicted values matched during moisture sufficiency, but actual values were considerably lower than predicted values when plant-available soil water dropped to approximately 6 percent (Ford et al. 2005). A similar lag effect of water deficit was observed by Addington et al. (2004) who reported that mature longleaf pine on a xeric site were unable to fully recover their ability to transport water from the soil to leaf after rainfall alleviated a severe drought. These observations indicate that in some situations, water deficit affects the acquisition or transport of water by southern pine species.

Other recent studies suggest that these negative effects of drought on water acquisition and transport are linked to root system function. This was demonstrated by Addington et al. (2006) who compared the structural differences between longleaf pine grown on xeric and mesic sites and found that the ratio of surface areas of roots, $< 1 \geq 12$ mm in diameter and foliage was greater on xeric than mesic sites. This pattern of carbon allocation on the xeric site contributed to the ability of longleaf pine to maintain stomatal conductances comparable to those on the mesic site. Water acquisition and transport may also rely on deep root placement to supply water for immediate aboveground processes or for the hydraulic redistribution of water from deep to shallow roots (Warren et al. 2007). Stand conditions that restrict the production of absorbing roots and ectomycorrhizae, and their ability to acquire and transport water and mineral nutrients could adversely affect southern pine vigor.

Pines are naturally more abundant on nutrient-poor soils compared to other conifers and hardwoods (Gower et al. 1995). Internal recycling of mineral nutrients by pines contributes to stand production in the presence and absence of added nutrition (Nambiar and Fife 1991). Extended periods characterized by disruption of mineral nutrient retranslocation, adverse effects on leaf area dynamics, or inadequate uptake and transport of soil resources could contribute to a non-sustainable situation and early pine decline. The progression of pine decline from poor vigor to mortality may simply be a function of the severity of stand conditions, the pathogenicity of root infesting fungi that block or destroy root vascular tissue, or the establishment of insect pests that kill trees directly or vector root pathogens.

If silvicultural decisions have an adverse effect on any of these critical elements, tree vigor and health could be set back even further. Where pine decline is plausible, simultaneous evaluation of stand production and physiology in response to silviculture, may help guide management activities so that the scope of pine decline is reduced. For example, Menard et al. (2006) linked the use of frequent prescribed fire with unhealthy loblolly pine root systems and an increase in pest insect activity near tree roots at the Fort Benning Military Reservation in Georgia. On the xeric, nutrient-poor sites of this facility, potentially slow leaf area recovery rates after scorch could contribute to pine decline symptoms. Furthermore, many southeastern pine forests on public lands are composed of third and fourth generation stands receiving less than intensive management (Conner and Hartsell 2002). Past research has reported a decrease in southern pine production over consecutive rotations in the absence of ameliorative management (Haywood 1994, Tiarks and Haywood 1996). Assessments of overlap between pine decline symptomology and forest management activities such as site preparation, fertilization, and prescribed burning may provide insight regarding the cause of pine decline and remedial management actions to offset this problem.

Results and Discussion

Outcome of Session Discussion during Workshop

As part of a three-day process, various experts were convened to discuss pine decline from the perspective of their expertise. A series of questions were posed, one of which was “What is the southern pine forest health/decline problem and how widespread is it?” During these interactions, a wide variety of topics were discussed that involved the health of natural longleaf pine and mixed pine forests as well as that of pine plantation and restoration settings of various ages. These discussions led to the identification of two primary issues, each reflective of a series of observations, research needs, and recommendations (ESA 2007).

Two issues evolved from our dialogue about the health of southern pine forests: (1) we do not know whether the observed problem is new, cyclic, or related to climate change; and (2) the locales, species, and forest types exhibiting pine decline symptoms or experiencing pine decline are unknown. Imbedded within both of these issues were observations related to the scope and severity of the problem, and its rate of advancement. Determining if the problem is new, cyclic, or climate-related was considered an important goal for developing methods of detection and risk analysis, and mitigation techniques. Discussion of the second issue emphasized the need to develop detection and risk analysis tools geared to pine decline settings based on a prioritization of those situations that are the most recoverable.

