United States Department of Agriculture

How Climatic Conditions, Site, and Soil Characteristics Affect Tree Growth and Critical Loads of Nitrogen for Northeastern Tree Species

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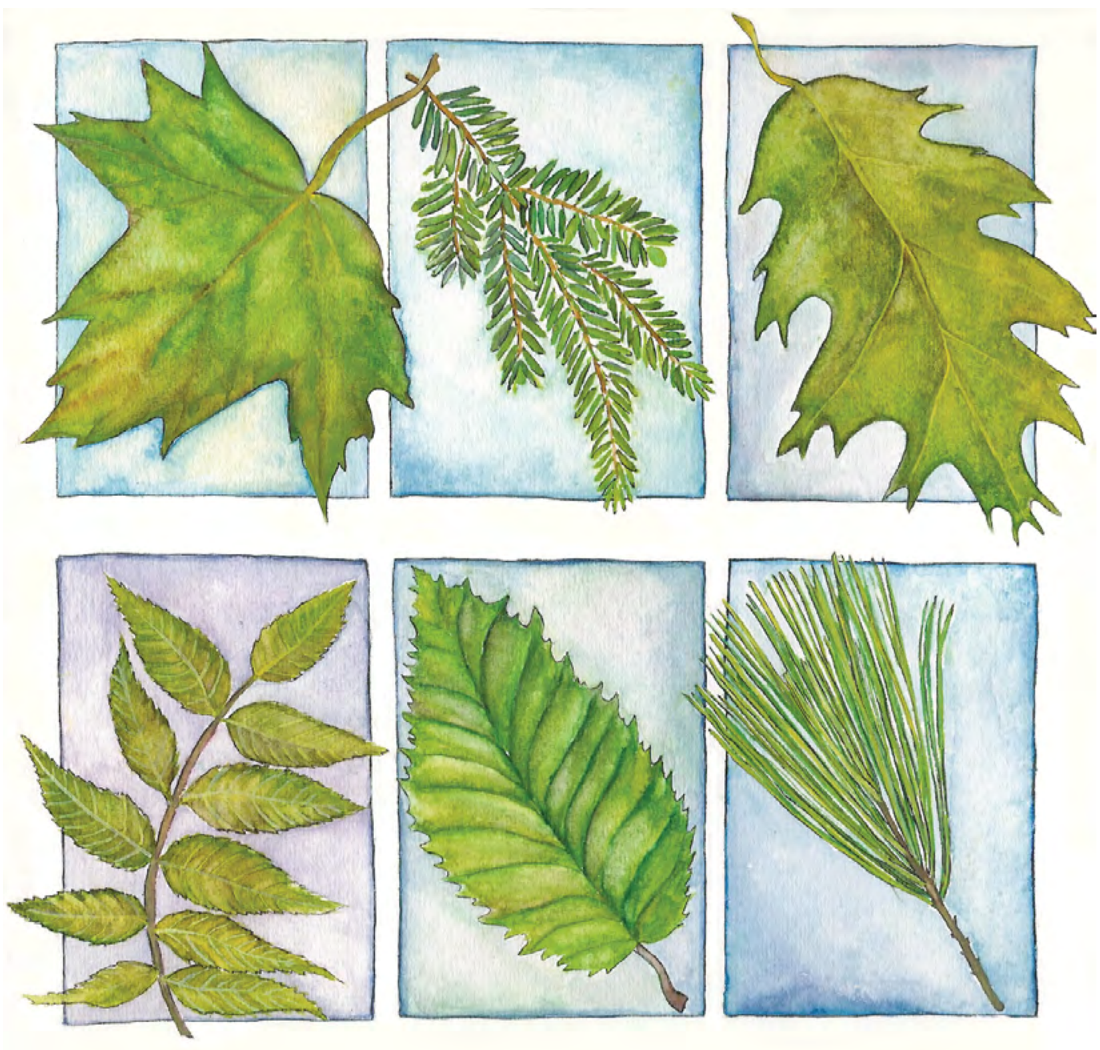

Forest Service　Northern Research Station　General Technical Report NRS-172　September 2017

Abstract

Forest health is affected by multiple factors, including topography, climate, and soil characteristics, as well as pests, pathogens, competitive interactions, and anthropogenic deposition. Species within a stand may respond differently to site factors depending on their physiological requirements for growth, survival, and regeneration. We determined optimal ranges of topographic (elevation, aspect, slope gradient), climatic (average temperature for January, July, and May to September; annual and May to September precipitation), and soil (pH, percent clay, percent coarse sand, permeability, depth to bedrock) parameters for 23 tree species of the northeastern United States. We primarily used importance values (a measure of how dominant a species is in a given forest area under existing site conditions) from a published analysis of more than 100,000 U.S. Forest Service Forest Inventory and Analysis plots to set optimal ranges for the abiotic factors. The region included in this assessment is defined by level 2 ecoregions: mixed wood plains in the Eastern Temperate Forest Ecoregion; Atlantic highlands and mixed wood shield in the Northern Forest Ecoregion. In addition to summarizing ranges for abiotic modifying factors, we also determined the critical load of nitrogen—the deposition below which no harmful ecological effects occur—for each species. The information can be used in forest health assessments to determine whether species growth at a site is expected to be optimal or suboptimal, and can also be used to modify critical load ranges for each species based on site conditions.

Quality Assurance

This publication conforms to the Northern Research Station's Quality Assurance Implementation Plan which requires technical and policy review for all scientific publications produced or funded by the Station. The process included a blind technical review by at least two reviewers, who were selected by the Assistant Director for Research and unknown to the author. This review policy promotes the Forest Service guiding principles of using the best scientific knowledge, striving for quality and excellence, maintaining high ethical and professional standards, and being responsible and accountable for what we do.

Cover Art

Leaves of northeastern forest trees. Image by Molly Robin-Abbott, used with permission.

Graphs for importance values versus climate and soil parameters for Acer rubrum, Acer saccharum, and Thuja occidentalis were added to Appendix 1 on November 28, 2018. Graphs for these species were inadvertently omitted from the original.

Manuscript received for publication 15 July 2015

Published by

U.S. FOREST SERVICE
11 CAMPUS BLVD SUITE 200
NEWTOWN SQUARE PA 19073

September 2017

For additional copies:

U.S. Forest Service
Publications Distribution
359 Main Road
Delaware, OH 43015-8640

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Acknowledgments

This project was funded, in part, by the National Park Service Air Resource Division and was supported by the Northeastern States Research Cooperative (NSRC) grant program. The conclusions and opinions in this paper are those of the authors and not of the NSRC, the Forest Service, or the USDA. We thank Jennifer Pontius for her general guidance and her geospatial expertise and Paul Schaberg for his generous advice and plant physiology expertise. Anantha Prasad and Matthew Peters provided data and insight from the Climate Change Tree Atlas. Jason Coombs developed the GIS tool based on information in this report. We appreciate the input of our reviewers: John Battles, Natalie Cleavitt, Benoit Côté, Anthony D'Amato, Michael Day, Martin Dovčiak, Timothy J. Fahey, Ivan Fernandez, Kendra Gurney, Richard Hallet, Joshua Halman, Kevin Horn, Daniel Houle, Laura Kenefic, Alexandra M. Kosiba, William B. Leak, Erik Lilleskov, Robert Long, Rock Ouimet, Michael Ostry, Alejandro Royo, R. Quinn Thomas, and Alan White.

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1 INTRODUCTION

BACKGROUND AND OBJECTIVES

The most significant threats that impact ecosystem health and sustainability over the long term are climate change, anthropogenic nitrogen (N) deposition, pest outbreaks, and land use change and fragmentation (Rockström et al. 2009). Recent work has improved our understanding of plant response to N deposition (Bobbink and Hettelingh 2011, Pardo et al. 2011c, Simkin et al. 2016) and climate change (Campbell et al. 2009, Groffman et al. 2012, Iverson et al. 2008, Ollinger et al. 2008). However, less is known about the impact of interactions between N deposition and climate change on plant communities (Porter et al. 2013). In spite of the lack of information about interactions among the most significant stressors, resource managers and policy makers must make decisions to manage and maintain forest health over the long term.

