EVALUATING WHITE SPRUCE DECLINE AND MORTALITY IN THE UPPER GREAT LAKES REGION

By

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ABSTRACT

Extensive decline and mortality of plantation origin white spruce (*Picea glauca* (Moench) Voss) is currently being observed across the upper Great Lakes region. White spruce stands are showing signs of stress with reduced primary productivity, needle loss, and a high number of bark beetle occurrences and root rot infestations. Thinning operations and other silvicultural treatments have proven ineffective in restoring the health of the trees. To understand the factors contributing to the decline in white spruce health, field surveys of plantations and natural mixed stands were conducted during the summers of 2007 and 2008. Tree-level and stand-level information, tree cores, needle samples, and samples of insects and diseases were collected in 43 white spruce stands in Michigan, Minnesota and Wisconsin. Using multiple regression analyses seven factors were identified that significantly increase the susceptibility, defined as the potential for the stand to experience decline, and the vulnerability, defined as the potential for the stand to experience tree mortality due to decline. Multi-criterion models for susceptibility and vulnerability were developed based on these factors and risk maps were created to describe the current regional extent and severity of decline. The results of this study found that older plantations experiencing decreased precipitation over the last 10 years were more likely to be susceptible to decline. Stands become vulnerable to decline with the added presence of bark beetles and spruce budworm (*Choristoneura fumiferana* (Clemens)). The model results classified 28 of the 43 surveyed stands as currently declining, seven as susceptible to decline, four as vulnerable, and four as healthy. By incorporating multiple abiotic and biotic factors, the newly developed models express the interaction among the factors involved in white spruce decline. These methods provide improved sensitivity when monitoring stands for the decline disease, and will help land managers in the Great Lakes region assess and prioritize stands for treatment.

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INTRODUCTION

Healthy forests are dependent on the balance and resiliency of the ecological processes that create and maintain them. The concept of forest health is defined by the USDA Forest Service as, "the ability of a forest to recover from natural or human-caused stressors" (USDA Forest Service 1992). Characteristics of healthy forests often include a fully functioning community of plants and animals and their physical environment (Monnig and Byler 1992). More specifically as outlined by Sampson (1996), healthy forests consist of tree and understory plant species that are within the historical range of variability for species composition, age, and stand density. Growth and mortality rates are consistent with ecosystem type and age of the dominant trees. Vegetation diversity is a balance between supply and demand for light, water, nutrients, and growing space. The stand has a level of resiliency that makes it capable of tolerating and recovering from natural disturbances that are within the normal ranges for the ecosystem, such as insects, disease, and fire frequencies. Unhealthy forests show characteristics of distress such as: reduction in primary productivity, nutrient resource loss, decreases in biodiversity, fluctuations in key populations, widespread incidence and severity of diseases, and disruptions in the normal successional processes that allow more specialized species to be replaced by opportunistic species (Rapport 1992).

In recent years, the health of white spruce (*Picea glauca* (Moench) Voss) forests in the upper Great Lakes region has become a concern to forest managers. Extensive decline and mortality of plantation origin white spruce has been observed across the region. White spruce stands are showing signs of distress with reduced primary productivity, needle loss, and high occurrence of bark beetle and root rot infestations. Thinning operations and other treatments have proven ineffective in restoring the health of the stands (O'Brien and Katovich 2003). Further effort is needed to understand the factors contributing to the deterioration of white spruce stands and to determine actions land managers can take to improve the health of the forests in the Great Lakes region.

Background

Wood resources played a key role in the development of the U.S. infrastructure in the early years as a nation. Timber production was one enterprise that allowed the nation to grow into an economic world leader (MacCleery 1992). In the first 100 years as a country, U.S. society exploited twenty-five thousand square miles of forest, clearing the land with religious and moral purpose (Forester 2004). In order to fulfill the developing society's demand for wood, the forests throughout Wisconsin, Minnesota, and Michigan were extensively cut and burned during the late 1800s and early 1900s. The timber market at the time was driven by the demand for construction materials, and carpenters favored the large saw logs of conifers such as red pine (*Pinus resinosa* Ait.) and eastern white pine (*Pinus strobes* L.) for constructing building frames. As large saw log timber was depleted, smaller trees were cut for pulp logs. Pulp logs from white spruce, balsam fir (*Abies balsamea* (L.) Mill.), and quaking aspen (*Populus tremuloides* Michx.) were valued for their wood fiber that could be made into a variety of products such as paper. Concerns about erosion, the protection of water resources, and the availability of future forest resources led to the creation of the public relief program, the Civilian Conservations Corps (CCC) in 1933. One of the tasks assigned to the CCC in the upper Great Lakes region was timber stand improvement through the planting of trees. Although much of the forests prior to logging were old-growth hardwoods dominated by sugar maple (*Acer saccharum* Marsh.), yellow birch (*Betula alleghaniensis* Britton), and eastern hemlock (*Tsuga Canadensis* (L.) Carr.), most of the replanting done by the CCC was with conifers (White and Mladenoff 1994). White spruce was one of the favored coniferous pulp wood species planted by the CCC crews. Forest replanting efforts continued to use white spruce as a plantation species after the termination of the CCC program in 1942.

The versatility and value of white spruce plays an important role in today's commercial forestry industry. It is used commercially for wood fiber and lumber products. Specialized uses include musical instruments, house logs, and paddles. Historically Native Americans used white spruce roots for lashing birch bark baskets and canoes, and the boughs for bedding. The resin and extracts from boiled needles were used for medicinal purposes. Not only valuable to human societies, many animals utilize white spruce forests for food and shelter. In particular red squirrels, pine grosbeaks, and crossbills eat the seeds, and spruce grouse feed on the needles.

White Spruce Silvics

White spruce is a geographically wide-ranging species, spanning across Canada, north into Alaska and south into the northeast and north central United States (Figure 1). Tolerant of many site conditions, white spruce is considered a "plastic species" for its ability to inhabit areas at the edge of receding glaciers. It grows at various altitudes, in extremely cold climates, and variable soil conditions. White spruce is found in areas with a short growing season ranging from 20 days in the north to 180 days at the southern reaches of its distribution (Nienstaedt 1990). The canopy architecture of spruce trees involves a matrix of needles and branches which decreases the reflectance of the surface, resulting in microclimates with elevated temperatures within the canopy. This leads to enhanced photosynthetic rates and efficiency for species growing in cold climates (Williams 1990).

The upper Great Lakes region is the southern edge of the white spruce range. This region is an ecotone that supports the transition from northern hardwood forests to the south and boreal forests to the north. Throughout this transitional zone white spruce is more commonly found as a component of a mixed conifer and hardwood forest, rather than growing in pure stands as it would further north. In the Great Lakes region natural stands of white spruce are part of a second-growth forest usually associated with boreal hardwoods such as quaking aspen and paper birch (*Betula papyrifera* Marsh.), and conifers including balsam fir, eastern white pine, eastern hemlock, northern white cedar (*Thuja occidentalis* L.), black spruce (*Picea mariana* (Mill.) B.S.P.), tamarack (*Larix laricina* (Du Roi) K. Koch), and jack pine (*Pinus banksiana* Lamb.) (White and Mladenoff 1994).

Throughout its range white spruce grows on a variety of soils of various origins. Generally podzolic soils are the most common; these soils are characterized by moderate leaching of organic material and soluble minerals, producing an accumulation of clay. In the upper Great Lakes region the most common order of soils that support white spruce are Alfisols. Alfisols are characterized by well-developed soils with efficient organic material cycling, moderate leaching, and high fertility levels. White spruce is usually a minor species on sandy podzol soils (Nienstaedt and Zasada 1990). In the Lake States, white spruce is naturally found on shallow, outwash soils on upper slopes and flats when mixed with other conifers. When mixed with hardwoods, white spruce will be found on the deep glacial till soils of lower slopes (Uchytil 1991). White spruce also tolerates a wide range of soil moisture conditions. A dependable supply of well-aerated water is optimal; however it will grow well on dry sites that are fertile. White spruce is not tolerant of stagnant water that reduces rooting volume (Nienstaedt and Zasada 1990). Even though white spruce is considered tolerant of many site conditions, it requires higher soil nutrient levels than other conifers to attain greatest growth (Wilde 1966).

White spruce is an early to mid successional species, since it grows slower than its early successional associates and has an intermediate tolerance of shade it does not mature until later stages of forest succession. Common seedbeds include exposed mineral soils from windthrows, rotten logs, and mossy organic soils (Dobbs 1972; La Roi and Stringer 1976). On favorable sites white spruce can grow 30m or taller and have a diameter of 60-90cm. White spruce grows slower than its early successional associates and will remain in the understory until a gap is created, releasing it to grow (Nienstaedt and Zasada 1990). White spruce growing on optimal sites will live 100-300 years throughout its range.

Numerous environmental disturbances and pathogens naturally affect white spruce. Historically the disturbance regime throughout the range of white spruce was dominated by fire. White spruce is very susceptible to fire and therefore a major determinant of white spruce distribution and growth (Nienstaedt and Zasada 1990). If fire frequency in an area is high with intervals less than 50 years the seed bank can be eliminated (Nienstaedt and Zasada 1990). Root diseases and bark beetles also kill large stands of white spruce. The spruce beetle (*Dendroctonus rufipennis* (Kirby) Coleoptera Scolytidae) is the leading cause of mortality in Alaska (Werner and Holsten 1985) and western Canada (Safranyik and Linton 1988). In the upper Great Lakes region attacks on healthy white spruce are less common, instead bark beetles tend to attack already stressed trees, or those windthrown or recently cut (Haberkern et al. 2002).

Tree Decline

The decline syndrome describes a slow progressive deterioration in tree health and vigor caused by an interaction of abiotic and biotic factors, eventually leading to the death of trees (Manion 1991). Declines affect the trees that represent the “best” genotypes, those that have survived natural selection forces to become well-established upper crown trees (Manion 1991). Since larger trees require great amounts of water and minerals, events that cause deficiencies in these resources have a significant impact on tree growth and survival. Trees respond to disturbance by allowing branches and photosynthetic surfaces to die back in order to reduce the demand for moisture. This causes reduced stem growth which eventually causes damage to the tree's transport system creating a slow disconnect between the roots and crown (Manion 1991). Trees affected by decline develop an asymmetrical appearance as potions of the crown die, leaves become discolored and undersized, foliage becomes tufted at the end of twigs as reduced growth produced shorter internodes, and dormant buds on the main stem and large branches sprout (Manion 1991). Root rot decay fungi and other parasitic fungi become evident on trees. Symptoms persist and intensify over a number of years. Generally trees showing symptoms of decline are randomly dispersed throughout the stand. When symptomatic trees are clustered it is usually caused by a signal agent (Manion 1991).

The etiology of decline is often a complex interaction of several factors that can be categorized into three stages of decline that ultimately result in tree death: (1) Predisposing, (2) Inciting, and (3) Contributing (Sinclair 1965). Trees affected by decline will experience at least one factor from each stage (Manion 1991). Predisposing factors are long-term factors that can weaken a tree. These are factors that trees are exposed to on a continuous basis; climate, soil characteristics such as texture, moisture, and nutrient levels, viruses, genetics, air pollution, and age are examples. Inciting factors are short-term events that a tree, if otherwise healthy, can recover from. If, however, the stress occurs more frequently and with increasing intensity, a tree already weakened from predisposing factors has a decreased chance of recovery. Examples of inciting factors are: insect defoliation, frost, drought, salt, and mechanical injury. The contributing factors typically consist of biotic agents such as bark beetles, canker fungi, and root decay fungi. These long-term factors ultimately kill the tree; however they cannot be credited entirely with the cause of death (Manion 1991).

One model suggested for visualizing the process of decline is the decline disease spiral (Manion 1991). Throughout the life of a tree it will encounter many stresses, represented by barriers within the spiral. Predisposing factors make up the outer spiral and nudge the tree along to the second spiral which is made up of inciting factors. As the tree continues to be weakened by the interactions of the factors, the spiral tightens to an inner spiral of contributing factors that eventually arrive to the center where death is the ultimate outcome (Manion 1991).

Symptoms of White Spruce Decline

Currently white spruce planted by the CCC and in other plantations in the upper Great Lakes region are less than 100 years old and should still be experiencing high levels of productivity. Instead, many are suffering from increased presence of disease and bark beetles, reduced annual growth, and higher rates of mortality. Trees have thin crowns compared to the complex matrix of branches and needles a healthy spruce will exhibit. White spruce should hold 5-7 years of needle growth before shedding; however, those displaying symptoms of decline may only support a current year's growth. Needle and branch loss occurs from the inner part of the branch out to the tips and from the bottom branches up, leaving trees with needles only on the top and the outer most tips of the branches. Remaining needles may be chlorotic, gradually turning from green to brown, leaving few healthy needles for photosynthesis. Typical thinning treatments to reduce resource competition are ineffective in restoring tree health and vigor. Speculative Predisposing, Inciting, and Contributing factors for white spruce decline are described below and in Table 1.

Predisposing Factors for Spruce Decline

The factors that may be important predisposing factors relate to abiotic conditions that characterize a site. In some cases white spruce plantations may be located “off-site” where site conditions are not conducive to optimal growth. The plantations planted by the CCC were created with little consideration for the ecological needs of the tree species planted. For example, at that time foresters believed that soils would not be deficient of essential nutrients if there was an adequate amount of mineral and organic matter. The podzolic soils of the upper Great Lakes region do not meet that assumption (Wilde 1966). Although white spruce grows on a wide variety of soils across its range, it requires higher minimum soil fertility standards than other conifers in the Lake States to attain optimal growth (Wilde 1966). Wang and Klinka (1997) found that as white spruce increased in height and diameter there was a need for increased concentrations of nutrients in the soil, supporting the conclusions of Wilde (1966). Likewise, white spruce is tolerant of a wide range of moisture conditions; however optimal growth requires a reliable supply of well-aerated water, or very fertile dry sites. Even though white spruce is tolerant of a range of soil types, less than optimal soil conditions combined with other factors may contribute to its decline.

Stand structure and composition may also predispose stands to decline. In the upper Great Lakes region white spruce naturally occurs as a dominant component in mixed stands of quaking aspen, paper birch, balsam fir, eastern white pine, eastern hemlock, northern white cedar, black spruce, tamarack, and jack pine (White and Mladenoff 1994). Mixed forest types can be more resilient than single-species stands to disturbances such as insect defoliators and root rot infections (Chen and Popadiouk 2002; Su et al. 1996). Outbreaks can be controlled as associated tree species can act as obstacles between the insect or fungi and the next host tree. Another factor that affects stand structure is different age classes of trees that result from succession. The complexity of multiple canopy levels is lost when all trees in a stand are the same age, such as in a plantation. The even-aged monoculture of white spruce that resulted from the CCC efforts represents an unnatural forest structure and composition for the southern edge of its range. This change in natural forest dynamics may leave white spruce predisposed to future decline.