To determine if the problem is new, cyclic, or climate-related, a series of observations were made:

- 1) Improved coordination and integration of forest health surveys among monitoring groups, and readily available quantitative forest health information are needed to address regional and local forest health concerns within urgent time frames.
- 2) Quantitative forest health information and analysis should include data on a novel set of stressors derived from legacy land use, current forest management, and/or cultural activities.

- 3) Direct (e.g., susceptibility to pests, physiological stress) and indirect (e.g. shift in pest or vector life cycle patterns) influences of climate change and climate cycles may be exacerbating the forest health problem.
- 4) Given a particular forest health condition, land management opportunities to improve forest health or avoid its deterioration may be limited by existing and future environmental policies, land-use demands and climate change.

Group deliberation resulted in a consensus view that to properly consider these observations and state whether pine decline is a new or cyclic problem, or is climate-related, several needs must be addressed by an appropriate research effort:

- 1) Current forest health monitoring requirements, frequencies, and intensities should be evaluated to determine whether they are adequate to quantify the scope, severity, and spread of pine decline.
- 2) An integrated model capable of forecasting the likelihood of forest recovery or mortality from pine decline is needed.
- 3) Forest health monitoring approaches should be integrated with established regional Forest Inventory Analysis (FIA)/Forest Health Monitoring (FHM) and Eastern Forest Threat programs being directed by the U.S. Forest Service.
- 4) The effectiveness of remote sensing tools (e.g., imagery analysis) should be improved so that they provide accurate information about the scope and spread of pine decline and a means of detecting early pine decline symptomology.
- 5) Using existing studies and data, management practices showing promise as tools to reduce possible stressors linked to pine decline should be evaluated.
- 6) Based on the results of (5), one or more studies of management effects on critical resources linked to pine decline should be established.
- 7) Desirable, yet realistic and flexible management “end points” for forest setting where pine decline may occur should be developed.
- 8) Thresholds of forest response to specific management activities should be identified so that alternative actions can be quickly applied in the event that pine decline becomes probable at a particular location.

- 9) New aspects of pine decline that complicate our understanding of it, or worsen its effects on southern pine forests should be investigated. These aspects include: (1) the involvement of invasive exotic pests, (2) advancement of pine decline into atypical forest systems such as longleaf pine plantations, and (3) departures from the anticipated dynamics of pine decline (e.g. a shift in pathogenicity with a change in fire regime or climate).

Discussion of the species and forest types experiencing pine decline symptoms resulted in a second series of observations focused on susceptibility to the problem. Information on susceptibility to pine decline is needed at several levels. These include: (1) forest age, type, and condition, (2) location (e.g., Piedmont province, Fall-line sandhills, etc.), and (3) setting (e.g., planted longleaf pine forest on abandoned farm land, naturally regenerated longleaf pine forest, etc.). To address these needs, the following are required:

- 1) The analysis of recently collected forest health monitoring data should be revised to address immediate questions regarding the scope of pine decline.
- 2) We need models that predict tree mortality as a function of species, age, location, site quality, legacy land-use, and forest management activity.
- 3) These models should be capable of predicting mortality across a diversity of locales that emphasize timber and non-timber (e.g., RCW habitat) land management expectations.
- 4) Models that predict mortality should be used to forecast forest susceptibility to pine decline and how pine decline will change the structure of future southern pine forests.

Approach to a Solution

Most forest health issues become visible when management objectives are jeopardized. For example, forests intended for “profitable” harvest have a different level of tolerance to health problems compared to forests intended for non-timber forest products such as soil rehabilitation, watershed protection, recreation, ecosystem restoration, and wildlife habitat. Therefore, acceptance of some tree mortality over a given period of time differs with forest objectives. Forest management for timber must balance natural and unexpected mortality, costs of

management and remediation, and indirect effects of mortality and remediation on non-timber opportunities that add value to the forest. A similar equilibrium is in place to meet non-timber forest management objectives, but it is less structured because non-timber goals are generally met over a longer time scale and with more tolerance to short-term changes in factors such as climate and the timber market.