Nitrogen is an element essential for growth and development of all organisms; increased N inputs can have a fertilizing effect on plant growth. However, over the past century human activity has resulted in large increases in N deposition over preindustrial levels (Galloway et al. 2003), which may lead to detrimental ecological effects. Detrimental effects of increased N deposition include changes in ecosystem structure and function such as acidification of soil and surface waters, changes in species composition, and increased susceptibility to secondary stresses (Galloway et al. 2003). The critical load concept is a useful technique for conveying the expected effects of a pollutant of concern, in this case N, on an ecosystem. A critical load is the estimate of exposure to a pollutant below which harmful effects on sensitive elements of the environment do not occur over the long term according to present knowledge (UBA 2004).

The previously reported critical load for northeastern forests (Pardo et al. 2011b) provided a single range of values, which encompasses all observed types of detrimental effects for forests across an entire ecoregion. However, the response to N deposition, and thus the critical load, may vary based on site conditions as well as species present; trees will respond to increasing N based on inherent nutrient requirements, functional traits, and abiotic site conditions (Leyton 1957). Thus, the same factors that affect forest growth and species characteristics—i.e., climate, soil composition, topographic position, competition, and other biotic interactions—should affect the critical load. At sites where growth conditions are optimal, we expect that plant nutrient demands will be higher, and more of the increased plant-available N will be incorporated into terrestrial biomass (Schimel et al. 1997). At sites with suboptimal growth conditions, plant nutrient demands should be lower, and less of the plant-available N should be incorporated into the terrestrial biomass. Therefore, in these suboptimal sites, more of the excess N will cycle through soil and aquatic systems with potentially detrimental ecosystem effects. The critical load for a species with higher potential nutrient N utilization growing at a site with optimal conditions for growth will thus be higher than for the same species growing at a suboptimal site. The critical load for a site where growth conditions are optimal for all species present would be higher than if growth conditions were suboptimal for most species present at that site.

The primary objective of this publication is to describe how site characteristics, climatic conditions, and soil characteristics influence the response of individual tree species to N deposition in the northeastern United States and how they affect the critical load. As a first step, we determined critical loads of N for individual species based on a comprehensive literature review. Previously reported critical loads were presented as a single range for each ecoregion for all tree species combined based on all types of detrimental responses observed for the Northern Forest ecoregion and for the Eastern Temperate Forest ecoregion (Pardo et al. 2011a, 2011c). In this project, we estimated critical loads for individual tree species. Next, to address our primary objective, we present a simple framework for determining the effects of abiotic site conditions (topographic, climate, and soil) on critical loads in order to determine critical loads at a finer scale than the ecoregion scale. It is important to characterize how species respond to climatic conditions in order to better understand how their response is likely to change with a changing climate. Forest managers and policy makers can use this framework to assess critical loads across the landscape as a function of site conditions and interactions between N deposition and climate. To facilitate critical load assessments, critical load values and abiotic modifying factors from tables presented in this report have been incorporated into a geographic information system (GIS)-based tool, Nitrogen Critical Loads Assessment by Site (N-CLAS), that can be accessed from the National Atmospheric Deposition Program (NADP) Web site at http://nadp.sws.uiuc.edu/committees/clad/links.aspx. N-CLAS can be used to calculate critical load and exceedance values for numerous geographic areas based on species present and site environmental conditions. The figures and tables that are generated summarize impacts by area and facilitate evaluation of the severity and extent of risk from N deposition across the landscape.

NITROGEN DEPOSITION EFFECTS AND CRITICAL LOADS

Elevated anthropogenic N inputs to terrestrial ecosystems may first alter N cycling (Aber et al. 1989, 1998) and then ecosystem structure and function (Fenn et al. 2010, Pardo et al. 2011a, 2011c). Ecosystem responses to elevated N deposition include changes in species composition through altered growth, survival, and regeneration dynamics. Responses in herbaceous dominated ecosystems and by epiphytic lichens have been particularly dramatic because changes in species composition can occur at low levels of N deposition and may occur rapidly. Statistically significant declines in grassland species abundance occurred at the lowest level of N deposition on a European gradient (Payne et al. 2013). Plant species richness was reduced with increasing N deposition in grasslands in Great Britain, with the number of N-sensitive species reduced at high depositions (Stevens et al. 2004). Changes in species composition in alpine environments in the Rocky Mountains occurred as deposition increased from 4 to 10 kg N $ha^{-1} yr^{-1}$ (Bowman et al. 2006), while shifts in lichens from oligotrophs to eutrophs occurred along an N deposition gradient of 2.7 to 9.2 kg N $ha^{-1} yr^{-1}$ in the Pacific Northwest (Geiser et al. 2010). The critical load of inorganic N in throughfall is estimated to be 1.54 kg N $ha^{-1} yr^{-1}$ for Pacific Northwest lichen communities (Root et al. 2015). Increased N deposition in temperate forests can result in decreased mycorrhizal biomass, diversity, and activity (Janssens et al. 2010).

Responses to elevated N deposition in forest ecosystems include increased soil N content, increased rates of N cycling and leaching, as well as elevated plant tissue N concentrations. Further responses include plant nutrient imbalances, increased susceptibility to secondary stressors (freezing, drought, and pests), and changes in tree growth and survival (Galloway et al. 2003). Increased N and sulfur (S) deposition can result in soil acidification and soil base cation depletion. Another outcome of increased N deposition can be N saturation, the series of ecosystem changes that occur as available N exceeds plant and microbial demand (Aber et al. 1989, 1998). Chronically elevated nitrate leaching is often considered an indication of N saturation at the catchment level. In Europe, a survey across 65 forested plots found little N leaching with deposition <10 kg N $ha^{-1} yr^{-1}$, moderate leaching with deposition from 10 to 25 kg N $ha^{-1} yr^{-1}$, and leaching from all sites with deposition >25 kg N $ha^{-1} yr^{-1}$ (Dise and Wright 1995). In the northeastern United States, nitrate leaching generally increased above 1 μmol L^{-1} when watershed N deposition was above 8 kg $ha^{-1} yr^{-1}$ (Aber et al. 2003). Factors that can affect soil N content, cycling, and leaching include tree species present (Lovett et al. 2004), growing degree days (Bedison and Johnson 2009), and soil texture.

In the northeastern and north central United States, responses to increasing N deposition vary by species. Thomas et al. (2010) reported decreased growth for three tree species and decreased survival for eight tree species along an N deposition gradient from 3 to 11 kg $ha^{-1} yr^{-1}$; growth and survival increased for eleven and three species, respectively. McNulty et al. (2005) found decreased basal area growth for spruce-fir plots in Vermont with annual fertilization of 15.7 kg N $ha^{-1} yr^{-1}$ in addition to 5.4 kg $ha^{-1} yr^{-1}$ bulk N deposition. Pardo et al. (2011b) set the critical load for northern forest ecosystems at >3 to <26 kg $ha^{-1} yr^{-1}$ N deposition based on decreased growth and survival of multiple species in published research, including Thomas et al. (2010) and McNulty et al. (2005). An analysis of global carbon flux found that canopy photosynthesis for evergreen needleleaf forests in temperate climates related positively to N deposition up to about 8 kg $ha^{-1} yr^{-1}$. In that study, N deposition effects in deciduous broadleaf forests in temperate climates were small or absent (Fleischer et al. 2013).

INTERACTING EFFECTS OF N DEPOSITION AND CLIMATE

Climate Predictions for the Northeast

Current research indicates that climate change in the northeastern United States has caused and will continue to cause increasing temperatures and precipitation, with longer, more drought-prone growing seasons and altered species distribution and ecosystem function (Allen et al. 2010, Hayhoe et al. 2007, Iverson and Prasad 2001, Iverson et al. 2008, Rustad et al. 2012). Extreme climate events are expected to have a larger effect on growth than smaller climatic variations (Graumlich 1993). Although productivity is initially expected to increase with warmer and longer growing seasons, competition, invasive species, drought, and pollution may confound expected effects. Insect pest ranges may expand, and forest pathogens may increase (Paradis et al. 2008, Rustad et al. 2012). Nutrient cycling, N leaching, mineral weathering, and base cation leaching are all expected to change with changing climate (Campbell et al. 2009, Rustad et al. 2012). Extension of the growing season coupled with a decreasing snow pack may lead to an asynchrony between the timing of when soil nutrients become available and when plant uptake is initiated (Groffman et al. 2012).