Inciting Factors for Spruce Decline

Moisture deficiency controls the southern limit of conifers, including white spruce (Zoltai, 1975; Hogg, 1994). White spruce located at the southern edge of the range in Manitoba, Canada showed strong radial growth-climate associations indicating the negative effects temperature-induced drought stress can have on growth (Chhin et al. 2004). The upper Great Lakes region has experienced several moderate to severe droughts in the past 30 years. Low snow accumulation in the winter impedes recharging of the water table, possibly setting it below the tree roots and forcing the trees to put more energy into root growth. Lack of snow also allows the ground to freeze deeper, possibly damaging root systems. According to Russell (1963) and Stiell (1976), white spruce roots are susceptible to frost damage and therefore require protection from deep frost. Healthy trees should be able to recover from the impacts of drought; predisposed trees may not be able to recover.

Defoliating insects and needlecast diseases are two more inciting factors that affect white spruce in the upper Great Lakes region. Both agents cause poor crown conditions resulting from the reduced needle matrix complexity. Rather than absorbing large amounts of solar energy, the reflectance of the leaf surface area is increased. This eliminates the protection the trees have against cold temperatures.

Spruce budworm (*Choristoneura fumiferana* (Clemens) Lepidoptera: Tortricidae) (SBW) is an insect defoliator that reduces crown density. The larvae eat the new foliage of white spruce and balsam fir produced in the spring. Spruce budworm is a persistent outbreak species, meaning populations remain high until they kill enough of the host trees to deplete their food resource. Impacts from SBW include reduction or loss of cone and seed production, mortality of small roots, reduced or no height growth, topkill and direct and indirect mortality (Raske 1980; Witter et al. 1984). Some trees recover well from an outbreak, however, two years of severe defoliation will cause reduced growth and possibly death. Mortality has been observed to continue to occur between 10 and 12 years after an outbreak (Baskerville and MacLean 1979). Spruce budworm has become the major cyclic disturbance factor controlling forest dynamics in the absence of fire (Baskerville 1975; MacLean 1984; Morin et al. 1993). The impact of an infestation is dependent on the spatial location of the stand in relation to other infested stands and stands of non-host species (MacLean, 1980). Parasitoid predators of the budworm are often found in stands with aspen and birch as they are the alternative hosts required for the budworm lifecycle (Maltais et al. 1989). The white spruce plantations in the upper Great Lakes region create an abundance of food and an obstacle-free arena due to lack of non-host species within a stand.

Rhizosphaera kalkhoffii (Bubak) is a needle pathogen that causes premature needle loss, leaving trees with only the current year's needles and infected second year needles. The lower branches are infected first with fruiting bodies that make the stomata appear black and fuzzy. Needles become infected in the spring, but symptoms are not visible until the following fall or spring when needles turn brown and fall off. Spores are spread by rain splash, making this pathogen difficult to monitor and control (Taylor and Nameth, 1996). *Stigmina lautii* (Sutton) is another fungus of concern that was identified in the early 1970s on white spruce in Canada and first found in the U.S. in 1999 (Hodges 2002). *S. lautii* is easily mistaken for *R. kalkhoffii* since it also produces black fruiting bodies in the stomatal pits. However, those of *S. lautii* are more elongated than the globoid shape seen in *R. kalkhoffii* (Walla and Kinzer 2006). Trees with *S. lautii* appear to have similar symptoms as those with *R. kalkhoffii*.

Setomelanomma holmii, a fungus identified in France in 1980 was observed in Wisconsin on Colorado blue spruce and white spruce in 1998. It is characterized by small black perithecioid fruiting bodies that develop on twigs during late May and early June and is associated with trees showing needle chlorosis and needle drop (Rossman et al., 2002). Termed spruce needle drop (SNEED), this fungus is another possible inciting factor in the spruce decline problem (O'Brien and Katovich, 2003).

Contributing Factors for Spruce Decline

Opportunistic organisms such as root rot pathogens and bark beetles attack and kill trees that are showing signs of decline. Large infestations lead to attacks on 'healthy' trees, increasing the levels of decline and mortality. Root rot fungi are part of the natural decomposition process of stumps and roots. The root rot fungi *Armillaria* spp., *Inonotus tomentosus* (Fries) Teng., and *Phaeolus schweinitzii* (Fr.) Pat. are commonly found in white spruce plantations. Root rot fungi girdle the root system, causing off-colored foliage, a reduction in growth, and eventually death. Once in a stand, the fungi travel through the soil to another suitable host, quickly spreading. Larger and more vigorous trees may persist for years by isolating the fungi to the roots first infected.

Bark beetles contribute significantly to the death of white spruce (Holsten et al. 1999). They bore through the bark into the phloem, creating galleries in the wood where they lay eggs. The girdling effects of bark beetles cause the needles to turn yellow-green then orange-red before falling off, resulting in tree mortality. A few species of particular significance to white spruce are the spruce beetle (*D. rufipennis),* northern engraver beetle (*Ips perturbatus* (Eichhoff) Coleoptera Scolytidae), and twig beetles *(Pityogenes spp*.). In the upper Great Lakes region it is not as common for bark beetles to kill healthy trees as it is in other parts of the white spruce range. Bark beetles are attracted to weakened trees and will not successfully colonize healthy trees unless beetle populations grow to outbreak levels. Some white spruce mortality does occur from bark beetles, but typically in association with spruce budworm defoliation or weather damage (Drooz 1985).

Justification and Objectives

There are an estimated 57870 hectares of white spruce plantations throughout the upper Great Lakes region, and some areas have reported over half of the trees to be in a state of decline or dead. Stands do not respond to thinning treatments and trees continue to show a decrease in productivity. The loss of white spruce creates significant loss of wildlife habitat and wood products. The spruce grouse, a Wisconsin Regional Forester's Sensitive Species (RFSS), prefers young spruce as a food and cover source, especially in the winter. With high rates of mortality among trees of cone bearing age, spruce grouse habitat is lost due to low regeneration rates. Also, white spruce is a desired tree species as a source of pulp. Early salvage of dead spruce is necessary since the wood degrades rapidly, diminishing its value. Finally, the presence of thousands of acres of dead fire-prone conifers, combined with recent droughts, has created a buildup of fuels. The increasing wild land urban interface (WUI) raises the potential fire hazard for people living near these stands (USDA Forest Service 2006).

Many stress factors could be contributing to the decline of white spruce throughout the upper Great Lakes region, and there is a high probability that there are multiple factors involved. The relative importance of each factor is largely unknown, as well as how factors may be interacting with one another. Whether the causes of decline are the same across the region or varying by stand is also unknown. This study was designed to explore the various factors and their significance in white spruce decline.

The objectives of this study were to: (1) determine the regional extent and severity of white spruce decline and mortality, (2) characterize the nature of the decline by identifying the factors that make white spruce susceptible and vulnerable, and (3) develop a multi-criterion model to create risk maps that identify and predict white spruce decline. To meet these objectives, field surveys were conducted to collect data for determining the current conditions of white spruce stands. Site conditions were studied for soil and habitat suitability, dendroclimatology was used to determine tree growth relative to climatic patterns, and diseases and pests were identified to assess their contribution to the decline. Using statistical analyses, factors that cause stand susceptibility and vulnerability were chosen for the multi-criterion model. The results from this study will be useful in determining patterns of decline, and will provide land managers with recommendations on where and under what conditions white spruce can be grown successfully.

METHODS

Objective 1: Determine the regional extent and severity of white spruce decline and mortality.

Stand Surveys

White spruce stands on state (DNR) and federal (USDAFS) lands were surveyed across the upper Great Lakes region in the Upper Peninsula of Michigan, northern Wisconsin, and northern Minnesota during the summers of 2007 and 2008. Both natural stands and plantations were surveyed to help determine whether both plantation origin white spruce and those found in more natural compositions are affected to the same extent.

A stand selection process was developed for choosing stands of a preferred size, density, and accessibility. The selection process criteria included a minimum stand size of 20 hectares, allowing for a minimum of 100 meters between prism plots and edge areas to avoid the overlap of plots and remove any edge effect on the data collected. To ensure at least 30 trees could be measured in a minimum of three plots, stands were required to have a minimum basal area of $124m^2$/ha for plantations and $25m^2$/ha for natural stands. Stands selected required a minimum age of 30 years since decline symptoms have only been observed on mature sites. Each stand also had to be accessible by road to allow for the most efficient use of time in the field. GIS shapefile polygons of white spruce stands for each state were obtained from state and federal land managers, and by use of the select feature command in ArcMap, stands that fit the required stand parameters were selected. Stands meeting the requirements were input to Microsoft EXCEL, and a random number generator was used to choose the stands for the survey. The GIS polygons were then placed as a layer on top of recent aerial photographs to help determine accessibility and if salvage work had taken place since the last update to the shapefile attribute records. Stands that had been cut were not included in this study.

Data collection provided information at two spatial levels: tree and stand. Stand information collected from past land manager surveys included: stand type (natural or plantation), age, soil type, and location (latitude and longitude). Stand level data derived from field surveys included: basal area, site index, evidence of white spruce regeneration, and habitat type. Habitat type was determined using Kotar's classification system for Wisconsin (Kotar et al. 2002) and Michigan (Kotar and Buger 2003), and the Native Plant Communities of Minnesota (Laurentian Mixed Forest Province) classification system for Minnesota (MNDNR 2003).

Field surveys created a current description of the stand condition. Forest Inventory and Analysis (FIA) protocols were used in developing survey techniques (USDA Forest Service 2007). Variable radius prism plots were used to collect individual tree data. Variable radius plots eliminate measuring trees that are too small in diameter or too far away from the plot center, thus emphasizing larger and more ecologically important trees. Variable radius prism plots use a 10 or 20 factor prism, 10 was the standard for this project. However, a 20 factor prism was used for five stands as the 10 factor prism was not powerful enough to include 5-12 trees in a plot.

The number of plots and trees measured varied by stand, however a minimum of three plots of at least 30 trees were required per stand. Prior to entering the stand, three plots were assigned locations using a random number table and a numbered grid overlay on an aerial photo of the stand. If more than three plots were required to include the minimum of 30 trees the same method for determining locations were used while in the stand. Plot locations were navigated to using a map, compass, and pace count.

Data collected on individual trees in each plot assessed tree health within the stand. Measurements were taken on all trees that were included in the plot. The species of a tree was documented and whether it was alive or dead. FIA crown measurements (live crown ratio (LCR), foliage density, foliage transparency, dieback, and vigor), tree height, and diameter at breast height (DBH) were determined for each tree. Each tree was also examined for evidence of bark beetles, carpenter ants, spruce budworm, root rot fungi, and other damage.

Needle samples and increment cores were collected throughout the stand to test for needle and twig pathogens and determine growth rates. Needle samples from four randomly selected trees throughout the stand were collected to test for the needle pathogens *R. kalkhoffii, S. lautii,* and the twig pathogen *S. holmii*.

Six increment cores were collected at random from four white spruce and two non-white spruce tree species in each stand. Tree growth trends were examined using the increment cores. Growth patterns were compared with past climate trends to determine limiting factors of growth and climate sensitivity. Both white spruce and non-white spruce were looked at to determine if white spruce growth patterns and reaction to climate conditions differ from other species.

Objective 2: Characterize the nature of the decline by identifying the factors that make white spruce susceptible and vulnerable to decline.

Needle Pathogen Analysis

The needle samples were sent to the Plant and Disease Diagnostics Clinic, Department of Plant Pathology at the University of Wisconsin-Madison. They were incubated in moist chambers for approximately two weeks to trigger sporalation in potential pathogens, facilitating identification. Each sample was microscopically examined for the presence of *R. kalkhoffii*, *S. lautii*, and *S. holmii*.

Tree Ring Analysis

Tree cores were mounted onto slotted pieces of finishing trim with wood glue and the surface was prepared for analysis by sanding with an electric palm sander. The flat surfaces of the cores were scanned at 2400 dots per inch (dpi) as a JPEG image. The computer program *Cybis CooRecorder* was used to count the rings. The *Cybis* dendro dating program, *Cdendro*, was used to measure annual growth in millimeters. The measurements were then transferred into a spreadsheet and growth curves were created to show growth trends for the past 10 and 30 years. Growth curves were used to determine if there was a reduction in growth for white spruce compared to other species in the stand.

Lifetime, intermediate, and recent growth were modeled as a function of temperature, precipitation, and drought. Historical monthly and annual temperature and precipitation data were obtained from weather stations throughout the region. The climatology department for each state maintains a website available to the public with raw climate data; additional data for Michigan was requested by direct correspondence (Michigan Climatology Resources Program 2009; Minnesota Climatology Working Group 2009; Wisconsin State Climatology Office 2009). Although research has determined that a distance of 20 miles or more between a sample tree and weather station will not substantially alter the correlation between ring width and climate (Julain and Fritts 1968), it was found that a weather station within close proximity to a survey stand was not always available, or in some cases a nearby weather station did not have complete data for the time period of interest. To overcome this lack of information, data were improved by averaging corresponding measurements from multiple nearby weather stations.

Growth relationships were analyzed using four measurements of temperature and precipitation data: (1) the average temperature for the growing season (April - September), (2) the average precipitation for the growing season, (3) the average monthly precipitation for the year, and (4) the total annual precipitation. Growth was looked at for three time periods: lifetime, intermediate, (the last 30 years) and recent (the last 10 years) to determine any change in climate-growth relationships over time as trees age. Regression analyses were used to detect significant correlations between each climate metric and each stand's mean annual white spruce growth for each time period.

Another set of multiple regression analyses were completed looking at annual growth averaged over the last 30 years and the last 10 years compared with the four climate metrics above. This same process was used for the non-white spruce species, except individual tree growth was used instead of creating a stand mean since only two non-spruce trees were sampled from each stand.

The Palmer Drought Severity Index (PDSI) was used to look for relationships between growth and drought for a growing season and a whole year. The PDSI is a formula developed in the 1960s that uses temperature and rainfall information to determine dryness. It has become a standard index for measuring drought, using 0 as a baseline (normal), a negative number as an indicator of less than normal moisture levels and a positive number indicates higher than normal moisture levels. PDSI was chosen for this study because it was shown to be a better linear predictor of ring width for pinyon pine (*Pinus edulis*) compared to other indices of water availability such as the standardized precipitation index (SPI) which is based on precipitation alone and the

Walter index which takes both precipitation and temperature into account (Kempes et al. 2008). State level PDSI data was obtained from the National Oceanic and Atmospheric Administration (NOAA) Climate Monitoring Data Center (National Oceanic and Atmospheric Administration 2009). Regression analyses of the average annual PDSI and average growing season PDSI were conducted to determine significant correlations between mean stand lifetime growth and 5, 3, and 1 year lags in growth response to drought.

Soils Analysis

Soil supplies the nutrients and moisture necessary for tree growth and stand productivity. White spruce require higher levels of nutrients than other conifers in the region (Wilde 1966). Many of the plantations established by the CCC were created without taking site characteristics into consideration, making it possible stands to be located on soils not optimal for white spruce. Soil type was analyzed to determine if soil fertility could play a role in stand decline. Plots within stands were found to have different soil characteristics according to county soil surveys making it necessary to look at soil effects on tree measurements at the plot level instead the stand level. Plot level data was compiled by averaging white spruce tree measurements and presence of pests and root rot diseases for each prism plot.