A forest health issue advances to become a forest health threat with an increase in the incidence of pathogens infecting and affecting healthy trees or stands and the likelihood that pathogenicity in one location will be transmitted to other locales. Because the magnitude of a forest health threat may be tempered or exaggerated by changing regional forces (e.g., climate, air quality, land use), evaluation of potential threats requires simultaneous investigation of stand environment and management history at appropriate scales.

At present, pine decline appears to be a forest health issue primarily affecting public land managed for multiple objectives that include but do not emphasize timber production (Hess et al. 1999, 2005a, 2005b, Menard et al. 2006, Eckhardt et al. 2007). Based on workshop consensus, information is insufficient to determine whether this problem is approaching threat-status or even has the potential to become a regional forest health threat. The outcome of this session of the workshop indicated that the negative effects of pine decline as a forest health issue or threat could best be avoided or remedied with knowledge of the scope and cause of the problem. From this information, actions to circumvent pine decline as a forest health issue, including detection and risk analysis, could be developed.

Recommended Actions

To properly address the issue of pine decline, information is needed in the following areas:

- 1) A better understanding of southern pine (with an emphasis on longleaf pine) physiological responses to interacting environmental stresses including those associated with climate extremes is needed. The study of longleaf pine should be conducted in naturally regenerated forests and plantations established after land abandonment.

- 2) A current and extensive geographic record of locales exhibiting forest health problems unrelated to, and linked to pine decline, and experiencing mortality should be maintained at the regional scale.
- 3) Models that predict spatial and temporal patterns of species- and forest system-specific pathogenic infection and spread, and tree mortality rates are needed. These models should include the influences of local and regional stressors and stand conditions.
- 4) In support of model development, efforts to develop scale- and forest setting-appropriate remote sensing technology that provides information regarding forest health and mortality should continue. This technology should be compatible with field monitoring tools (i.e., GPS) for the efficient validation of models.

Summary

To date, pine decline appears to be a forest health issue caused by environmental stress arising from interaction among several abiotic and biotic factors that include resource availability, weather conditions, insects and fungal pathogens, anthropogenic disturbances, and forest management activities. Because pine decline has already been observed among several southern pine species and at locations across the southeastern United States, the scope of the problem appears broad. Several unique aspects of pine decline suggest that it is possible to narrow its scope because many of the observations are associated with the establishment of “off-site” species, an absence of stand density management allowing the carrying capacity of a site to be exceeded, climate events and forest management activities that strain resource acquisition and carbon fixation, and the opportunistic nature of Scolytids and *Leptographium* spp. Narrowing the scope of this forest health problem at this point, however, would be based on speculation rather than scientific information.

Discussion among workshop participants indicated that we do not have the information to determine whether pine decline is new, cyclic, or related to climate change, nor do we have an understanding of the locales, species, and forest types exhibiting pine decline. Because the ecological and economic consequences of pine decline have the potential to adversely affect the sustainability of southern yellow pine forests, and currently, we do not have a scientifically sound basis to narrow the scope of this problem, research is urgently needed in four areas. First, knowledge of the ecophysiological condition that predisposes stands to pine decline is needed. Furthermore, immediate steps should be taken to assess forest health trends and rates of mortality across the southern pine region. With this information, models that forecast the susceptibility of stands to pine decline, its rate of spread, and its impact on timber and non-timber southern pine forest products should be developed. Finally, for these models to accurately predict the potential spread of pine decline across the landscape, their development should integrate repeated observations using field monitoring tools (i.e., GPS) and remote sensing technology. As research results are generated from these four areas, forest management choices can be tailored to avoid further loss, and sustain southern yellow pine forests that support both timber and non-timber land management expectations.

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