Carbon and Tree Growth

Climate change can initiate rapid change and stress in forest ecosystems; however, less is known about its interaction with N deposition. Climate change and N deposition may act synergistically or antagonistically, depending on ecosystem-specific and taxa-specific dynamics (Porter et al. 2013). Increased temperature, carbon dioxide (CO_2), and N can result in increased net primary productivity (NPP) (Hyvönen et al. 2007). Mathematical modeling in Scotland (Cannell et al. 1998) showed that increases in N, CO_2, and temperature might account for 50 percent of forest growth enhancement in the 20th century. An analysis of four decades of forest growth in British Columbia, Canada, attributed 70 percent of growth enhancement to changes in climate (primarily temperature but also precipitation, solar radiation, and water vapor pressure), with the rest of the growth enhancement due to increased CO_2 and N (Wu et al. 2014). European modelling generally predicts increasing NPP with increasing N, temperature, CO_2, or the interactions of these factors, assuming precipitation is sufficient (Laubhann et al. 2009, Mäkipää et al. 1999, Wamelink et al. 2009). Increases in CO_2 without concomitant increases in N could limit growth increases (Reich et al. 2006), although the complexity of biogeochemical cycling makes future predictions difficult (Lukac et al. 2010). Other factors might complicate these interactions. For example, ozone-induced declines in photosynthesis can offset potential growth resulting from increased CO_2 and N (Ollinger et al. 2002).

Differences by Species and Ecosystem

Increased productivity does not occur equally across species or ecosystem types. Across a region with small climatic contrasts, differences between species were greater than differences between sites (Graumlich 1993). Deciduous species in the Northeast are expected to have increased growth with increased temperatures, while coniferous species are expected have a smaller increase or decreased growth in response to increased temperatures (Ollinger et al. 2008, Way and Oren 2010). Actual response by species may depend on timing of precipitation and temperature increases. For example, in the Great Lakes region, cooler April temperatures favor growth of mesic hardwoods over growth of drought tolerant hardwoods and conifers, while warmer April temperatures favor conifers (Graumlich 1993). Abiotic site conditions also influence growth responses differentially by species. In the Canadian boreal forest, this can be seen with soil organic layer thickness. Black spruce (*Picea mariana*) basal area increment, a measure of growth, was not affected by soil organic layer thickness, but increasing soil organic layer thickness did have a negative effect on basal area increment for quaking aspen (*Populus tremuloides* Michx.) (Gewehr et al. 2014). This is related to temperature and moisture preferences. Growth of black spruce is favored by cooler temperatures and wetter conditions, while quaking aspen growth is favored by higher temperatures and drier conditions (Drobyshev et al. 2012). Responses to changing temperature and precipitation vary by region. In the western United States where conditions are already warm and dry, increasing temperatures and decreasing growing season precipitation resulted in a decrease in suitable habitat for quaking aspen, especially in marginal areas (Worrall et al. 2013).

Variable responses of tree species to elevated N inputs, climate change, pests, and pathogens may ultimately lead to alterations in species composition. Over a 40-year period in the Green Mountains of Vermont, basal area of northern hardwoods, primarily sugar maple (*Acer saccharum* Marsh.), increased while basal area decreased in most boreal species, especially red spruce (*Picea rubens* Sarg.) and paper birch (*Betula papyrifera* Marsh.), in the lower half of the northern hardwoods-boreal forest ecotone (Beckage et al. 2008). In the upper part of the ecotone, balsam fir (*Abies balsamea* [L.] Mill.) and paper birch had the greatest increase in basal area. Over this time there was a 1.1 degree increase in temperature and a 34 percent increase in precipitation. It is not clear if increased red spruce mortality was due to acid precipitation, climate change, or an interaction of both factors (Beckage et al. 2008). In the White Mountains of New Hampshire, Landsat aerial surveys from 1987 to 2010 show increased greenness in early spring at lower elevations, indicative of increased conifer composition at lower elevations, possibly a result of increased balsam fir growth and decreased paper birch growth (Vogelmann et al. 2012). At the Hubbard Brook Experimental Forest in New Hampshire, several species, including yellow birch (*Betula alleghaniensis* Britton), beech (*Fagus grandifolia* Ehrh.), and paper birch, experienced a decline in biomass over a 10-year period ending in 2006 (van Doorn 2011). Biomass increased in other species including sugar maple, balsam fir, red spruce, red maple (*Acer rubrum* L.), hemlock (*Tsuga canadensis* [L.] Carrière), and white ash (*Fraxinus americana* L.) (van Doorn 2011).

Soil characteristics can also influence the response of tree species to climate and deposition. At Hubbard Brook, declines in sugar maple growth, especially at high elevation sites, have been attributed to soil acidification and low calcium (Ca) availability (Juice et al. 2006). Similarly, increased mortality of sugar maple in the Appalachian Plateau of Pennsylvania was attributed to low levels of soil Ca and magnesium (Mg) in combination with insect defoliation events (Bailey et al. 2004). In Vermont, paper birch growing on sites already impacted by elevated N deposition with consequent low soil calcium availability were not able to recover from ice storm damage (Halman et al. 2011); such storms are projected to increase with climate change.

ABIOTIC MODIFYING FACTORS, CRITICAL LOADS OF N, AND FOREST HEALTH

The interaction of multiple factors can make it difficult for forest managers and policy makers to accurately assess the effect of changing environmental conditions on forest health. Our previous report provided a broad range of critical loads for northern and eastern forests but was neither species nor site specific and did not differentiate between growth and survival responses (Pardo et al. 2011c). In this report, we used previously reported data for tree species growth ranges and optimal growing conditions to determine potential effects of N deposition on tree species response under different site, climate, and soil conditions. Land managers and policy makers can use this information via N-CLAS, our online GIS-based tool, to determine critical loads of N for forested sites across the northeastern United States. N-CLAS, when combined with climate change scenarios, pest and pathogen abundances, and land management, could be used to predict forest health in the face of changing environmental conditions. Additional receptors, including lichens and herbaceous plants, would increase the scope of this analysis and may be included in future iterations of N-CLAS.

REPORT ORGANIZATION

In this report we assess critical loads for 23 tree species of concern in northeastern U.S. forests and delimit topographic, climatic, and soil variables that affect growth and critical loads. In Chapter 2, we describe the approach we used to determine species specific critical loads for trees and the general approach we used to determine how the abiotic modifying factors of topography, climate, and soil affect tree growth. Subsequent chapters in this report present critical loads and threshold values for abiotic modifying factors by species, organized alphabetically by scientific name. Each chapter includes details of the methods that apply specifically to that species, and any deviations from the general methods are explained. Appendix 1 contains scatter plots of importance values versus climate and soil characteristics for each species; the data from these plots were used to establish threshold values for abiotic modifying factors. Appendix 2 contains bar charts summarizing ranges for optimal and suboptimal growth for each site, climate, and soil variable for all species. A detailed description of N-CLAS, the GIS based tool that utilizes these tables, is not included in this report. N-CLAS can be accessed via the NADP Web site at http://nadp.sws.uiuc.edu/committees/clad/links.aspx.

2 METHODS

As part of the development of N-CLAS, we evaluated how abiotic site conditions affect individual species' response to nitrogen (N) deposition and the critical load for N deposition. N-CLAS is a geographic information system (GIS)-based tool for resource managers and policy makers used to assess the combined impacts of nitrogen deposition and climate change on forest ecosystems in the northeastern United States. The tool uses geospatial data layers for key topographic, climatic, and soil abiotic factors to predict whether growth at a site will be optimal or suboptimal for each species. In this chapter, we first describe the approach we used to determine the critical load of N for 23 tree species based on previously reported growth, survival, and regeneration responses to N deposition. Next, we describe the approach we used to determine the range of values for each abiotic parameter that are expected to result in optimal growth for each species. At each site, the combined effect of all modifying factors on growth determines whether the critical load for a specific species will be in the lower half or upper half of the species' critical load range. The critical load for a given site can be determined in a variety of ways depending on management objectives and conservation concerns. For example, critical loads for all species at the site can be combined so the range spans the critical load for all species of management concern at that site. Alternatively, the critical load for a site can be set more conservatively to protect the most sensitive species.