County soil survey manuscripts and spatial data were downloaded from the USDA National Resources Conservation Service (NRCS) website (U.S. Department of Agriculture 2009). ArcGIS ArcMap 9.3 was used to view soil spatial data. Soil data was layered with the white spruce stands that were used in the survey so soil map unit codes from the GIS attribute files could be recorded. Individual county soil survey publications were referenced to determine each soil type's physical properties (USDA 1987; USDA 1988; USDA 1991; USDA 1997; USDA 1997; USDA 1998; USDA 1998; USDA 1999; USDA 1999; USDA 2005; USDA 2006).

Texture was the soil feature used for analysis since it is a characteristic that can be used to determine other attributes such as nutrient and moisture levels. The Soil Texture Class Triangle was used to combine the soil textures present in plots into three categories; (1) silt, (2) sand, (3) clay (Table 2). Low occurrence rate necessitated combining more specific soil textures into broader categories based on similar composition percentages. Since the Minnesota and Michigan county soil survey projects are still in progress, only 32 of the 43 stands (117 plots) had an adequate amount of soil data to be included in this analysis. Using SPSS version 16, a one-way ANOVA was used to test for differences in average tree measurements and presence/absence of pests and root rot fungi among the three soil texture categories.

Statistical Analysis

Multiple regression analyses were used to determine which factors had a significant impact on the health of white spruce and which stand and tree measurements best represented those factors. Multiple regression analysis was suggested by Manion (1991) as a method for identifying possible factors in the decline syndrome. SPSS version 16 was used to run all statistical analyses. All analyses conducted were considered significant at a p-value of 0.05.

Nine multiple regression analyses were run using the following factors as dependent variables: foliage density, foliage transparency, tree vigor, LCR, percentage of white spruce mortality, average white spruce growth in the past 10 years, average white spruce growth in the past 30 years, average growth of all other tree species in the past 10 years, and average growth of all other tree species in the past 30 years. Each analysis used the following 15 variables as independent factors: stand type, stand age, total basal area, bark beetles, root rot, SBW, carpenter ants, SNEED, *S. lauti* , total average annual precipitation last 5 years, average monthly precipitation last 5 years, average growing season precipitation last 5 years, average growing season temperature last 5 years, average annual PDSI last 5 years, and average growing season PDSI last 5 years (Table 3).

Objective 3: Develop a multi-criterion model to create risk maps that will identify and predict white spruce decline.

Multi-criterion Model and Risk Mapping

A spatial-based model using GIS was created for the entire study region. The National Forest System's National Insect and Disease Risk Map (NIDRM) structure was used as a guide for the development of the model. The NIDRM was created to provide strategic assessments for tree mortality due to insects and disease. These risk models are constructed with a GIS-based, multi-criteria framework (Krist 2005; Krist et al. 2007). A multi-criteria approach is used to combine information about multiple factors and constraints to create a single index of evaluation (Eastman et al. 1995). Four steps from the NIDRM process were used to create a map showing stand susceptibility and vulnerability to white spruce decline: 1) identify risk agents and host species; 2) identify, rank, and weight the criteria; 3) standardize and combine criteria; 4) flag pixels to create a risk map (Krist et.al. 2007).

Step 1 involved identifying the risk agents that contribute to the decline disease that are specific to white spruce decline. Possible factors of decline were described in the literature review and used to focus the data collection. Data analysis determined the criteria that have the potential to stress trees and make the stand susceptible to the agents that can cause tree mortality. The NIDRM developers suggest using a correlation analysis, however, multiple regression analysis was used instead as it is a more powerful statistical test for relationships. Step 2 inputs the independent factors that were found significant from the multiple regression analyses into the Risk Model Worksheet developed by the NIDRM framework (Figure 4). Each criterion was categorized as one that makes a stand susceptible or vulnerable to decline. Susceptibility is the potential for introduction and establishment of one or multiple factors that lead to decline within the range of white spruce. Vulnerability is potential for white spruce to experience mortality due to one or multiple factors (Krist et al. 2007). Criteria were categorized based on the factor's decline characterization. Predisposing factors were considered conditions of susceptibility while factors of vulnerability included Inciting and Contributing factors.

After the factors were inputted into the Risk Model Worksheet they were ranked and weighted within the worksheet. The beta coefficients from the multiple regression results were used to determine which factor had a greater impact on the dependent variable. This was then used to rank and weight factors in their importance to the decline disease as a whole. The beta coefficient is the standardized regression coefficient of a multiple regression model. It can be used to compare the relative strength of the predictors within the model. Since the beta coefficient is measured in standard deviations rather than individual variable units, it is possible to compare variables to one another. The beta coefficient value represents estimated average change in standard deviation units. A positive beta coefficient value indicates a positive relationship between the dependent variable and the predictive variable; a negative value represents a negative relationship.

In order to rank the factors, the absolute value of the each variable's beta coefficient from the multiple regression results were added together and divided by the total of the beta coefficients for each category to express a ratio between the factors. The calculated ratio was used to determine the factor's rank as a fraction in the worksheet. The Risk Model Worksheet uses pre-determined rankings. Once the rank is inserted, the worksheet auto-calculates the factor's weight as a percentage.

A common evaluation scale must be used to standardize all of the factor values in order to compare criteria with different values (inches, square feet, degrees). This is done in Step 3 by determining the risk potential for each criterion. Risk potential is described as the point when risk (a) begins, (b) peaks, (c) decreases, and (d) ends or no longer changes. This scale was determined by the data collected in the field and lab. Presence/absence factors were designated as 1 (present) or 0 (absent). A stand is considered at risk if the factor is present, therefore risk begins and peaks at 1 and decreases and ends at 0. Precipitation and temperature risk potential were determined based on high and mid records over the last five years. The risk potential for stand age was determined by the amount of average yearly tree growth compared to the stand age. Risk begins at age 60 when most stands show a decline in growth. Risk peaks, decreases, and ends at the same age, based on the assumption that the decline disease affects a mature, but not over mature, cohort of trees (Manion 1991).

The values calculated in the Risk Model Worksheet were used in ArcGIS Model Builder 9.3 to create two map layers. A Susceptibility Model created a layer showing the study stands that, based on the field data collected, have characteristics that make them susceptible to decline. A Vulnerability Model created a layer showing those stands that are likely to experience mortality as the result of the decline factors present. Using ArcMap 9.3 the Susceptibility layer and Vulnerability layer were combined into a map to highlight the stands that are susceptible and vulnerable to decline. Those stands that are both susceptible and vulnerable are currently in a state of decline.

RESULTS

Objective 1: Determine the regional extent and severity of white spruce decline and mortality.

Stand Surveys

A total of 43 stands were surveyed across the entire study area, 13 stands in Wisconsin, 16 in Minnesota, and 14 in Michigan (Figure 2). Based on state and federal stand classification records, 13 of the stands surveyed were considered natural mixed stands with white spruce as a co-dominant species, and 30 stands were plantations composed mainly of white spruce. Five natural stands were surveyed in Wisconsin, one in Minnesota, and seven in Michigan. Of the 30 plantations, eight were located in Wisconsin, 15 in Minnesota, and seven in Michigan.

Although there were few statistically significant differences between stands based on stand location and stand type, it is noteworthy to point out variations among states and plantations and natural stands. Plantations in Wisconsin were on average older than the stands in Minnesota and Michigan. Wisconsin plantations had an average age of 63, Minnesota 55, and Michigan 56. The average age of natural stands varied by state, with Minnesota the youngest, 37, and Michigan averaging the oldest, 69. Plantations in Wisconsin and Minnesota were on average older than the natural stands in the same state. The natural stands in Michigan were on average 12 years older than the plantations in Michigan (Table 4).

Individual white spruce in Wisconsin were significantly taller than those in Minnesota and Michigan (p = .039). Plantation white spruce in Wisconsin were on average taller (17.43m) and had a larger average DBH (27.89cm) than plantation white spruce in Minnesota (height 14.68m; DBH 24.24cm) and Michigan (height 15.97m; DBH 26.68cm). The natural stands in Wisconsin also had the tallest white spruce of the three states (WI 17.88m; MN 13.89m; MI 14.67m); however unlike the plantations, DBH was similar across the entire region (WI 25.97cm; MN 28.60cm; MI 27.24cm) (Table 4).

There were no significant differences for stand total basal area factor by location or stand type (p = .159 and p = .189). Plantations had a significantly higher white spruce basal area factor compared to natural stands throughout the entire study area (p = .009). Michigan and Minnesota plantations had a greater average white spruce basal area factor than plantations in Wisconsin (MI 156; MN 157; WI 143). On average plantations were composed of at least 75% white spruce trees, the most common non-white spruce species were quaking aspen, balsam fir, or red pine. The Minnesota natural stand had a greater white spruce basal area compared to natural stands in both Wisconsin and Michigan (MN 84; WI 62; MI 55). Wisconsin and Michigan natural stands had a significantly larger percentage of non-white spruce species than plantations (p = .035). Both Wisconsin and Michigan were composed of less than 40% white spruce, the natural stand in Minnesota was 62% white spruce. Natural stands were commonly mixed with quaking aspen, balsam fir, red pine, white pine, paper birch, sugar maple, red maple, tamarack, and black spruce (Table 4).

Statistically, most crown measurements for white spruce in plantations and natural stands were similar across the region. As measured in the field plantations averaged: 40% LCR, 40% foliage density, 55% foliage transparency, and an overall vigor class of 2. White spruce crown measurements in natural stands varied more than plantations throughout the region. Both foliage density and transparency ranged from 40-55%; Michigan averaged the lowest density (40%) and highest transparency (53%), and Minnesota averaged the highest density (50%) and lowest transparency (43%). White spruce LCR was significantly higher in natural stands than plantations (*p* = .019). LCR ranged from 50-65% for natural stands throughout the region, Wisconsin averaged the lowest (52%) and Minnesota averaged the highest (66%) (Table 4).

White spruce mortality did not differ significantly by location or stand type (*p* = .101 and *p* = .226). Although, plantation white spruce mortality in Wisconsin and Michigan was similar, 22% and 20% respectively, spruce mortality in Minnesota plantations was only 6%. Both Michigan and Minnesota natural stands had a relatively low percentage of white spruce mortality, 7% and 0% respectively. Wisconsin, on the other hand, had a 22% white spruce mortality in natural stands, equivalent to that in Wisconsin plantations (Table 4).

Objective 2: Characterize the nature of the decline by identifying the factors that make white spruce susceptible and vulnerable to decline.

Biotic factors

Of the total 43 stands surveyed, 28 had indications of bark beetle presence such as galleries and frass (beetles were only found on two occasions). The percent of stands with bark beetles was similar for Wisconsin and Minnesota for both plantations and natural stands (Wisconsin plantation 63%; Minnesota plantation 61%; Wisconsin natural 60%; Minnesota natural 63%). Michigan had bark beetles present in 86% of both plantation and natural stands (Table 5). There was no significant difference between the percent of stands with bark beetles present for stand location or stand type (*p* = .276 and *p* = .395).

Mycelial mats or fruiting bodies of root rot fungi were found in 32 stands throughout the entire region. Statistically there was no significant difference between the percentage of stands with evidence of root rot for location of stand type (*p* = .505 and *p* = .296). All plantations in Wisconsin had evidence of root rot diseases, 92% in Minnesota, and 86% in Michigan. The percent of natural stands in Michigan and Wisconsin with root rot were similar, 60% and 57% respectively. The natural stand in Minnesota also had evidence of root rot. The majority of occurrences were identified as *Armillaria spp.;* however, all incidences were combined into one group for analysis (Table 5).

Fourteen stands of the 43 total stands had evidence of spruce budworm activity in recent years. Both plantations and natural stands in Minnesota had fewer occurrences of spruce budworm, 8% of plantations and 0% natural, although statistically there was no difference of occurrence by location (*p* = .125). Half of the plantations and 40% of the natural stands in Wisconsin had evidence of spruce budworm. In Michigan 71% of plantations and 29% of natural stands showed spruce budworm activity. There was no significant difference of occurrence by stand type (*p* = .211) (Table 5).

All 43 stands surveyed had *R. kalkhoffii* needle cast present. For this reason, *R. kalkhoffii* was eliminated from the multiple regression analysis as a possible factor of decline. Five samples tested positive for *S. lautii;* two in Wisconsin, one in Minnesota, and one in Michigan (Figure 1). Thirteen percent of plantations and 20% of natural stands in Wisconsin, 14% of plantations in Michigan, and 8% of plantations in Minnesota had *S. lautii* (Table 5). There was no significant difference for the percent of presence by stand location or stand type (*p* = .407 and *p* = .507). Evidence of SNEED was found at three sites; two in Minnesota, and one in Michigan (Figure 3). Fifteen percent of the plantations in Minnesota and 14% of plantations in Michigan have SNEED present (Table 5). Again there was no significant difference for stand location or stand type and the presence of SNEED (*p* = .421 and *p* = .524).

Tree Ring Analysis

Based on average growth patterns developed from tree core samples, 82% of the stands surveyed showed decreased growth for white spruce over the past 30 years. In the last 10 years the percentage of stands with reduced growth increased to 86%. Less than 1% of the stands showed an increase or a constant amount of growth over the last 10 and 30 years (Table 6). Since the two non-white spruce samples collected from each stand were typically different species, the growth patterns were looked at individually as opposed to calculating a mean non-white spruce species growth curve for each stand. Fifty-five percent of the stands had decreased growth in the last 30 years. Over the last 10 years 75% of the stands showed a decline in growth. In the last 30 years 14% of the non-white spruce trees increased growth and 11% showed no change. In the last 10 years 30% showed an increase in growth and 16% remain constant (Table 7).

Regression analyses were completed to find correlations between stand growth and climatic measurements. Analyses were done for three time periods of stand growth, the past 10 years, past 30 years, and lifetime growth to look for changes in sensitivity to climate over time. Climatic measurements included average growing season temperature, average growing season precipitation, average monthly precipitation, and total annual precipitation. Significant correlations for the three time periods of white spruce growth were found for at least one stand for all climate measurements (Table 8). ANOVA results indicate there are no significant differences between climatic measurements or time periods based on the total number of correlated stands in each category (*p* = .415 and *p* = .257). Significant differences were present between locations, ANOVA analyses for lifetime growth and growth over the last 30 years indicate that a significantly higher number of stands in Michigan were correlated with any of the four climatic measurements (*p* = .001 and *p* = .041). In the last 10 years there were a significantly higher number of stands with growth correlations to climate in Wisconsin (*p* = .005). Plantations had a significantly higher number of stands correlated with a climatic measurement over the last 30 years (*p* = .035). Figure 4 demonstrates a representative positive correlation between plantation white spruce growth and average growing season temperature. Figure 5 demonstrates a representative negative correlation between white spruce growth in a natural stand and average growing season temperature. Figure 6 demonstrates a representative positive correlation between plantation white spruce growth and average monthly precipitation.