CRITICAL LOADS OF N

We determined critical loads of N for 23 tree species in the northeastern United States (Table 2.1). The tree "species of concern" were selected with input from resource managers in Vermont, New Hampshire, and Maine and include species of management concern, species of commercial interest, or dominant species in the northern forest.

Table 2.1—Tree species of concern in the forests of the northeastern United States

Scientific name	Common name	Reason for concern
Abies balsamea	Balsam fir	Wildlife habitat; commercial
Acer rubrum	Red maple	Wildlife; commercial
Acer saccharum	Sugar maple	Commercial–sap, lumber
Betula alleghaniensis	Yellow birch	Wildlife; commercial–lumber
Betula papyrifera	Paper birch	Wildlife; commercial–lumber
Castanea dentata	American chestnut	Rare species
Fagus grandifolia	American beech	Wildlife habitat
Fraxinus americana	White ash	Wildlife; commercial–lumber
Fraxinus pennsylvanica	Green ash	Wildlife; commercial–lumber
Juglans cinerea	Butternut	Rare species in the northeast
Picea mariana	Black spruce	Wildlife habitat
Picea rubens	Red spruce	Commercial–lumber
Pinus resinosa	Red pine	Commercial–lumber
Pinus rigida	Pitch pine	Rare species in the northeast
Pinus strobus	Eastern white pine	Commercial–lumber
Populus grandidentata	Bigtooth aspen	Wildlife habitat; commercial–pulp
Populus tremuloides	Quaking aspen	Wildlife habitat; commercial–pulp
Quercus alba	White oak	Wildlife; commercial–lumber
Quercus prinus	Chestnut oak	Rare species in the northeast
Quercus rubra	Northern red oak	Wildlife; commercial–lumber
Thuja occidentalis	Northern white-cedar	Wildlife; commercial–lumber
Tsuga canadensis	Eastern hemlock	Commercial; wildlife habitat
Ulmus americana	American elm	Wildlife habitat; commercial

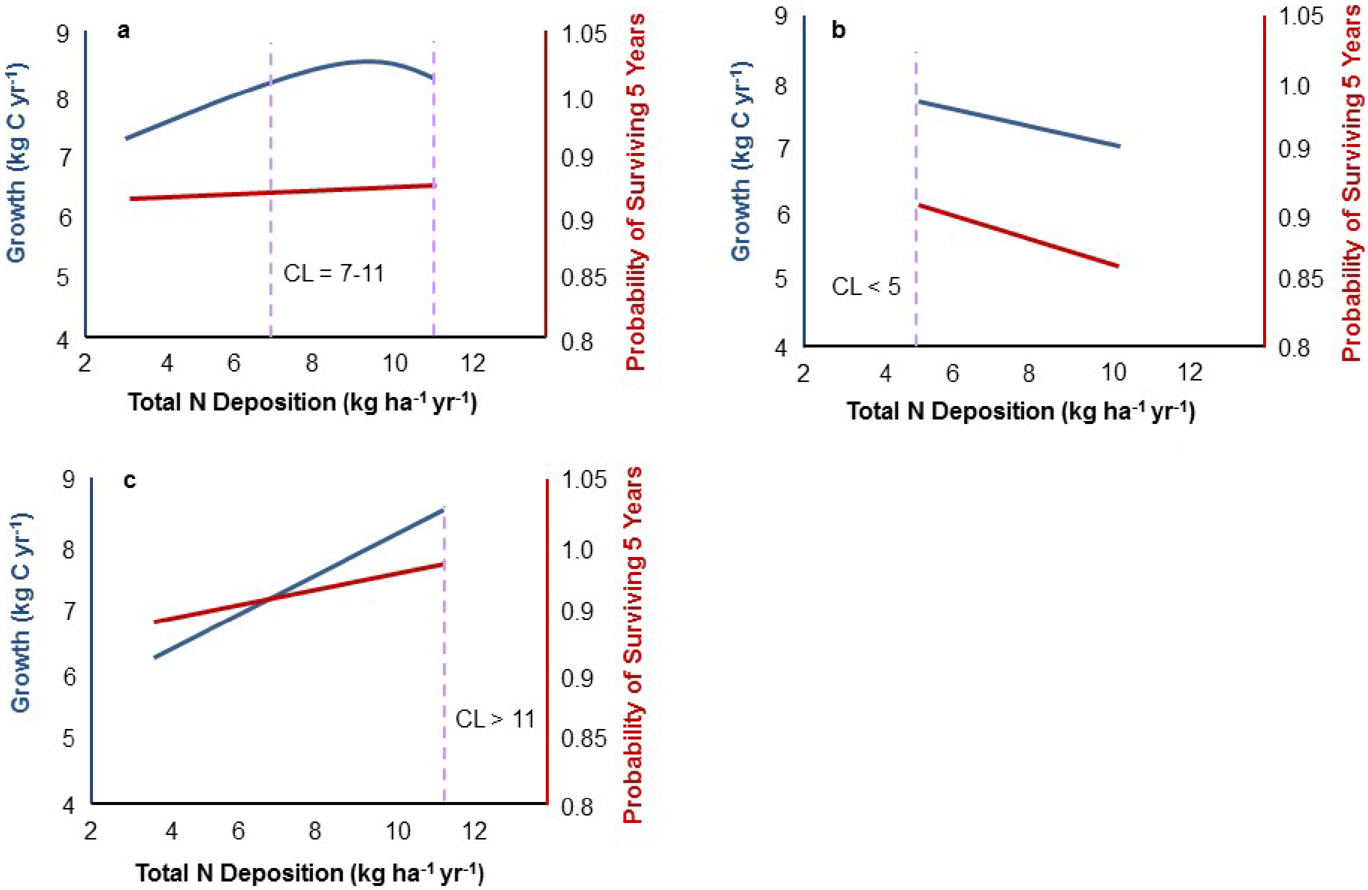

Figure 2.1—Hypothetical examples of critical loads (CL) derived from Thomas et al. (2010) using growth and survival responses.

The critical load is based on the deposition range over which detrimental responses, including decreased growth rate, survival, and regeneration, are observed. Many factors, including genetic variation, stand structure, competition, and site conditions, affect the response of trees to N deposition. Critical loads are expressed as a range to account for some of this variability. Specific descriptions of data sources and the decisionmaking process for setting the critical load range are described in each species chapter. Growth and survival data from the U.S. Forest Service, Forest Inventory and Analysis (FIA) program (http://www.fia.fs.fed.us/) analyzed along an N deposition gradient (Thomas et al. 2010) were the primary source of information for most species. The spatially extensive correlation analysis spanned a deposition range of 3 to 11 kg ha^{-1} yr^{-1} total (wet + dry) inorganic N and included more than 2,000 trees for each species. Nitrogen deposition was calculated using data from the National Atmospheric Deposition Program (wet; see http://nadp.sws.uiuc.edu) and CASTNET (dry; see http://www.epa.gov/castnet/).

The responses of growth and survival across a deposition gradient were used to determine species specific critical loads for nitrogen. If growth or survival rate in an analysis showed an inflection point (an increase in response to N deposition followed by a decrease), the critical load based on that response was set as a range of 2 kg N ha^{-1} yr^{-1} on either side of the inflection point (Fig. 2.1a). The range accounts for variation across sites. If both growth and survival rates in a study decreased across the deposition range, the critical load based on that response was set below the deposition range (Fig. 2.1b). If growth or survival rate increased and the other factor increased or remained static, the critical load was set above the high end of the N deposition range for that study (Fig. 2.1c). Whenever possible, multiple studies were used to set the critical load ranges. Study scale and strength of response were considered when setting the critical load ranges based on multiple studies. When species specific responses to N deposition were not available in the literature, responses from species in the same genus or family were used to set the critical load.