Regression analyses were also completed for stand growth and PDSI measurements including; average annual PDSI, average growing season PDSI, average annual PDSI for lag times of 5, 3, and 1 years, and average growing season PDSI for lag times of 5, 3, and 1 years. Significant correlations for white spruce were found for at least one stand with all PDSI measurements (Table 9). All correlations were positive indicating that as PDSI decreases to negative numbers growth also decreases and when PDSI is increasing positively growth also increases (Figure 7). ANOVA results indicate that Wisconsin had a significantly higher number of stands with correlations (*p* = .001) and plantations throughout the entire study area had a significantly higher number of correlations than natural stands (*p* = .002). There were no significant differences between the eight PDSI measurements (*p* = .239).

Significant correlations for climate measurements and PDSI were looked at further for patterns with site characteristics including stand type, location, soil texture, soil moisture, and habitat type. The results did not fall into any patterns allowing one time period, climatic, or PDSI measurement importance over another for different abiotic conditions.

A similar set of regression analyses were completed for non-white spruce growth and the four climatic measurements over the three time periods. In most cases the non-white spruce samples collected for a stand were two different species; therefore analysis was completed for individual trees instead of creating a stand mean as was done for the white spruce samples. Significant correlations for individuals ranged from 0-26% of the sample size for all climatic measurements (Table 10). ANOVA results indicate significant differences between climatic measurements (*p* = .033). ANOVA results indicate that a significantly higher number of non-white spruce individual trees showed lifetime growth correlations (.002). Similar to the results for white spruce, over the course of a lifetime and in the past 30 years Michigan had a significantly higher number of trees correlated to climate conditions (*p* = .003 and *p* = .010); and in the last 10 years Wisconsin had a significantly higher number of trees with correlations (*p* = .031). Lifetime growth and growth in the last 30 years had significantly more trees from plantations with correlations to climate (*p* = .014 and *p* = .003).

Multiple regression analyses were also completed for the mean growth in the last 10 and 30 years and the four climatic measurements during three time periods (5, 10 and 30 years) and two drought indices. White spruce growth in the last 10 years did not show any significant correlation with any climatic factor. The regression analysis for white spruce growth in the last 30 years resulted in a model using the growing season precipitation averaged over the last five years as a significant predictor variable (*p* = .024

and $R^2 = .130$). Growth for the other species in the stand did not result in any significant relationships.

Soils Analysis

Clay samples were removed from the one-way ANOVA comparing soil textures due to small sample size, leaving silt and sand for comparisons. The results showed soil texture has a significant impact on the percent of white spruce mortality and the presence of bark beetles ($p = .000$ and $p = .019$ respectively). Mortality of white spruce was significantly higher on soils of silt derivation ($p = .000$) (Figure 8). Plots on silt soils had a significantly higher occurrence of bark beetles than stands on sand soils ($p = .019$) (Figure 9).

Statistical Analysis

Multiple regression analysis was used to create models that predict the predisposing, inciting, and contributing factors that play a part in decline. The nine dependent variables used were measurable features of a stand that can be used to determine its health. In total the multiple regression models for the dependent variables drew out six predictor factors: stand type, stand age, average annual precipitation in the last 5 years, average growing season temperature in the last 5 years, bark beetle presence, and SBW presence (Table 11).

Regression analysis results indicated that the presence of SBW and bark beetles and an increase in average annual precipitation for the last 5 years leads to significantly decreased foliage density ($p = .001$ and $R^2 = .333$). Stands with SBW defoliation had significantly higher foliage transparency than stands without SBW ($p = .000$ and $R^2 = .281$). Plantations with SBW present had significantly lower tree vigor than natural stands or stands without SBW ($p = .000$ *and* $R^2 = .356$). Plantations with SBW and bark beetles present had a significantly lower LCR than stands without SBW and bark beetles present or natural stands ($p = .000$ and $R^2 = .420$). White spruce mortality is significantly increased with the presence of SBW and bark beetles and an increase in the average growing season temperature in the last 5 years ($p = .000$ and $R^2 = .474$). Older white spruce were more likely to have decreased average annual growth in the last 10 and 30 years compared to younger white spruce ($p = .003$ and $R^2 = .199$; $p = .009$ and $R^2 = .169$), and older non-white spruce were more likely to have decreased growth in the last 10 years ($p = .004$ and $R^2 = .289$).

Objective 3: Develop a multi-criterion model to create risk maps that will identify and predict white spruce decline.

Multi-criterion Model and Risk Mapping

The significant factors from the multiple regression analyses (stand type, stand age, average annual precipitation in the last 5 years, growing season temperature in the last 5 years, bark beetle presence, and spruce budworm presence) were used as the criteria for the Risk Model Worksheet (Figure 10). Predisposing factors including stand type, stand age, and precipitation and temperature variables were considered conditions that make a stand susceptible to decline. Spruce budworm, an inciting factor, and bark beetles, a contributing factor, were categorized as criteria of vulnerability.

The resulting map highlights the stands that are susceptible and vulnerable to decline, as defined by the Risk Model Worksheet (Figure 11). Twenty-five of the 43 stands surveyed are considered both susceptible and vulnerable to decline; currently in a state of decline or actively declining. Five of these stands are in Minnesota, ten are in Wisconsin, and 10 in Michigan. Ten stands are currently only susceptible, seven in Minnesota and three in Wisconsin; and seven stands, three in Minnesota and four in Michigan are only vulnerable. According to the model, one stand, in Minnesota, is considered healthy. ANOVA results found that a significantly higher number of the stands surveyed were in a state of decline ($p = .016$). Of the 25 stands in decline, 14 were plantations, and seven of the 10 stands susceptible to decline and all seven stands vulnerable to decline were plantations. A significantly higher number of plantations were either susceptible to decline, vulnerable to decline, or currently in decline ($p = .037$).

DISCUSSION

Factors of Decline

White spruce and non-white spruce intermediate (30 years) and recent (10 years) growth were significantly affected by stand age. Growth decreased as the stands aged. This follows the general forest growth pattern of an increase in biomass production after stand initiation, a peak in biomass when maximum leaf area is attained, followed by a decline in growth as the stand continues to age (Ryan et al. 1997; Binkley et al. 2002; Taylor and MacLean 2005). The major cause of mortality in younger stands that are still increasing in volume is competition for light and soil resources, but as a stand ages and becomes more stable in biomass production the major causes of tree mortality are age and disturbances (Ryan et.al 1997; Binkley et.al 2002; Taylor and MacLean 2005). The stand may begin to break up at a younger age even though individual trees may reach the species maximum age (Taylor and MacLean 2005). In a study of balsam fir-spruce stands in New Brunswick, Canada, Taylor and MacLean (2005) found that stands declined in volume after reaching a peak stand age, which agreed with growth model forecasts for volume stabilization and decline after age 90 (Erdle and MacLean 1999). The only stand that was neither susceptible nor vulnerable to decline was the youngest stand in the study. White spruce in plantations measured in this study may have already reached a peak stand age, based on the decreased growth patterns and decline symptoms many stands are experiencing.

The results from field work and data analysis indicated that the presence of spruce budworm (SBW) in white spruce stands was a significant decline factor. Multiple regression model results specified the presence of SBW was a significant predictor for crown measurements including density, transparency, LCR, and overall tree vigor. MacLean and MacKinnon (1997) deduced that since SBW is a natural defoliator, the probability of a spruce-fir forest being attacked by SBW is 100%.

Regression models showed SBW was a significant predictor for white spruce mortality. It has been shown that defoliation from SBW can reduce white spruce survival up to 90% (MacLean 1980) and mortality can remain high for up to 20 years after the outbreak (Taylor and MacLean 2009). In eastern North America SBW is one of the most influential non-human biotic factors on stand structure and composition (Burleigh et al. 2002). SBW-caused mortality leaves gaps in the canopy that creates conditions that make surrounding trees more susceptible to wind throw and root rot fungi. This can cause rapid stand decline and break up in aging stands (Taylor and MacLean 2009).

Forests of the upper Great Lakes region have experienced increased SBW defoliation from 2003-2007 with a peak in defoliation in 2005. More extensive defoliation was recorded in Michigan and Wisconsin. Based on regional SBW activity records from 1997-2008, a significantly fewer number of the stands surveyed in Minnesota were reported to have SBW defoliation. Based on results from other studies that show mortality from SBW remaining high years following an outbreak (Baskerville and MacLean 1979; Taylor and MacLean 2009), some of the mortality seen during the course of this study may be residual mortality from the 2003-2007 outbreak. It can also be expected that the region may experience continued residual white spruce and balsam fir mortality, especially in Michigan and Wisconsin.

Plantations of white spruce provide large quantities of resources for SBW and other outbreak and infectious species. Plantations in the current study averaged less than 25% non-white spruce species and 33% of the plantations showed recent SBW defoliation. Natural stands throughout the study range averaged 57% non-white spruce species composition and 31% of the natural stands surveyed had some evidence of SWB defoliation. Although white spruce can sustain longer periods of SBW defoliation than the favored host balsam fir, the resulting longer infestations can be intensified in plantations by the lack of non-host trees (Burleigh et al. 2002). Studies of balsam fir stands in Canada show that stands with reduced SBW host density due to higher hardwood content have lower SBW mortality than stands with higher host densities (MacLean 1980; van Raalte 1972; Crook et al. 1979; Su et al. 1996). Su et al. (1996) found that when hardwood content was less than 40% SBW defoliation levels were significantly higher than when hardwood content was greater than 40%. There was no significant difference between SBW presence among natural stands and plantations in this study; however, the data collected were not intended to quantify white spruce mortality due to SBW defoliation.

Plantations were found to have a significantly higher number of stands that were susceptible to decline, vulnerable to decline, or currently declining. White spruce does not naturally occur in pure stands in the Great Lakes region, instead white spruce is more commonly found in mixed compositions with other conifers and hardwood species. White spruce plantations were planted as part of a large-scale restoration effort in the upper Great Lakes with the intent of harvesting timber the future. With the exception of Wisconsin, natural mixed white spruce stands had lower white spruce mortality. Plantations in Michigan, Minnesota and Wisconsin had an average of 16% white spruce mortality and natural stands 10%. Statistical analysis showed plantations had significantly lower LCR and vigor compared to stands of mixed compositions. This may be attributed to high stocking densities and resource competition. Plantations averaged basal areas of 173-247m^2/ha greater than natural stands. Twenty-five of the thirty plantations surveyed have had no silvicultural work since initial planting.

Bark beetle presence was significantly important in three regression models (foliage density, LCR, and white spruce mortality) accounting for 50% of the weighted vulnerability criteria in the risk model. In the Great Lakes region bark beetles are categorized as a contributing factor of decline. Bark beetles commonly attack and kill stressed, windthrown, or recently cut white spruce. It is not as common, however, for bark beetles to attack healthy trees in the Great Lakes region as is in other areas of the range of white spruce. For example, the spruce beetle, *D. rufipennis,* is an important cause of white spruce mortality in the eastern part of the host range, and the leading cause of white spruce mortality in the west (Safranyik and Linton 1988; Gara et al. 1995). Haberkern et al. (2002) hypothesize the reason for the differences in bark beetle-caused mortality throughout the range of white spruce could be due to the differences in tree species diversity as well as diversity of bark beetle species. In northern regions, white spruce is found in pure stands compared to natural mixed composition in the Great Lakes region. However, with the large acreage of white spruce plantations throughout the region that are stressed, bark beetles now play a larger role in white spruce decline and mortality. Studies have shown that susceptibility of white spruce to spruce beetles is related to radial growth; trees killed first in an outbreak are larger than average in diameter, but more significantly they had slower average growth in their last five years (Hard et al. 1983). Hard (1985) hypothesized that slow growing trees may not have adequate energy reserves to produce resin to repel bark beetle attacks. Studies of site and tree characteristics have found that stands with high tree densities often have increased frequency of bark beetle attacks and mortality. Stand density was shown to be a good predictor of stand mean cumulative radial growth; stands with higher stocking levels had slower growth and were more susceptible to spruce beetle attack (Hard 1985; Doak 2004). The plantations in this study had both higher stand densities of white spruce and declining growth, indicating the possibility of increased tree susceptibility to bark beetle attacks.

The majority of the stands that are currently in a state of decline are located in the eastern portion of the study region based on the results of the model. Two regression analyses were run to determine if there were any differences in white spruce mortality based on longitude and latitude. The average white spruce mortality rate was significantly different for different longitudes and latitudes (p = .014, R^2 = .143 and p = .001, R^2 = .241). Stands east of 92°W longitude had an increase in average white spruce mortality of up to 30%, and stands south of 47°N latitude had a 10% increase (Figure 12). Variations in taxonomic characteristics, monoterpenes, and DNA content suggest there are two major populations of white spruce, one east and one west of 95° longitude (Nienstaedt and Teich 1972). The study area for the current project is located between 88° and 95° longitude.

Needle Pathogen Analysis

Needle samples collected for the current study were analyzed for presence of needle and twig pathogens. All white spruce needle samples tested positive for *Rhizosphaera kalkhoffii*. Since not all stands in the study were experiencing white spruce decline, *R. kalkhoffii* may not play a large role in the decline. However, this does not eliminate it from having a minor role as foliar diseases affect the photosynthetic activity of trees. *R. kalkhoffii* causes the needles to turn purplish-brown and fall off, and since conifers cannot re-foliate, affected trees may experience reduced vigor with the loss of photosynthetic surfaces. Future studies testing for the severity or virulence of *R. kalkhoffii* may give insight into the relationship between the fungus and white spruce. The status of *Rhizosphaera* as a pathogen in natural habitats is still unclear. Koch's postulates for proof of pathogenicity on *Picea* species in Wisconsin and Minnesota showed *R. kalkhoffii* to be pathogenic on Colorado blue spruce (*Picea pungens* Engelm.), Norway spruce (*Picea abies* (L.) Karst.), black spruce, and white spruce (Juzwik, 1993). But, no clear relationship between disease presence and vigor loss or severity has been documented. Similarly, results from research in Japan found *R. kalkhoffii* to be a weak pathogen of Japanese red pine (*Pinus densiflora* Sieb. et Zucc.) (Tanaka and Chiba 1971). However, results for Norway spruce in Europe concluded *R. kalkhoffii* was an epiphytic saprophyte living on needle surfaces (Dotzler 1991).

A small portion of the stands tested positive for *S. lautii* or SNEED. Neither the needle nor the twig pathogens were significant factors in the decline model. All stands with *S. lautii* or SNEED were either actively declining or susceptible to decline, however, not all stands currently in decline or susceptible to decline had *S. lautii* or SNEED. It is possible the needle sampling method was not thorough enough to detect the presence of pathogens. Random sampling was limited to needles that could be reached with an extended pruner. In many cases, due to small LCRs, canopy needles were out of reach, requiring samples to be collected from younger trees or those located along the stand edge. Both *S. lautii* and SNEED have been recently identified in the upper Great Lakes region; relatively little is known regarding each pathogen and its ecological role (Hodges 2002; Rossman et al. 2002).