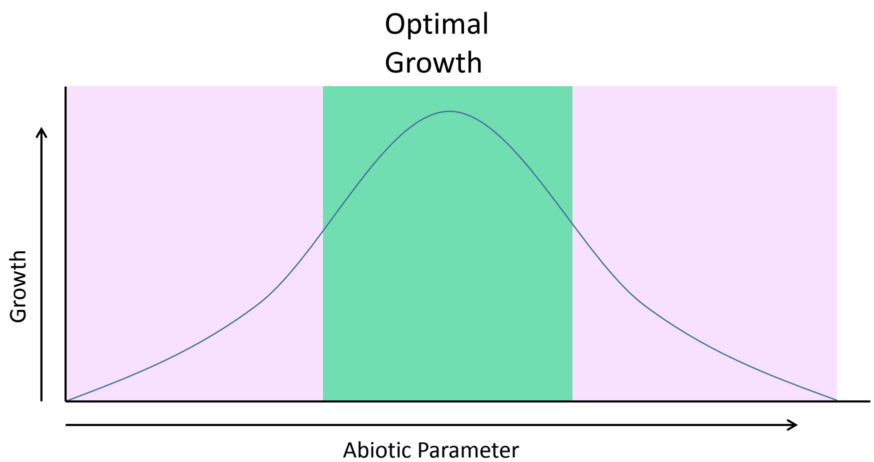

Figure 2.2—A range of values exists for optimal growth (green shaded region) for each abiotic parameter; above and below that range of values, growth is not optimal.

Critical load values for these species will be reevaluated when relevant information becomes available. If a species specific upper estimate for the critical load range was not available, the upper critical load was set at 26 kg N ha^{-1} yr^{-1} based on Pardo et al. (2011b), where an upper critical load value of 26 kg N ha^{-1} yr^{-1} was set for northern forests in the United States. In a European study, leaching occurred at all forested sites with deposition >25 kg N ha^{-1} yr^{-1} (Dise and Wright 1995), indicating a similar potential upper limit for N deposition.

Empirical critical loads for N in the United States have been calculated by ecoregion (Pardo et al. 2011a). However, land managers typically need to evaluate susceptibility to air pollution and assess potential impacts on forest health at smaller spatial scales. Because factors such as growth respond to site conditions, response to N deposition (and thus critical loads) can also vary with site conditions. An approach for modifying critical loads based on site factors was proposed in Europe in the early 2000s (e.g., Achermann and Bobbink 2003). However, it was not implemented at that time because of the challenges in determining the direction of impact and considering interactions of multiple factors across the diverse climatic and site conditions in Europe. The approach was later used on a smaller scale in the United Kingdom (Hall and Wadsworth 2010). In our study, we evaluated how abiotic site conditions are likely to affect species response to N deposition. Data presented can be used to determine site-level critical loads based on an approach that determines conditions favorable for optimal growth.

Abiotic factors that may influence critical loads at the site level include topographic, climate, and soil variables. Based on a fundamental concept in ecology and plant nutrition (Jenny 1994), we expect that for each parameter, a range of values for optimal growth exists; for values above or below that range, growth is not optimal (Fig. 2.2). In any given location, the observed values for the abiotic factor may not span the entire theoretical range. In that case the actual growth response curve only represents a portion of the theoretical curve, resulting in a curve that, for example, increases or decreases across the entire observed range.

Optimal growth conditions should result in increased N use (Hyvönen et al. 2007), pushing the critical load to the upper half of the range, as will conditions that mitigate the detrimental impact of increased levels of N deposition. Suboptimal growth conditions should result in decreased N use, pushing the critical load to the lower half of the range, as will conditions that exacerbate the negative effects of increased levels of N deposition. In N-CLAS, our GIS tool, the impact of individual modifying factors on the site critical load is determined by the weight of evidence for each factor; the weight of evidence is a measure of the certainty of the effect of the modifying factor on the critical load. In addition, N-CLAS has the ability to incorporate the weight of influence of each factor on tree growth for each species. For a given species, one factor (e.g., temperature) may be far more significant than all others; for another species, several factors may be important. The combined impact of all abiotic modifying factors will determine whether the critical load is in the lower or upper half of the range.

Table 2.2—Weight of evidence assessment for abiotic modifying factor thresholds based on FIA importance values (IV)

	Weight of evidence				
Weighting criteria	Weak – 1	Moderately weak – 2	Moderate – 3	Moderately strong – 4	Strong – 5
Number of samples	<50	50-149	150-299	300-449	≥450
Shape of response curve	Weak response, no obvious peak, points dispersed over a wide range	Some clustering of points, points dispersed over wide range	Definite peak but numerous points outside of the main peak, thresholds unclear	Definite peak, several points outside of the main peak make determining precise thresholds difficult	Clear peak, clear thresholds, no or single outliers
Accuracy of parameter measurements	Inaccurate measurement techniques; geospatial values represent highly generalized data	Inaccurate measurement techniques; geospatial values represent primarily modeled data	Accurate measurement techniques; geospatial values represent primarily modeled data	Accurate measurement techniques; geospatial values represent mix of real data and modeled data	Accurate measurement techniques; geospatial values represent real data or very accurate models

Table 2.3—Weight of evidence assessment for literature-based abiotic modifying factor thresholds

Weight of evidence				
Weak – 1	Moderately weak - 2	Moderate – 3	Moderately strong – 4	Strong - 5
General value, unreliable source	General value, reliable source	Species value, reliable source	Species value, multiple studies, reliable source	Species value, thresholds well established

Assessment of Uncertainty: Weight of Evidence

A key part of this analysis was to clearly define the basis of the relationships we report, the inherent assumptions, and the level of certainty of our evaluation. Thus, for each abiotic modifying factor, we also assessed the weight of evidence (*sensu* Hall and Wadsworth 2010), which is a measure of our certainty of the modifying factor thresholds. The weight of evidence is rated from 1 to 5, with 1 being weak and 5 being strong evidence. Abiotic modifying factor tables in each species chapter provide the weight of evidence for each factor.

We determined the weight of evidence for abiotic modifying factors using two matrices (Tables 2.2 and 2.3). The matrix in Table 2.2 was used to assign the weight of evidence for abiotic modifying factor thresholds set by using FIA-based importance value data from the Climate Change Atlas (U.S Forest Service, n.d.). The overall uncertainty rating was determined through the arithmetic mean of three weighting criteria: number of samples, shape of response curve, and accuracy of parameter measurements. Graphs of each modifying factor were visually inspected to determine the weight for the shape of the response curve. The matrix in Table 2.3 was used to assign the weight of evidence for abiotic modifying thresholds set by using data from the Forest Service silvics handbook, "Silvics of North America" (Burns and Honkala 1990a, b), the PLANTS database (NRCS 2014), or other literature sources.

Weight of Influence

The importance of an abiotic factor in critical loads calculations is determined by the weight of influence. Simply put, some factors have a greater impact on site suitability than others. For example, a tree will not grow at a site with optimal soil conditions if the climate conditions are unsuitable.

ABIOTIC MODIFYING FACTORS

For each tree species in this study, we identified the optimal range for growth for specified topographic, climatic, and soil abiotic modifying factors. Ranges were based on importance values and distribution data from the Climate Change Atlas (U.S. Forest Service, n.d.) and information from other sources, including the Forest Service silvics handbook, "Silvics of North America" (Burns and Honkala 1990a, b); the PLANTS database (NRCS 2014); additional

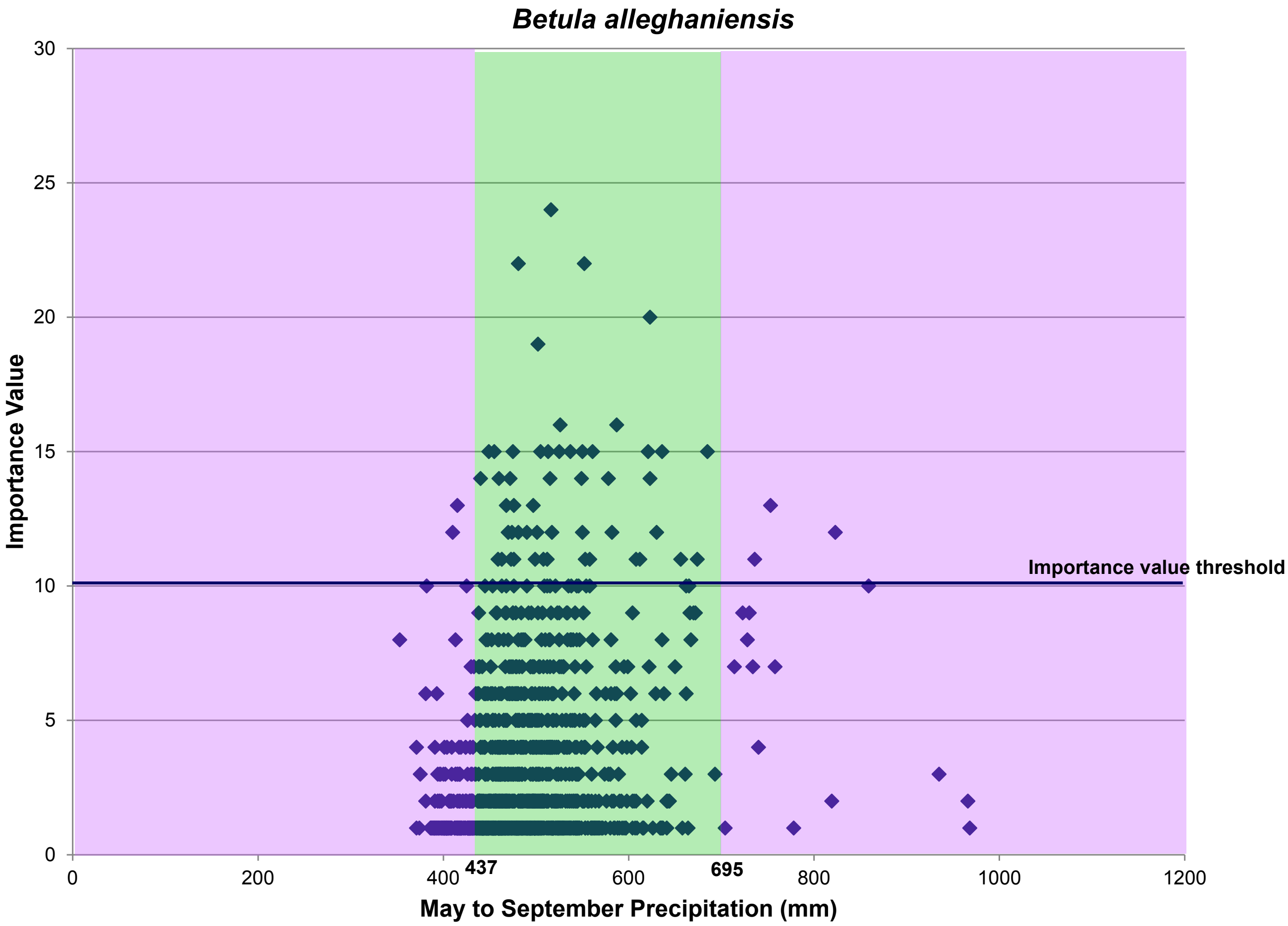

Figure 2.3—Abiotic modifying factor range determined using importance value threshold. The optimal range is shaded green; suboptimal range is shaded purple.

literature sources; and input from experts on individual tree species. It is important to note that data were evaluated in an ecosystem context, so the optimal ranges are for tree growth with competition from other trees. For many species, optimal growth conditions without competition from other species may differ from the optimal growth ranges provided in this report. In addition, the optimal ranges we defined are based on the available data. For species with low numbers of samples, e.g., butternut (*Juglans cinerea)* and American chestnut (*Castanea dentata)*, the threshold may not accurately represent the optimal ranges (see discussion of uncertainty in this chapter). We believe the thresholds established for modifying factors will help delineate optimal growing conditions for most forested sites. However, as with any system that uses a threshold approach, sites with values close to the threshold might not fit well into either optimal or suboptimal growth categories. Finally, other modifying factors not considered in our analysis may positively or negatively affect site growing conditions.

Tree species importance values based on FIA data from the Climate Change Atlas (U.S Forest Service, n.d.) are our primary source for determining optimal growth ranges. Importance values are used to indicate the relative importance of a species within a plot. Importance Values(X) = (50 * basal area(X) / basal area(all species)) + (50 * number of stems(X) / number of stems(all species)), where X is a single species. We compared importance values with abiotic modifying factor values (U.S Forest Service, n.d.) using a threshold importance value of 10, which is above the median importance for all species in this analysis, to select plots with good growth conditions for each species. We then determined the range for each modifying factor above the importance value threshold. In order to exclude outliers, we used the 5th to 95th percentile of the modifying factor values. We refer to this as the high importance value range throughout this document. Figure 2.3 demonstrates the optimal range set using this technique. For those species that were not sufficiently represented by importance values greater

Table 2.4—Abiotic modifying factors and data sources

Abiotic modifying factor	Units	Primary Data source
Elevation, northeastern U.S.	m	Beckage et al 2008, Burns and Honkala 1990, Leak and Graber 1974
Aspect		NRCS 2014
Slope Gradient	%	Soil Conservation Service 1991[a]
January temperature average	°C	Hayhoe et al. 2007 [a]
July temperature average	°C	Hayhoe et al. 2007 [a]
May to September temperature average	°C	Hayhoe et al. 2007 [a]
Precipitation, annual	mm	Hayhoe et al. 2007 [a]
Precipitation, May to September	mm	Hayhoe et al. 2007 [a]
Soil pH		Soil Conservation Service 1991 [a]
Soil clay	%	Soil Conservation Service 1991 [a]
Soil coarse sand	%	Soil Conservation Service 1991 [a]
Soil permeability	cm hr^{-1}	Soil Conservation Service 1991 [a]
Soil depth to bedrock (minimum rooting depth)	m	NRCS 2014

[a] As cited in Climate Change Atlas (U.S. Forest Service, n.d.).

than 10, we used a lower importance value threshold. Scatter plots of importance values versus climate and soil data used to establish threshold values for abiotic modifying factors for each species are available in Appendix 1, and bar charts summarizing ranges for optimal and suboptimal growth for each site, climate, and soil variable for all species are in Appendix 2. When sources other than the Climate Change Atlas (U.S. Forest Service, n.d.) were used to set optimum growth thresholds, values were generally taken directly as reported in the source material.

In the following sections, we describe the abiotic modifying factors and provide an overview of methods used to determine thresholds for topographic, climatic, and soil modifying factors. We initially considered a large number of site-based factors that could potentially modify vegetation responses to N deposition, including temperature, precipitation, growing degree days, elevation, aspect, soil wetness, depth to bedrock, soil orders, Ca:Al (calcium: aluminum), base saturation, nitrification, N mineralization, leaching potential, and management intensity. Some factors were eliminated because they provided similar information (e.g., growing degree days are related to temperature parameters), and other factors were eliminated because the effect of the factor on growth and critical loads was not clearly defined (e.g., soil C:N, nitrification, mineralization, and leaching potential). We included factors for which GIS data are available, as well as factors that can be used to assess critical loads if more geospatial information becomes available. Data from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to set thresholds for many modifying factors. Abiotic modifying factors included in this report are shown in Table 2.4.