Tree Ring Analysis

Significant correlations were found for white spruce growth and climate metrics (precipitation and temperature) and drought (PDSI), however there were no statistically significant results indicating the importance of one climatic or PDSI measurement over another. Lifetime, intermediate, and recent periods of growth were tested to determine if there have been changes in sensitivity to climate as trees age. Statistical analyses showed a higher number of white spruce and non-white spruce in Michigan were correlated significantly with one or more climate metric over a lifetime of growth and growth over the last 30 years. In the last 10 years, however, a higher number of white spruce and non-white spruce in Wisconsin were correlated to one or more climate metric. In Michigan the average annual precipitation over the last 10 years dropped approximately 14 centimeters compared to the averages over the last 30 and 100 years. A similar decrease in precipitation was not recorded in Wisconsin. A change in precipitation in Michigan can explain a change in growth-climate relationship; however, it would be assumed that if the trees are responding to climatic conditions a dramatic change in those conditions would be reflected in tree growth. Since statistical analyses did not show a significant relationship, there may be a weak relationship and the possibility that other factors are affecting growth. Plantations had a higher number of significant correlations for both white spruce and non-white spruce growth and climate and PDSI metrics than natural stands. These relationships may indicate that tree growth in more natural compositions is affected by more than climate and drought conditions. Overall, there was a lack of consistency among the stands significantly correlated for growth-climate relationships. Stands with significant relationships were not significantly similar in other aspects.

Average white spruce growth over the last 30 years showed a significant relationship with average growing season precipitation for the last five years indicating that the last five years of growth was greatly influenced by the precipitation in the last five years. If this is the case, growing season precipitation averaged for the last 10 years would have a significant effect on growth in the last 10 and 30 years. However, this relationship was not significant. This indicates that the accuracy of the test results is merely a relationship in numbers and not a relationship in growth and amount of rainfall during a growing season.

This study did not find a consistent relationship between tree growth (white spruce and non-white spruce) and climate (precipitation and temperature) or drought (PSDI) in the upper Great Lakes. This contradicts other studies in different regions of the species' range. In the boreal forests of Alaska, Barber et al. (2000) found low-elevation white spruce had decreased radial growth in response to increased temperatures, similarly treeline white spruce were found to have a negative response to the previous July temperature (Wilmking et al. 2004). Little research has been done on white spruce at its southern limits; however, Chhin et al. (2004) concluded that temperature-induced drought intensifies moisture deficiency creating conditions that determine growth for white spruce at the southern limit of distribution in the ecotone between Canadian prairies and northern boreal forests. Although many studies have shown growth-climate relationships, most did not deal with cohorts affected by a decline disease syndrome, instead reduced growth was explained by changes in normal temperature and precipitation ranges. Manion (1991) explains that a correlation analysis that results in weak relationships is often an indicator of a decline disease. A strong correlation with weather or other site variables suggests it is a decline disease syndrome but instead a single causal agent. However, both precipitation and temperature were significant factors in the decline risk model, indicating that weather patterns do have an important affect on other aspects of white spruce health.

White spruce, as a species, exhibits substantial variation across its range as it has the ability to adapt to local conditions making it important to adhere to seed zones for seed and seedling distribution (Nienstaedt and Zasada 1990). As noted earlier it has been suggested there may be Eastern and Western populations of white spruce (Nienstaedt and Teich 1972). The seed origin for the trees planted by the CCC is not documented. If the seeds came from a location outside the upper Great Lakes region, such as Canada, the trees could be genetically intolerant of the warmer temperatures and longer growing season found at the southern limit of the range. It is postulated that global warming affects tree species more strongly at the edge of their distribution (Rizzo and Wilken, 1992; Lenihan and Neilson, 1995).

Soils Analysis

According to the statistical analysis, soil had a significant impact on two symptoms of white spruce decline. Plots on silt derived soils had significantly higher white spruce mortality and presence of bark beetles indicating silt soils may not maintain the optimal fertility or draining characteristics white spruce need. Since the soil analysis was completed at the plot level instead of the stand level like all other analysis, the results were not included in the risk model. Further research is recommended to pinpoint an explicit feature of soil or condition that impacts soil that can be included in the risk model.

More detailed analysis of the different qualities of soil and how they relate to root and mycorrhizal health may prove valuable. It has been found in other decline studies that non-woody tree roots and mycorrhizae will degenerate prior to the onset of above ground symptoms (Manion 1991). Ectomycorrhizae fungi increase water uptake and are beneficial for trees growing on soils with low temperatures (Landhausser et al.

2002). Nurseries in the Lake States found that fumigation for pests may kill the beneficial mycorrhizae, resulting in seedlings with foliage phosphorous deficiency when the soil with adequate phosphorus (Croghan et al. 1987).

Stand age and composition may also impact soil nutrient qualities. As trees in a stand mature, the nutrient level of the mineral soil decreases, and nutrients available at the forest floor increases as a result of an accumulation of leaf litter (Gale et al. 1991; Gordon et al. 2000). It is possible that white spruce at different developmental stages require different soil characteristics to achieve the best possible production. Wang and Klinka (1997) found foliar phosphorus, potassium, and nitrogen levels decreased as stands aged and growth decreased. Nutrient cycling can also be affected by the species present and the nutrients available in the leaf litter (Gordon et al. 2000). White spruce at the southern edge of the range are naturally associated with other tree species, especially hardwood species. The relationship may be necessary to maintain the high level of soil fertility necessary for optimal white spruce growth.

Although soil is the main source of vegetation climax, it has been noted that soil surveys do not always coincide with a given habitat type (Kotar 1986). Habitat type classification is considered a more encompassing method of characterizing the ecological foundations of vegetative communities and landscapes. Areas capable of producing similar mature plant communities are classified as habitat types. Habitat types were developed using current and potential natural vegetation, the physical characteristics, and the natural trends of a site (Kotar et al. 2002; Kotar and Buger 2003; MNDNR 2003). Of the 43 stands surveyed throughout the study area, 21 stands are on sites of habitat types that have white spruce as a common canopy associate. Four additional stands have habitat types that include white spruce as a less frequent successional pathway associate. Eighteen stands can be considered growing ‘off-site,’ thirteen of which are plantations. Of the stands with habitat types that include white spruce, three are considered healthy, three stands are susceptible, three are vulnerable, and 16 are in a state of decline. Site characteristics and natural community pathways are important to stand health; however, it is apparent that other factors are also contributing to the current white spruce decline.

Multi-criterion Model and Risk Mapping

Currently the Forest Service uses a set of thresholds to monitor stands determined to be at high risk for decline. The following trigger points, as stated in the Environmental Assessment for the 2004 Spruce Decline Project, initiate prescription treatment actions when the “stand averages less than 1/3 live crown per tree; or stand averages greater than 15% mortality; or stand crown conditions are rated poor and average radial growth is less than 0.1 inch per year” (USDA Forest Service 2005). If one or more of these thresholds are exceeded salvage actions are taken. In this study 15 of the surveyed white spruce stands had greater than 15% white spruce mortality. Eleven of these stands were categorized as declining in the decline model developed for this study. Eight of the stands surveyed had on average less than 1/3 live crown. Six of these stands were included in the decline model as declining. The third guideline is a combination of growth and overall stand vigor. Forty-one of the 42 stands with growth measurements had less than 0.1 inch average radial growth in the last 10 years, and one stand had overall poor vigor (vigor class 3). The one stand with poor vigor also had low growth making it the only stand considered declining using this guideline. This stand is also included as declining by the model.

The decline model developed for this study highlights 25 stands, 14 plantations and 11 natural stands, as both susceptible and vulnerable currently to decline, classifying them as currently in decline. Ten stands, seven plantations and three natural stands are currently susceptible to decline, or in an early phase of decline. These stands have characteristics that predispose them to decline, such as increased age and monoculture composition. When the stands experience drought conditions they have increased susceptibility to high levels of mortality if bark beetles or SBW enter the stand, however, when precipitation is increased trees become more susceptible to needle pathogens that are spread by rain splash. Seven stands, all plantations, are classified by the model as only vulnerable to decline meaning there was evidence of bark beetles or SBW, but the stand does not have the characteristics that can make it susceptible to extensive mortality due to decline. Regardless of how vulnerable the stand is, the trees will not experience mortality caused by the risk agent if the region is not susceptible to attack (Krist 2005). Although, these stands may become susceptible to decline as they age.

The NIDRM framework used as a guideline for the development of the current model is a relatively new GIS-based tool developed for mapping risk of insect and disease damage and mortality. Accuracy of the model output is dependent on the knowledge of the pest or disease behavior (Krist et al. 2007). The framework was developed to map the risk of susceptibility and vulnerability to a single causal agent, mapping a decline disease is more complicated due to the lack of understanding of the interactive affects among multiple stressors (Krist et al. 2007). The nature of a decline disease is complex and requires a concentrated investigation to determine the risk factors. Statistical methods were used for the current research to establish the particular factors involved in white spruce decline and to weigh the relative importance for each factor.

The resultant model is much more sensitive than the current method the Forest Service uses. The decline model incorporates seven stand features, both biotic and abiotic, which more accurately describe the interaction between a set of factors involved in a decline syndrome. By looking at several factors at one time the range of decline is broadened. For example, by focusing solely on mortality, once a stand reaches a predetermined value, it is considered to be in a state of decline. To exhibit that level of mortality within the stand, however, the stand had to be actively declining for a period of time prior to reaching that predetermined point. This decline model identifies stands at risk of decline and those stands that are already in decline earlier than the current guidelines used by forest managers.

Management Recommendations

Based on the results of this study, stand type and stand age are two factors that, when altered by management strategies may reduce the susceptibility and therefore the vulnerability to decline disease syndromes. It was shown that plantations have lower LCRs, less vigor, higher stand density, and higher white spruce mortality. This is because plantations provide abundant hosts and few obstacles for defoliating pests and needle pathogens. High density, even aged stands experiencing age related radial growth reduction make trees more susceptible to bark beetle attacks and windthrow. Stand age and composition also impact nutrient cycling within the stand. Hard (1985) combined his research with others to suggest increased tree spacing may enhance stand resistance to bark beetle infestation. Increased spacing may increase tree growth and vigor, reducing the probability of beetle movement to an adjacent host tree (Geiszler et al. 1980). Further, opening the canopy may disrupt back beetle communication by reducing pheromone entrapment (Fares et al. 1980). Su et al. (1996) also recommended management strategies that favor mixed compositions at the stand and forest level to reduce defoliation from SBW.

A recent study completed by the University of Minnesota on thinning effects in white spruce plantations found that thinning had a positive effect on tree vigor due to increased LCR and growth and decreased mortality rates (Troumbly et al. 2009). Troumbly et al. (2009) concluded that white spruce plantations should be thinned frequently enough to maintain an LCR of at least 50%, making the stands more responsive to future thinnings and more resilient by increasing vigor. However, damage caused by silviculture operations can also leave trees susceptible to pathogens. Root damage caused by logging operations is a common problem in plantations when the amount of slash used for the equipment to roll over is not adequate. Root rot fungi will take advantage of the wounded roots and quickly infest the stand (Albers 2007).

The stands surveyed for this study have had little or no active management since their establishment. They represent an unnatural forest community for the upper Great Lakes region. Silvicultural practices that manage stands away from monoculture even-aged stands may enhance the vigor of residual trees making them more resistant to insect pests and pathogens. The decline model may be a useful tool for determining the state of a stand as either healthy, susceptible to decline, vulnerable to decline, or actively declining, and therefore help managers prioritize stands that require management practices. The development of different management plans based on different stages of decline is recommended. For example prevention plans for healthy or susceptible stands, and salvage plans for those declining stands that will not respond to treatment. It is not recommended to re-establish white spruce in plantations or on sites that are susceptible to decline.

Conclusions

This research was an effort to determine the driving forces behind white spruce decline in the upper Great Lakes region. The data indicate that white spruce decline and mortality in the upper Great Lakes region is the outcome of a complex etiology and not a single causal agent, allowing us to consider it a product of decline disease syndromes. Based on the results of this study white spruce decline is extensive and ongoing throughout the study area. Both plantations and natural stands are being affected by the phenomenon; however plantations represent an unnatural age and species composition making stands more vulnerable to mortality due to SBW and bark beetles. Climate conditions appear to play a partial role in decreased growth seen across the region. Recent precipitation was shown to have a negative impact on white spruce foliage transparency and mortality. Although not included in the final model, soil may play a role on nutrient and moisture availability as a significantly higher level of white spruce mortality was seen on stands with silt derived soil. Approximately half of the surveyed stands can be considered 'off-site' according to habitat type classifications for the study area, however stands on habitat types that have white spruce as a canopy associate were also classified as declining.

As proposed by Manion (1991), the decline and death of a large number of trees may be required for the proper development of the next generation. This may not necessarily be an abnormal phenomenon as long as it is a natural decline and not human-induced. In the case of the white spruce plantations that are declining, it may be a natural decline in response to the human-induced situation that created the unnatural even-aged monocultures that make the stands susceptible to decline. Although diseased and dying trees only become a problem when human expectations are considered (Manion 1991) the health of state and federal forests are reliant on past and future management practices. The GIS model developed in this study and the management recommendations offered strive to aid land managers in the sustainment of the health, diversity, and productivity of the Nation's forests.

Tables and Figures

Table 1. Possible Predisposing, Inciting, and Contributing factors for white spruce decline.

PREDISPOSING FACTORS	INCITING FACTORS	CONTRIBUTING FACTORS
Climate: may be more susceptible to climate change at the southern edge of its range.	**Drought**: area has experienced several severe droughts since the 1970s.	**Wood boring insects**: *Ips pertubatus, Dendroctonus rufipennis, Pityogenes spp.*
Stand Age: mature trees showing signs of decline.	**Spruce Budworm defoliation**: persistent outbreak species.	**Root Rot Fungi**: *Armillaria spp., Inonotus tomentosus, Phaeolus schweinitzii*
Site conditions: soil fertility and moisture, monoculture composition	**Foliage and twig fungi**: *Rhizosphaera kalkhoffii*, *Stigmina lautii*, *Setomelanomma holmii* (SNEED)	

Table 2. Soil Texture Classification for plot level soil analysis. Classification determined by grouping plot level soil textures based on the Soil Texture Class Triangle. Silt=1, Sand=2, Clay=3

Stand Soil	% Sand	% Silt	% Clay	Classification
Silt loam	20-50	50-87	0-28	1
Loamy coarse sand	80-85	0-30	10-15	2
Loamy fine sand	70-75	0-30	10-15	2
Sand	85-100	0-15	0-10	2
Fine sandy loam	50-55	30-50	15-20	2
Very fine sandy loam	45-50	30-50	15-20	2
Sandy loam	50-70	30-50	15-20	2
Sandy loam muck	50-70	30-50	15-20	2
Coarse loam	45-52	28-50	8-28	2
Silty clay/Clay	0-45	0-60	55-100	3
Muck				3

Table 3. Dependent and Independent factors used in multiple regression analyses to determine criteria used in the white spruce decline risk models.

Dependent Factors	Independent Factors
Foliage Density	Stand Type (Plantation/Natural)
Foliage Transparency	Stand Age
Tree Vigor	Bark Beetles
Live Crown Ratio	Spruce Budworm
Percent Mortality (white spruce)	Carpenter Ants
Average Growth last 10 years (white spruce)	Root Rot
Average Growth last 30 years (white spruce)	*Rhizosphaera kalkhoffii*
Average Growth last 10 years (other species)	*Stigmina lauti*
Average Growth last 30 years (other species)	*Setomelanomma holmii* (SNEED)
	Total Annual Precipitation (5yrs)
	Average Monthly Precipitation (5yrs)
	Average Growing Season Precipitation (5yrs)
	Average Growing Season Temperature (5yrs)
	Average Growing Season Palmer Drought Severity Index (5yrs)
	Average Annual Palmer Drought Severity Index (5yrs)

Table 4. Average stand measurements for each state by stand type with standard deviations in parenthesis. ANOVA analyses and Tukey's SD post hoc test were used to compare stand characteristics by stand type and location. Letters denote significant measurement differences between region or stand type at *p* = ≤ .05.

Region	Stand Type	Sample Size	Age	White Spruce BA (m^2/ha)	% Non-white Spruce	DBH (cm)	Height (m)	Density (%)	Transparency (%)	LCR (%)	Vigor	Mortality (%)
WI	Plantation	8	63.4(15.9)a	142.8(40.9)a	22.4(18.8)a	27.89(3.5)a	20.34(2.2)a	36.7(8.4)a	55.9(6.4)a	39.2(15.5)a	1.8(0.7)a	22.3(20.0)a
WI	Natural	5	57.6(21.7)a	61.8(19.1)b	61.2(10.9)b	25.97(10.1)a	17.88(3.1)a	41.5(5.3)a	51.5(8.6)a	52.3(8.8)b	1.6(0.5)a	21.8(18.2)a
MN	Plantation	13	45.5(10.3)a	157.8(42.5)a	12.7(12.6)a	20.93(3.2)a	14.68(2.8)b	40.2(2.5)a	50.5(3.4)a	45.5(9.1)a	1.8(0.4)a	5.6(8.2)a
MN	Natural	1	37(0)a	84(0)b	38(0)b	28.60(0)a	13.89(0)b	50.0(0)a	42.6(0)a	66.0(0)b	1(0)a	0(0)a
MI	Plantation	7	56.1(9.8)a	156.4(46.0)a	22.4(18.3)a	22.53(3.6)a	15.97(1.5)b	40.9(5.7)a	55.5(5.2)a	35.9(8.3)a	1.9(0.4)a	20.1(12.2)a
MI	Natural	7	69.3(23.8)a	55.3(20.0)b	73.1(8.3)b	27.24(3.9)a	14.67(1.2)b	39.6(4.3)a	52.9(4.8)a	54.1(10.0)b	1.4(0.5)a	6.9(9.1)a

Table 5. Percent of stands with presence of bark beetles, spruce budworm, root rot, *R. kalkhoffii*, *S. lautii*, and SNEED, and the percent of stands with white spruce regeneration for each state by stand type. ANOVA analyses and Tukey's SD post hoc test were used to compare stand characteristics by stand type and location. Letters denote significant measurement differences between region or stand type at *p* = ≤ .05.

Region	Stand Type	Sample Size	Bark Beetles	Spruce Budworm	Root Rot	*R. kalkhoffii*	*S. lautii*	SNEED	White Spruce Regeneration
WI	Plantation	8	63 a	50 a	100 a	100 a	13 a	0 a	0 a
WI	Natural	5	60 a	40 a	60 a	100 a	20 a	0 a	0 a
MN	Plantation	13	61 a	8 a	92 a	100 a	8 a	15 a	31 a
MN	Natural	1	0 a	0 a	100 a	100 a	0 a	100 a	100 a
MI	Plantation	7	86 a	71 a	86 a	100 a	14 a	14 a	29 a
MI	Natural	7	86 a	29 a	57 a	100 a	0 a	0 a	43 a

Table 6. Percent of stands with white spruce experiencing a decline in growth, an increase in growth, and no change in growth over the last 10 and 30 years for each state. The total percentage for each growth category across the entire study region are shown in bold. Significant differences between the percentage of stands within each growth class based on ANOVA results are denoted by letters (*p* = ≤ .05). (n=42)

	Declining Growth		Increasing Growth		No Change in Growth	
	Last 10 Years	**Last 30 Years**	**Last 10 Years**	**Last 30 Years**	**Last 10 Years**	**Last 30 Years**
Michigan	79% a	72% a	14% b	21% b	7% b	7% b
Wisconsin	86% a	92% a	14% b	8% b	0% b	0% b
Minnesota	94% a	84% a	6% b	8% b	0% b	8% b
Total Means	**86%**	**82%**	**9%**	**13%**	**5%**	**5%**

Table 7. Percent of stands with non-white spruce species experiencing a decline in growth, an increase in growth, and no change in growth over the last 10 and 30 years for each state. The total percentage for each growth category across the entire study region are shown in bold. Significant differences between the percentage of stands within each growth class based on ANOVA results are denoted by letters (*p* = ≤ .05). (n=42)

	Declining Growth		Increasing Growth		No Change in Growth	
	Last 10 Years	**Last 30 Years**	**Last 10 Years**	**Last 30 Years**	**Last 10 Years**	**Last 30 Years**
Michigan	70% a	57% a	21% b	24% b	9% b	19% b
Wisconsin	83% a	50% a	6% b	43% b	11% b	7% b
Minnesota	69% a	56% a	13% b	22% b	13% b	22% b
Total Means	**75%**	**55%**	**14%**	**30%**	**11%**	**15%**

Table 8. Stands with significant correlations between white spruce growth and climate over three time periods. ANOVA results indicate no differences between the climate categories or the time periods (*p* = .256 and *p* = .368). Letters denote significant differences at *p* = ≤ .05. (n=42)

	Lifetime		Last 30 Years		Last 10 Years	
	Number of Stands	**Percent of Stands**	**Number of Stands**	**Percent of Stands**	**Number of Stands**	**Percent of Stands**
Average Growing Season Temperature	6	14 a	3	7 a	1	2 a
Average Growing Season Precipitation	3	7 a	7	17 a	7	17 a
Average Monthly Precipitation	5	12 a	10	24 a	5	12 a
Average Annual Precipitation	5	12 a	9	21 a	5	12 a

Table 9. Stands with significant correlations between white spruce growth and moisture deficiency measured by the Palmer Drought Severity Index (PDSI). Analysis covered average annual PDSI for the current year and 5, 3, and 1 year lags, and average growing season PDSI for the current year and 5, 3, and 1 year lags. ANOVA results indicate no significant differences between PDSI measurements (*p* = .239). Letters denote significant differences at *p* = ≤ .05. (n=42)

	Number of Stands	Percent of Stands
Average Annual PDSI (current year)	8	19 a
Average Annual PDSI (5 year lag)	9	21 a
Average Annual PDSI (3 year lag)	12	29 a
Average Annual PDSI (1 year lag)	7	17 a
Average Growing Season PDSI (current year)	6	14 a
Average Growing Season PDSI (5 year lag)	10	24 a
Average Growing Season PDSI (3 year lag)	6	14 a
Average Growing Season PDSI (1 year lag)	6	14 a

Table 10. Individual non-white spruce trees with significant correlations between growth and climate over three time periods. ANOVA results indicate a significantly higher number of individual trees showing lifetime growth correlations (*p* = .002).

	Lifetime		Last 30 Years		Last 10 Years	
	Number of Individuals (n=57)	Percent of Individuals	Number of Individuals (n=42)	Percent of Individuals	Number of Individuals (n=57)	Percent of Individuals
Average Growing Season Temperature	9	16 a	2	5 b	0	0 b
Average Growing Season Precipitation	9	16 a	5	12 b	6	11 b
Average Monthly Precipitation	15	26 a	6	14 b	6	11 b
Average Annual Precipitation	14	25 a	6	14 b	6	11 b

Figure 1. Natural distribution of white spruce throughout North America (Nienstaedt and Zasada 1990).

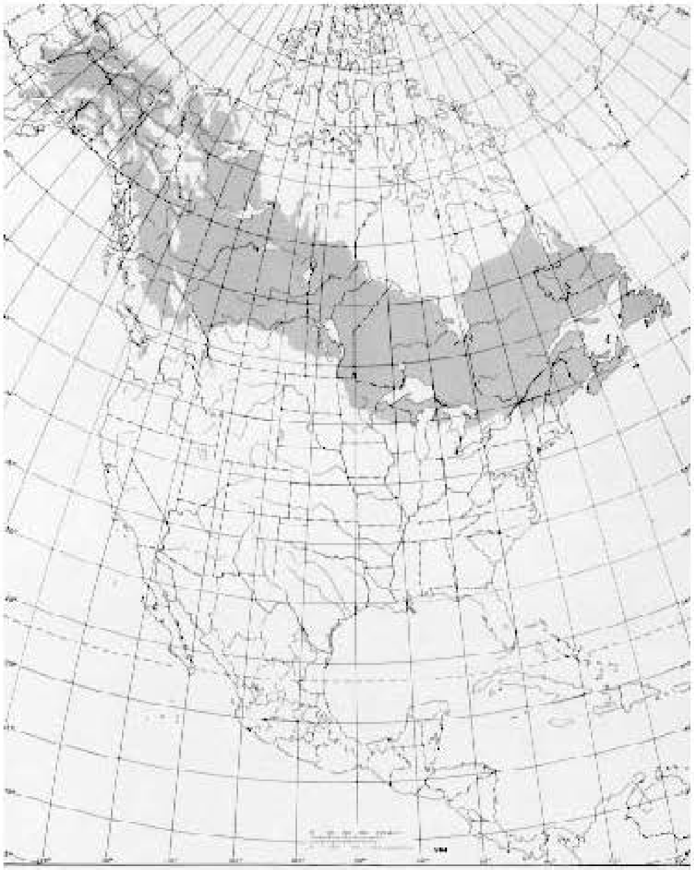


Figure 3. Study stands with positive results for presence of *S. lautii* (Stigmina) and *S. holmii* (SNEED). There were no significant differences for the presence of either pathogen for stand location or stand type (*S. lautii*: location *p* = .407 and stand type *p* = .507; *S. holmii*: location *p* = .421 and stand type *p* = .524).

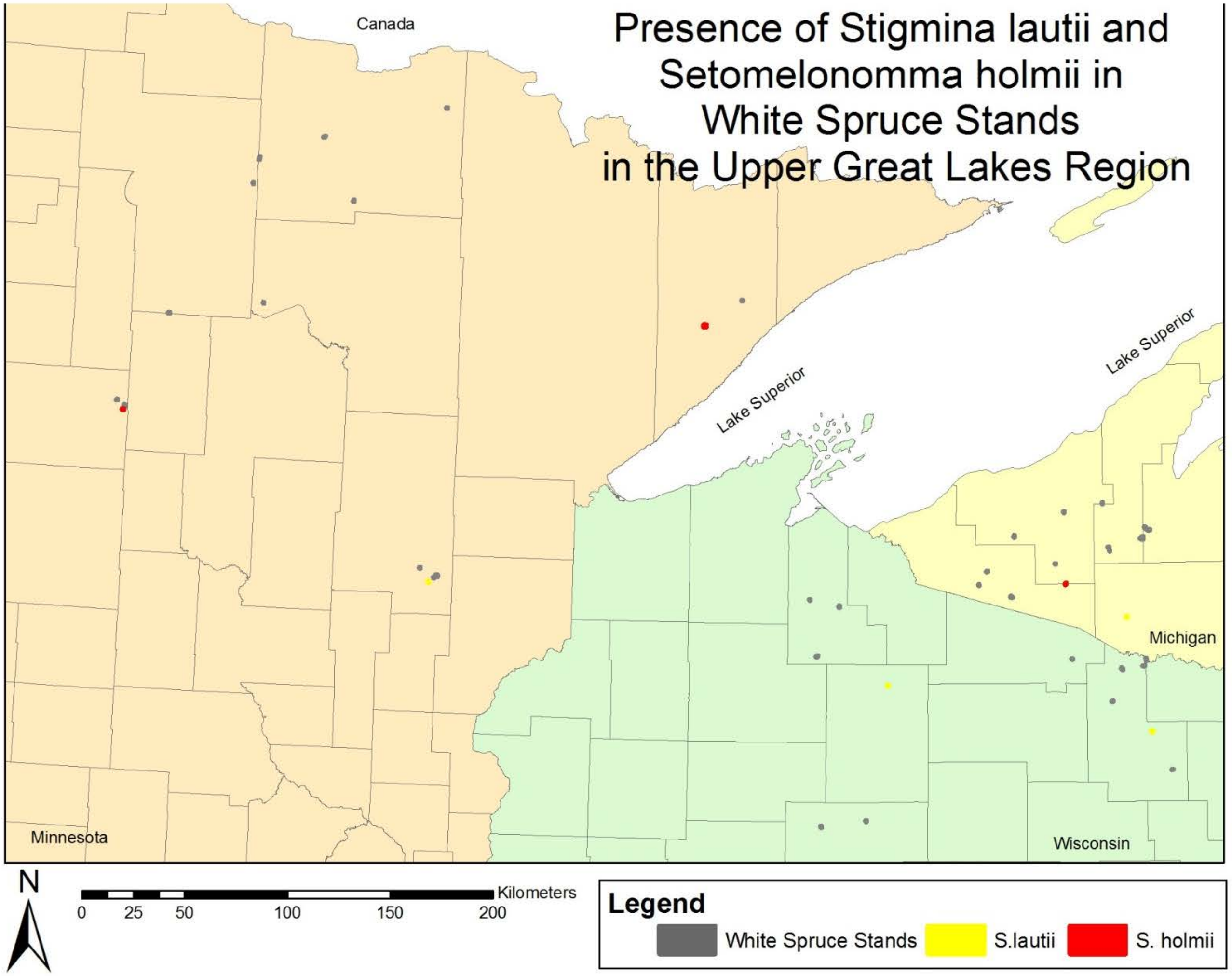


Figure 4. Graph representing a typical positive correlation between mean plantation white spruce growth and average growing season temperature.

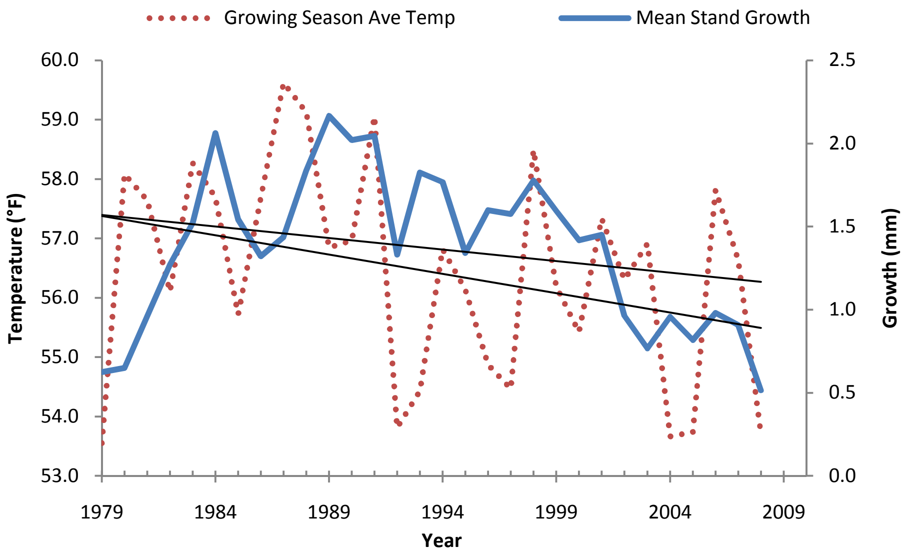


Figure 5. Graph representing a typical negative correlation found between mean stand growth of a natural stand and average growing season temperature.