Topography

Elevation

The effects of elevation on growth are due to multiple interacting factors, including temperature, soil depth, precipitation, and exposure. For many species in the northeastern United States, colder temperatures at high elevations limit growth relative to milder temperatures at low elevations. Thus high elevations would result in suboptimal growth, while low elevations would result in optimal growth. In the southeastern United States, growth responses might be reversed at high and low elevations for some species. We determined the effect of elevation on growth based on species abundance by elevation; elevations at which the species occurred infrequently or not at all were associated with suboptimal growth, while elevations where species were abundant were associated with optimal growth. We used information on forest vegetation related to elevation in New Hampshire (Leak and Graber 1974), elevation ranges from "Silvics of North America" (Burns and Honkala 1990a, b), basal area dominance at various elevations in the Green Mountains of

Vermont (Beckage et al. 2008), and other sources to set approximate elevation ranges for each species for the northeastern United States. Data from the Climate Change Atlas (U.S. Forest Service n.d.) were not used for elevation because of the potential influence of latitude on the importance value analysis. The weight of evidence for elevation ranges from 2 to 4.

Aspect

Aspect can affect species composition and soil properties, including soil moisture, pH, organic matter content, and nutrient cycling (Gilliam et al. 2014). Southwestern slopes are generally warmer and more exposed than northeastern slopes at the same elevation and latitude, which suggests that growth of drought tolerant and shade intolerant species would be better on southwestern aspects, while growth of drought intolerant and shade tolerant species would be better on northeastern aspects. Effects of aspect on growth were based on species' shade and drought tolerances reported in the PLANTS database (NRCS 2014), aspect preferences reported in the "Silvics of North America" (Burns and Honkala 1990a, b), and general assumptions about moisture and temperature characteristics of different aspects. The weight of evidence for aspect is 2 for all species.

Slope Gradient

Slope gradient can affect soil thickness, water retention, and nutrient retention, among other factors. In the Catskill Mountains of New York, slope was significantly correlated with organic horizon thickness and exchangeable cations (Johnson et al. 2000). In the Rocky Mountains of Wyoming and Colorado, catchment slope and terrain roughness were positively correlated with stream nitrate concentrations and negatively correlated with dissolved inorganic nitrogen retention (Sickman et al. 2002). Tree mortality probability generally increases with increasing slope gradient for the pines and hardwoods species groups, while other conifer groups are unaffected or have slightly decreased mortality probability with increased slope gradient (Dietz and Moorcroft 2011). We determined the optimum range for slope gradient based on the range above a threshold importance value of 10 using data from the Climate Change Atlas (U.S. Forest Service, n.d.) unless otherwise indicated. Values outside of this range were considered suboptimal. The weight of evidence for slope gradient ranges from 2 to 4.

Climate

Temperature

Empirical and experimental evidence supports optimal temperatures for growth and nutrient uptake (i.e., a response curve as in Figure 2.2), as well as increased nutrient demand with increased growth. Globally, maximum growth for mature forests (expressed as biomass carbon density) occurs around 10 °C mean annual temperature (Liu et al. 2014). The optimal temperature for activity of Rubisco, the enzyme responsible for catalyzing a major step in carbon fixation during photosynthesis, is around 25 °C (Lukac et al. 2010). Optimal winter and summer temperature ranges for growth and survival vary by species (Drobyshev et al. 2012, Ollinger et al. 2008, Way and Oren 2010). Multivariate analyses of red spruce across the eastern United States indicate that annual growth is negatively correlated with anomalously warm late summers and anomalously cold early winters (McLaughlin et al. 1987). Warm late summer months are negatively correlated with growth for multiple species (Kipfmueller et al. 2010, Leonelli et al. 2008, Tardif et al. 2001). If a tree is growing below optimal temperatures, increasing temperatures may promote growth. An analysis of changing growth on experimental plots in Europe indicates that increased temperatures and extended growing seasons can result in increased growth rates for forest stands; growth increases are strongest on fertile sites (Pretzsch et al. 2014). Rising temperatures can result in increasing nutrient uptake up to a maximum threshold. For example, Gessler et al. (1998) found maximum ammonium uptake in spruce occurred at 20 °C.

Average January, July, and May to September Temperatures

For most species, we determined the optimum range for average January, July, and May to September temperatures based on the range above a threshold importance value of 10 using data from the Climate Change Atlas (U.S. Forest Service, n.d.) unless otherwise indicated. Values outside of this range were considered suboptimal. When possible, we confirmed temperature range values using information from the Forest Service silvics handbook, "Silvics of North America" (Burns and Honkala 1990a, b). The weight of evidence for January, July, and May to September temperature ranges from 3 to 5.

Annual Precipitation and May to September Precipitation

Liu et al. (2014) found that globally, biomass carbon density in mature forests reaches a maximum when precipitation ranges from 1000 to 2500 mm annual precipitation. Annual precipitation in most of the northeastern United States falls within this range (http://nadp.sws.uiuc.edu/NADP). Because the optimal precipitation range for growth varies by species, some Northeastern tree species will have optimal growth outside the reported global range for maximum biomass.

In addition to affecting growth, suboptimal precipitation may affect plant response to increasing nitrogen. Davis et al. (1999) found decreased bur and pin oak seedling survival with increasing N at dry sites compared to wet sites. It is also likely that growing season precipitation affects tree growth more than annual precipitation. Leonelli et al. (2008) found a positive correlation of quaking aspen growth in British Columbia, Canada, with prior year summer precipitation, while Kipfmueller et al. (2010) found a positive relationship of red pine, white pine, and northern white-cedar growth with current year June to July precipitation in northern Minnesota. Radial growth of eastern hemlock, sugar maple, and American beech in southwestern Quebec was positively correlated with summer precipitation (Tardif et al. 2001).

Precipitation below optimal ranges may be more detrimental than precipitation above optimal ranges. In Tennessee, Hanson et al. (2001) found increased growth rates for multiple species, including chestnut oak, white oak, and red maple, growing in years with annual and May to September precipitation above our high importance value range compared to years with precipitation within the range. Years with relatively lower growth rates experienced May to September precipitation below our high importance value range. Extreme precipitation events such as floods and droughts may have a bigger impact on tree growth, survival, and forest health in general than average annual or May to September precipitation in the northeastern United States.

We determined the optimum range for mean annual precipitation and May to September precipitation based on the range above a threshold importance value of 10 using data from the Climate Change Atlas (U.S. Forest Service, n.d.) unless otherwise indicated. Values outside of this range were considered suboptimal. The range was verified using species specific data in "Silvics of North America" (Burns and Honkala 1990a, b). The weight of evidence for annual and May to September precipitation ranges from 3 to 5.

Soil Characteristics

Soil pH

Although most forest species grow well over a large range of pH (Williston and Lafayette 1978), individual species have a preferred pH range. Nutrients can become either toxic or unavailable at pH extremes (<4.5 and >8.5; Londo et al. 2006), while soils with a pH of 6.0-7.0 often have the highest concentration of available nutrients (Williston and Lafayette 1978). High rates of N and sulfur (S) deposition can result in increasing soil acidity, leaching of base cations, and increased mobilization of aluminum (Al) (Driscoll et al. 2001). When determining the optimal pH range, we considered both the optimal range for growth as well as the potential of the soil to buffer against increasing acidity. The optimal range for pH was based on the range above a threshold importance value of 10 using data from the Climate Change Atlas (U.S. Forest Service, n.d.) unless otherwise indicated. Values outside of this range were considered suboptimal. Information from the PLANTS database (NRCS 2014) and "Silvics of North America" (Burns and Honkala 1990a, b) were also considered when setting the range. The weight of evidence for soil pH ranges from 2.3 to 4.3.

Soil Texture and Permeability

Soil physical characteristics affect many factors that influence tree growth and establishment, including nutrient and water availability, retention, movement, and aeration. Although trees can grow over a wide range of soil textures, they typically grow best on moist, well-drained soils (e.g., sandy loams to clay loams). These soils generally have sufficient water, nutrients, and air, as well as adequate drainage (Osman 2013). Clay soils are often fertile but heavy and poorly drained. Sandy soils are lighter but lack water and nutrients.