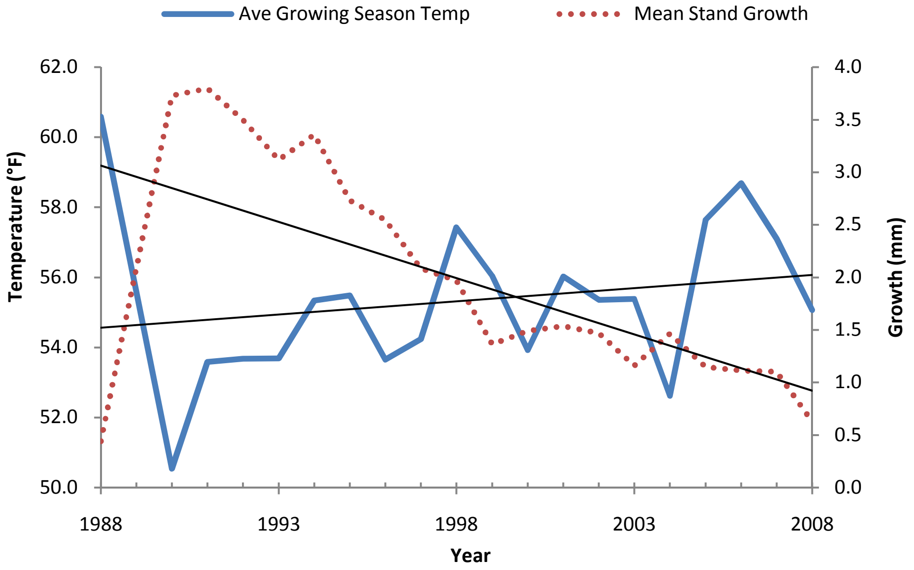


Figure 6. Graph representing a typical positive correlation found between mean plantation white spruce growth and average monthly precipitation.

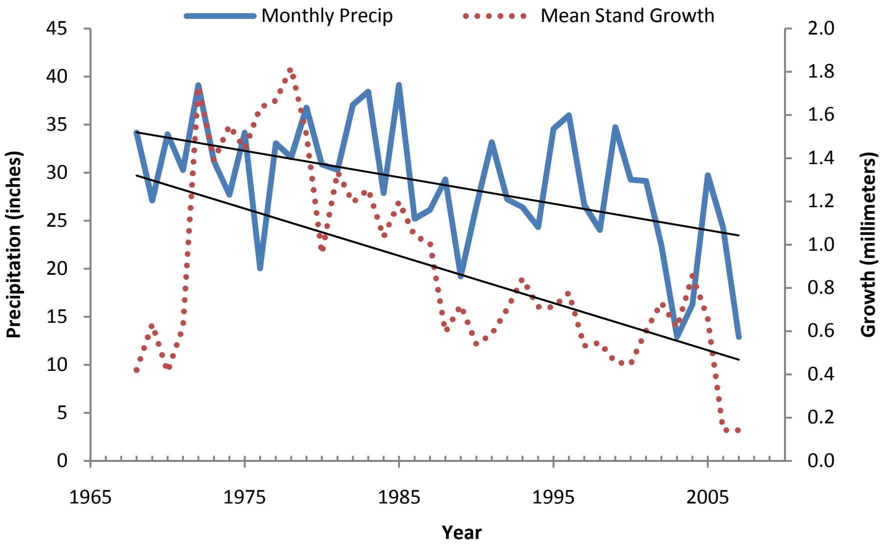


Figure 7. Graph representing a typical positive correlation between mean plantation white spruce growth and moisture levels indicated by the Palmer Drought Severity Index (PDSI).

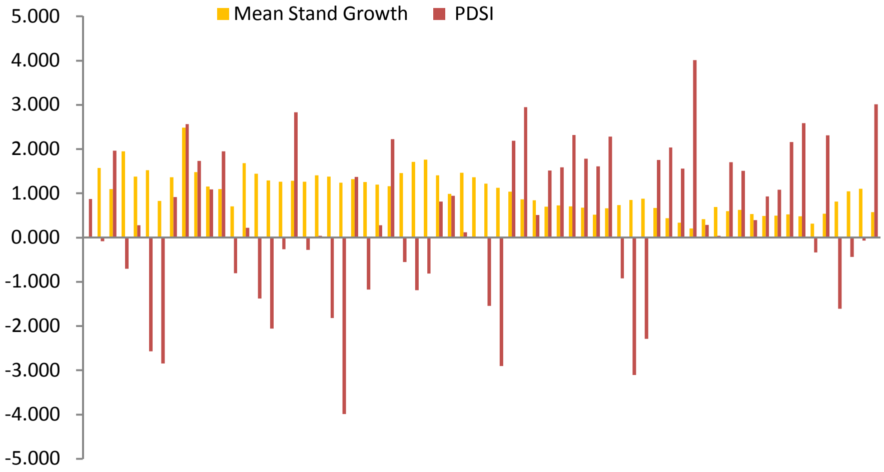


Figure 8. Percent white spruce mortality on silt and sand soil textures. Plots on silt soils had a significantly higher white spruce mortality than plots on sandy soils (p = .000).

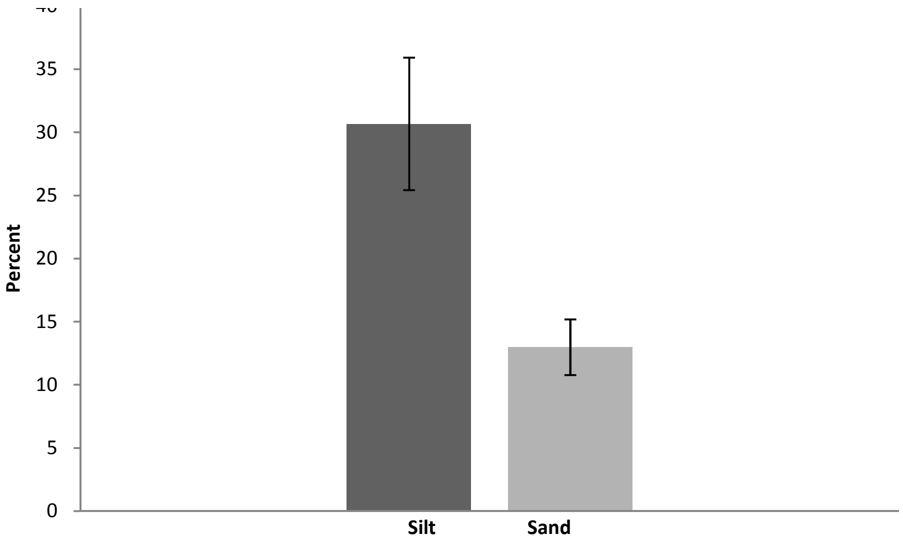


Figure 9. Percent of plots on silt and sand soil textures that have bark beetles present. Silt soils had a significantly higher number of plots with bark beetles present (p = .019).

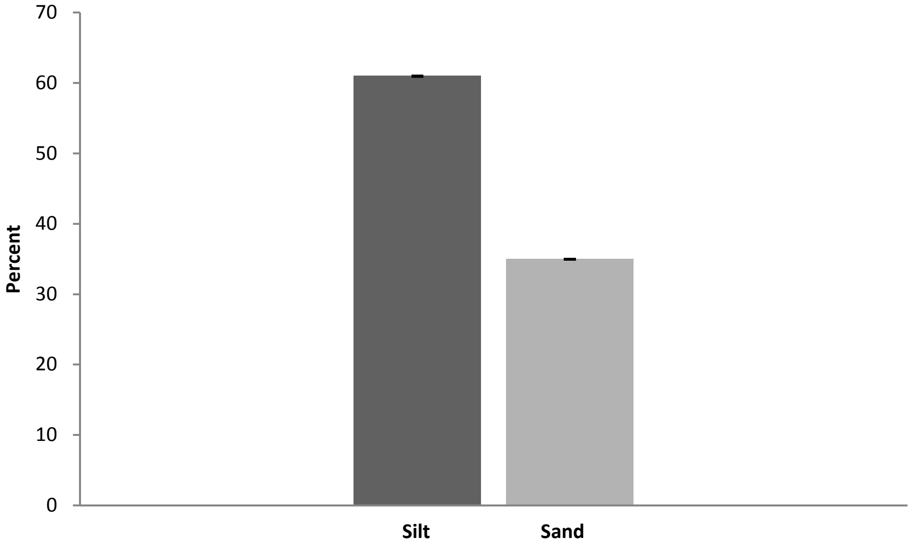
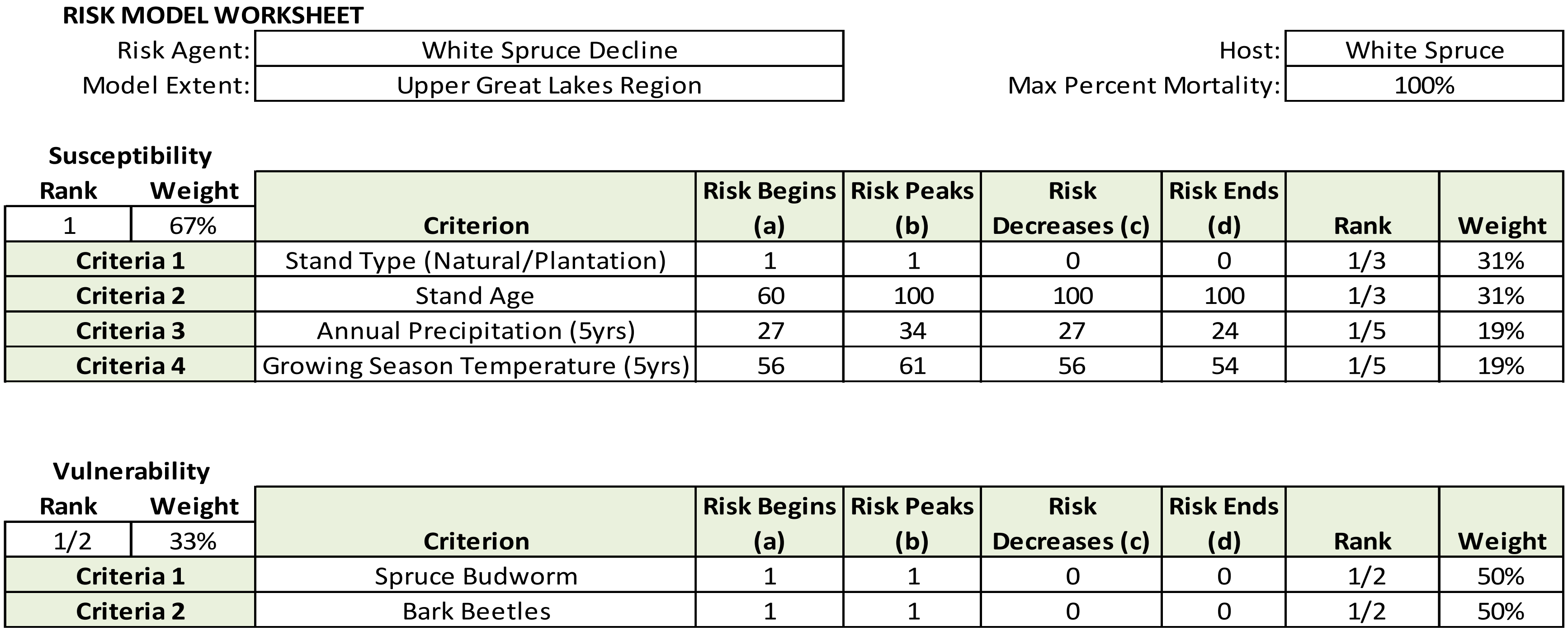


Table 11. Predictor variables from multiple regression analyses for determining factors of decline.

Dependent Factor	Predictor Variable	Model Significance	Model R^2	Variable beta coefficient
Foliage Density		.001	.333	
	Spruce Budworm			-.456
	Bark Beetles			-.386
	Annual Precipitation (last 5 years)			-.297
Foliage Transparency		.000	.281	
	Spruce Budworm			.530
Tree Vigor		.000	.356	
	Spruce Budworm			.458
	Stand Type (Plantation/Natural)			-.371
Live Crown Ratio		.000	.420	
	Stand Type (Plantation/Natural)			.481
	Bark Beetles			-.340
	Spruce Budworm			-.261
Percent Mortality (white spruce)		.000	.474	
	Bark Beetles			.481
	Spruce Budworm			.414
	Growing Season Temperature (last 5 years)			.257
White Spruce Growth (last 10 years)		.003	.199	
	Stand age			-.446
White Spruce Growth (last 30 years)		.009	.169	
	Stand age			-.411
Other Species Growth (last 10 years)		.004	.289	
	Stand age			-.537
Other Species Growth (last 30 years)		-------------	-------	------------
	None			

Figure 10. White spruce decline risk model worksheet based on the National Insect and Disease Risk Map framework.



RISK MODEL WORKSHEET

Risk Agent:	White Spruce Decline	Host:	White Spruce
Model Extent:	Upper Great Lakes Region	Max Percent Mortality:	100%

Susceptibility

Rank	Weight	Criterion	Risk Begins (a)	Risk Peaks (b)	Risk Decreases (c)	Risk Ends (d)	Rank	Weight
1	67%							
Criteria 1		Stand Type (Natural/Plantation)	1	1	0	0	1/3	31%
Criteria 2		Stand Age	60	100	100	100	1/3	31%
Criteria 3		Annual Precipitation (5yrs)	27	34	27	24	1/5	19%
Criteria 4		Growing Season Temperature (5yrs)	56	61	56	54	1/5	19%

Vulnerability

Rank	Weight	Criterion	Risk Begins (a)	Risk Peaks (b)	Risk Decreases (c)	Risk Ends (d)	Rank	Weight
1/2	33%							
Criteria 1		Spruce Budworm	1	1	0	0	1/2	50%
Criteria 2		Bark Beetles	1	1	0	0	1/2	50%

Figure 11. White spruce decline risk map. Map shows the study sites used in this project with characteristics that make them susceptible and vulnerable to decline disease. Those stands that are both susceptible and vulnerable are currently in a state of decline. Stands that are neither susceptible nor vulnerable are considered healthy.

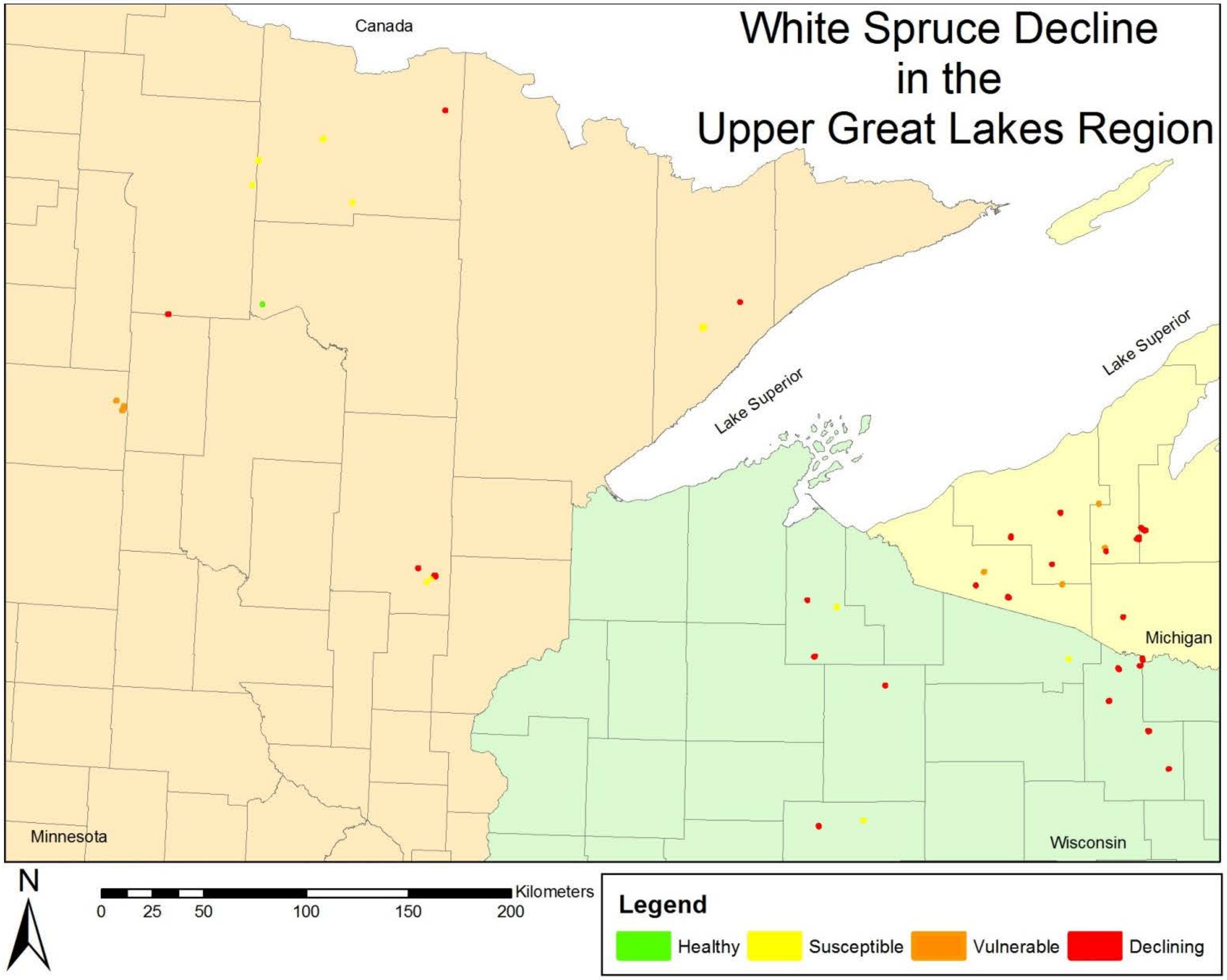
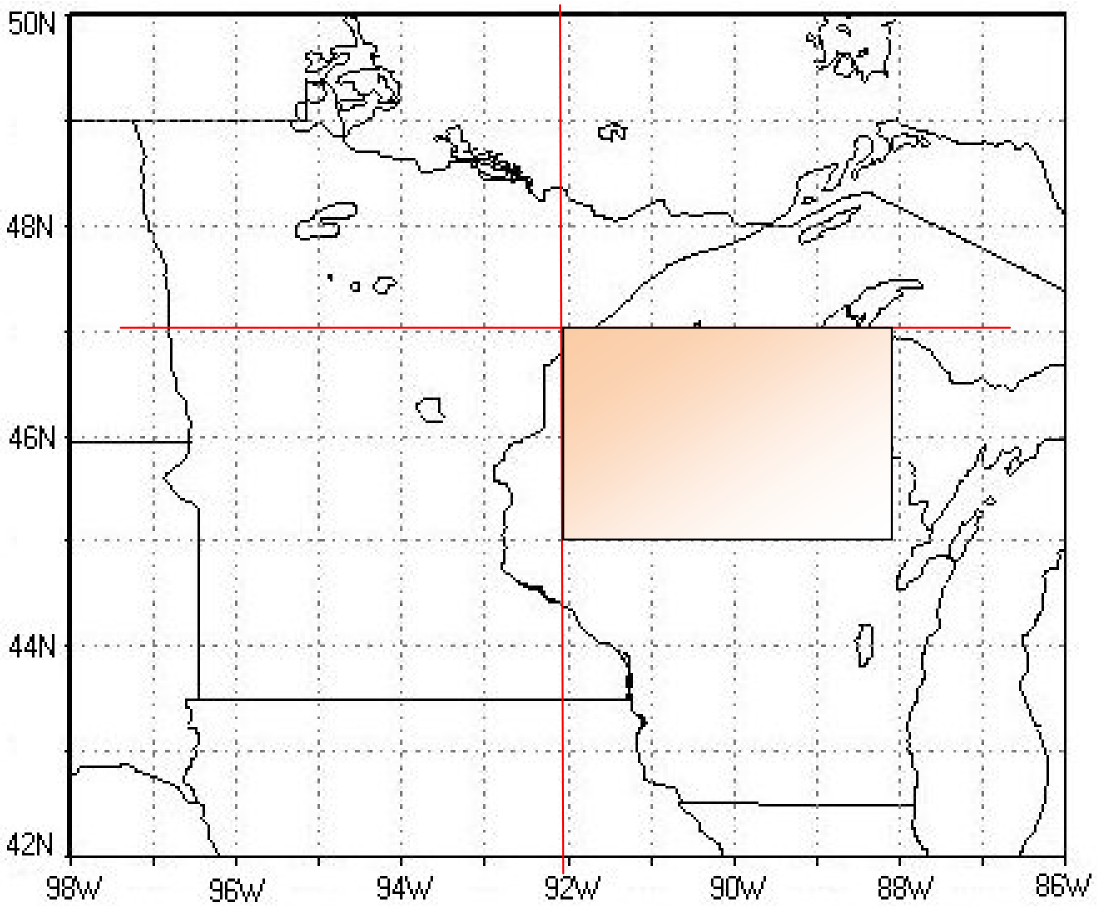


Figure 12. Area within the study region that had a significantly higher white spruce mortality. Average white spruce mortality rate was significantly higher east of 92°W and south of 47°N (*p* = .014, R^2 = .143 and *p* = .001, R^2 = .241). The shaded area shows the area of significantly higher white spruce mortality.



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Appendix A: Tree Ring Analysis Results

Table 1. White spruce lifetime growth and climate significant regression analysis results by state and stand type. (significant at p < .05) (n=42)

		Natural Stands (n=13)				**Plantations** (n=29)			
Average Growing Season Temperature		**Stand ID**	**p-value**	**Multiple R**	**Correlation**	**Stand ID**	**p-value**	**Multiple R**	**Correlation**
	Wisconsin	---	---	---	---	---	---	---	---
	Minnesota	2341	.001	.653	negative	1615	.046	.367	positive
	Michigan	1273	.025	.252	positive	3687	.034	.286	positive
		3623	.016	.286	positive	1630	.039	.282	positive
Average Growing Season Precipitation		**Stand ID**	**p-value**	**Multiple R**	**Correlation**	**Stand ID**	**p-value**	**Multiple R**	**Correlation**
	Wisconsin	---	---	---	---	---	---	---	---
	Minnesota	---	---	---	---	---	---	---	---
	Michigan	3643	.004	.284	positive	3687	.002	.410	positive
		3623	.011	.303	positive				
Average Monthly Precipitation		**Stand ID**	**p-value**	**Multiple R**	**Correlation**	**Stand ID**	**p-value**	**Multiple R**	**Correlation**
	Wisconsin	---	---	---		---	---	---	---
	Minnesota	---	---	---		---	---	---	---
	Michigan	3643	.000	.348	positive	3022	.010	.402	positive
		3623	.007	.318	positive	3687	.000	.490	positive
						32	.013	.408	positive
Average Annual Precipitation		**Stand ID**	**p-value**	**Multiple R**	**Correlation**	**Stand ID**	**p-value**	**Multiple R**	**Correlation**
	Wisconsin	---	---	---	---	---	---	---	---
	Minnesota	---	---	---	---	---	---	---	---
	Michigan	3643	.002	.298	positive	3022	.020	.367	positive
		3623	.011	.301	positive	3687	.000	.481	positive
						32	.009	.430	positive

Table 2. White spruce growth over the last 30 years and climate significant regression analysis results by state and stand type. (significant at $p < .05$) (n=42)

		Natural Stands (n=13)				**Plantations** (n=29)			
Average Growing Season Temperature		**Number**	**p-value**	**Multiple R**	**Correlation**	**Number**	**p-value**	**Multiple R**	**Correlation**
	Wisconsin	---	---	---	---	1	.052	.358	positive
	Minnesota	---	---	---	---	1	.046	.367	positive
	Michigan	1	.049	.362	negative	---	---	---	---
Average Growing Season Precipitation		**Number**	**p-value**	**Multiple R**	**Correlation**	**Number**	**p-value**	**Multiple R**	**Correlation**
	Wisconsin	1	.003	.523	positive	2	.004	.507	negative
							.032	.391	positive
	Minnesota	---	---	---	---	---	---	---	---
	Michigan	1	.004	.507	negative	3	.027	.403	positive
							.011	.459	positive
							.042	.373	positive
Average Monthly Precipitation		**Number**	**p-value**	**Multiple R**	**Correlation**	**Number**	**p-value**	**Multiple R**	**Correlation**
	Wisconsin	1	.027	.404	positive	2	.032	.391	positive
							.047	.366	negative
	Minnesota	---	---	---	---	2	.028	.402	negative
							.003	.529	negative
	Michigan	2	.028	.401	positive	3	.007	.480	positive
			.004	.516	negative		.002	.545	positive
							.003	.528	positive
Average Annual Precipitation		**Number**	**p-value**	**Multiple R**	**Correlation**	**Number**	**p-value**	**Multiple R**	**Correlation**
	Wisconsin	1	.027	.404	positive	1	.047	.366	negative
	Minnesota	---	---	---	---	2	.004	.515	negative
							.032	.392	negative
	Michigan	2	.018	.428	positive	3	.005	.499	positive
			.001	.581	negative		.001	.565	positive
							.006	.487	positive

Table 3: White spruce growth over the last 10 years and climate significant regression analysis results by state and stand type. (significant at p < .05) (n=42)

		Natural Stands (n=13)				**Plantations** (n=29)			
Average Growing Season Temperature		**Number**	**p-value**	**Multiple R**	**Correlation**	**Number**	**p-value**	**Multiple R**	**Correlation**
	Wisconsin	---	---	---	---	1	.050	.632	positive
	Minnesota	---	---	---	---	---	---	---	---
	Michigan	---	---	---	---	---	---	---	---
Average Growing Season Precipitation		**Number**	**p-value**	**Multiple R**	**Correlation**	**Number**	**p-value**	**Multiple R**	**Correlation**
	Wisconsin	3	.011	.761	positive	3	.002	.843	negative
			.001	.860	positive		.007	.780	positive
			.021	.711	positive		.025	.700	positive
	Minnesota	---	---	---	---	---	---	---	---
	Michigan	1	.006	.793	negative	---	---	---	---
Average Monthly Precipitation		**Number**	**p-value**	**Multiple R**	**Correlation**	**Number**	**p-value**	**Multiple R**	**Correlation**
	Wisconsin	2	.004	.818	positive	3	.013	.749	positive
			.045	.641	positive		.047	.637	positive
							.023	.705	positive
	Minnesota	---	---	---	---	---	---	---	---
							---	---	---
	Michigan	---	---	---	----	---	---	---	---
Average Annual Precipitation		**Number**	**p-value**	**Multiple R**	**Correlation**	**Number**	**p-value**	**Multiple R**	**Correlation**
	Wisconsin	2	.004	.818	positive	3	.013	.749	positive
			.046	.641	positive		.049	.637	positive
							.023	.705	positive
	Minnesota	---	---	---	---	---	---	---	---
	Michigan	---	---	---	---	---	---	---	---

Table 4. Regression analysis results for lifetime growth of white Spruce and moisture deficiency measured by the Palmer Drought Severity Index (PDSI). Average annual PDSI for the current year, with 5, 3, and 1 year lags and the average growing season PDSI for the current year and with 5, 3, and 1 year lags. (n=42)

	State	**Natural** (n=13)			**Plantation** (n=29)		
		Number	**p-value**	**Multiple R**	**Number**	**p-value**	**Multiple R**
Average Annual PDSI (current year)	Wisconsin	---	---	---	4	.011	.313
						.004	.380
						.032	.284
						.013	.345
	Minnesota	---	---	---	1	.005	.586
	Michigan	2	.059	.204	1	.018	.289
			.001	.360			
Average Annual PDSI (5 year lag)	Wisconsin	1	.042	.292	4	.031	.289
						.013	.334
						.018	.314
						.022	.302
	Minnesota	---	---	---	---	---	---
	Michigan	4	.016	.270	---	---	---
			.001	.338			
			.008	.313			
			.000	.390			
Average Annual PDSI (3 year lag)	Wisconsin	---	---	---	6	.034	.281
						.045	.266
						.029	.286
						.005	.373
						.000	.443
						.042	.252
	Minnesota	1	.005	.585	2	.029	.334
						.039	.336
	Michigan	3	.057	.206	---	---	---
			.049	.260			
			.004	.310			
Average Annual PDSI (1 year lag)	Wisconsin	---	---	---	4	.029	.295
						.006	.337
						.030	.288
						.045	.266
	Minnesota	---	---	---	1	.018	.513
	Michigan	1	.002	.324	1	.006	.449
Average Growing Season PDSI (current year)	Wisconsin	---	---	---	4	.008	.365
						.040	.275
						.012	.312
						.006	.358
	Minnesota	---	---	---	1	.004	.606
	Michigan	1			---	---	---
Average Growing Season PDSI (5 year lag)	Wisconsin	1	.036	.300	4	.050	.262
						.033	.283
						.052	.256
	Minnesota	---	---	---	4	.046	.340
						.037	.344
						.046	.340
						.045	.318
	Michigan	2	.019	.253	---	---	---
			.001	.358			
Average Growing Season PDSI (3 year lag)	Wisconsin	---	---	---	3	.014	.352
						.002	.404
						.044	.268
	Minnesota	1	.006	.574	1	.023	.346
	Michigan	1	.013	.267	---	---	---
Average Growing Season PDSI (1 year lag)	Wisconsin	---	---	---	3	.030	.293
						.011	.312
						.052	.258
	Minnesota	---	---	---	1	.010	.547
	Michigan	1	.228	.351	1	.036	.351