We determined optimal ranges for percent clay, percent coarse sand, and permeability for mineral soil. Permeability is generally determined from soil texture (Table 2.5) and can be used as a modifying factor when soil texture information is not available. Clay soils with very slow permeability and poor drainage

Table 2.5—Permeability and Textural Class from O'Geen (2012)

Permeability class	Permeability ($cm\ hr^{-1}$)	Textural class
Very slow	<0.13	clay
Slow	0.13–0.5	sandy clay, silty clay
Moderately slow	0.5–2.0	clay loam, sandy clay loam, silty clay loam
Moderate	2.0–6.3	very fine sandy loam, loam, silt loam, silty clay loam, silt
Moderately rapid	6.3–12.7	sandy loam, fine sandy loam
Rapid	12.7–25.4	sand, loamy sand
Very Rapid	>25.4	coarse sand

are considered suboptimal for growth, as are sandy soils with rapid and very rapid permeability. Growth is expected to be optimal with moderately slow to moderately rapid permeability. We determined the optimal range for percent clay, percent coarse sand, and permeability based on the range above a threshold importance value of 10 using data from the Climate Change Atlas (U.S. Forest Service, n.d.) unless otherwise indicated. Values outside of this range were considered suboptimal. Soil texture preferences were confirmed using "Silvics of North America" (Burns and Honkala 1990a, b). The weight of evidence for clay ranges from 2.3 to 3.7, the weight of evidence for coarse sand ranges from 2 to 4, and the weight of evidence for permeability ranges from 1.3 to 3.3.

Depth to Bedrock (minimum rooting depth)

Depth to bedrock, which indicates potential soil thickness, can be used to assess whether minimum rooting depth requirements are met. Trees growing in soils of adequate depth are assumed to have better growing conditions, including access to a larger pool of nutrients and base cations, and thus a higher tolerance for increased N deposition. Optimal growth conditions are assumed to occur when depth to bedrock is greater than the minimum rooting depth. Values for minimum rooting depth were obtained from the PLANTS database (NRCS 2014) and were used to set depth to bedrock values. The weight of evidence for depth to bedrock is 3 for all species.

Base Saturation

Research indicates that low base saturation can result in forest stress. Cronan and Grigal (1995) reported that forest stress from increased Al availability occurs when soil base saturation is less than 15 percent of effective cation exchange capacity. In research focusing on sugar maples and red oaks, trees on soils with a higher base saturation have increased growth, decreased mortality, and decreased susceptibility to nutrient imbalance associated with N saturation (Demchik and Sharpe 2000, Duchesne et al. 2002, Horsley et al. 2000, Sullivan et al. 2013). Sites with low base saturation experience decreased foliar and forest floor Ca, as well as the potential for increased dieback, reduced sugar maple regeneration, and reduced basal area with increased N deposition or N and S inputs (Moore and Houle 2013, Sullivan et al. 2013). Sullivan et al. (2013) found little sugar maple regeneration when B horizon base saturation was below 12 percent; the greatest amount of regeneration occurred when base saturation was greater than 20 percent. Unless species specific information is available, mineral soil base saturation greater than 15 percent is associated with upper critical loads while base saturation less than 15 percent is associated with lower critical loads. The weight of evidence for base saturation is 2 for all species except sugar maple, for which the weight of evidence for base saturation is 3.

Ca:Al

The ratio of calcium to aluminum in the soil solution is another metric used to assess susceptibility to elevated N (and S) deposition. Aluminum, which is toxic to plants, is mobilized by acid deposition inputs and subsequent soil acidification. General soil solution Ca:Al thresholds were set based on the work of Cronan and Grigal (1995), who found a 50 percent chance of adverse impacts on tree growth and nutrition with a molar ratio of 1, a 75 percent chance of adverse impacts with a Ca:Al ratio of 0.5, and a 95 percent or greater chance of adverse impacts with a molar ratio of 0.2. With a Ca:Al molar ratio of 2, the chance of adverse impacts is approximately 25 percent. A Ca:Al ratio of 2 is associated with optimal growth. The weight of evidence for the Ca:Al ratio is 2 for all species.

External Influences

Biomass removal

The effect of biomass removal on critical loads is considered from a nutrient budget perspective as opposed to an optimal growth perspective. As biomass removal increases, N and other nutrients are removed from the site. Critical loads on sites with high biomass removal are expected to be higher than sites with low biomass removal as long as base cations and other nutrients are sufficient.

Pests

Increased foliar N can make forest trees more palatable to insect pests (McClure 1991). A meta-analysis by Furong et al. (2016) indicates that elevated N inputs increase food sources and palatability for insects and decrease tree resistance to herbivores, especially for broadleaved species. Defoliation can decrease tree growth and increase mortality (Lovett et al. 2002). We expect that having an abundance of insect pests would result in suboptimal growth, while having low levels or an absence of insect pests would result in optimal growth.

Pathogens

Increased N can make forest trees more susceptible to pathogens (Latty et al. 2003). Colonization with fungal pathogens can result in reduced growth and, in some cases, decreased survival. Trees weakened by fungal pathogens are expected to have suboptimal growth; trees with minimal or no fungal pathogens are expected to have optimal growth.

3 *ABIES BALSAMEA* (BALSAM FIR)

SPECIES RANGE AND CRITICAL LOAD

Balsam fir, *Abies balsamea* (L.) Mill., grows in the northeastern and northern midwestern United States, mountainous areas of the eastern United States, and much of eastern and central Canada. Optimum growth occurs in cool, moist areas with precipitation from 760 to 1100 mm, average January temperatures from -18 to -12 °C, and average July temperatures from 16 to 18 °C. Balsam fir can be found on silty or stony loams and grows best on moist soil with an organic layer pH of 6.5 to 7.0. Growth is slowest on gravelly sands and in peat swamps. It can be found from sea level to approximately 1917 m elevation in the northern part of its range (Frank 1990).

We assigned a critical load of 9 to 21.1 kg N $ha^{-1} yr^{-1}$ for balsam fir. Bedison and McNeil (2009) found increased basal area increment along a deposition gradient of <3.5 to >7 kg N $ha^{-1} yr^{-1}$, and Thomas et al. (2010) found increased growth and increased survival as deposition increased from 3 to 9 kg N $ha^{-1} yr^{-1}$; the critical load from these studies is >9 kg N $ha^{-1} yr^{-1}$. As fertilization increased N inputs on Mt. Ascutney in Vermont from 5.4 (bulk deposition) to 21.1 kg N $ha^{-1} yr^{-1}$ (McNulty et al. 1996), however, balsam fir basal area growth decreased; the critical load for this study is less than 21.1 kg N $ha^{-1} yr^{-1}$. Critical load values and citations are shown in Table 3.1.

ABIOTIC MODIFYING FACTORS

Multiple sources were used to set the ranges of modifying factors for balsam fir, including the balsam fir section of the Forest Service silvics handbook (Frank 1990), the PLANTS database (NRCS 2014), and high importance value data from the Climate Change Atlas (U.S. Forest Service, n.d.). In general, any factor that inhibits balsam fir growth would be expected to result in a decreased need for N and thus a lower critical load; optimal growth conditions would result in an increased demand for N and a higher critical load. General values were used for base saturation, Ca:Al, and biomass removal as described in Chapter 2 (pages 13-14). Graphs showing importance values for abiotic modifying factor ranges by species are in Appendix 1. Optimal and suboptimal growth ranges and weight of evidence values are shown in Table 3.2.

Elevation

We set optimal elevation ranges for the northeastern United States based on basal area dominance of trees at various elevations in the Green Mountains of Vermont (Beckage et al. 2008) and elevation ranges from the White Mountains of New Hampshire (Leak and Graber 1974). Balsam fir was present in significant numbers on plots in the Green Mountains between 762 and 1158 m, with greatest abundance around 1000 m (Beckage et al. 2008). In the White Mountains, balsam fir was present between 610 and 1373 m, with an increasing percentage of total basal area at the highest elevations (Leak and Graber 1974). We associated elevations from 900 to 1400 m with optimal growth and elevations outside of this range with suboptimal growth.

Aspect

Because balsam fir is drought intolerant, shade tolerant (NRCS 2014), and generally more cold tolerant, we associated southwestern aspects with suboptimal growth and northeastern aspects with optimal growth.

Slope Gradient

High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to set thresholds for slope. Growth for balsam fir is expected to be optimal from 0 to 6.4 percent.

Average January, July, and May to September Temperatures

Reported optimal average January temperatures range from -18 to -12 °C, and average July temperatures range from 16 to 18 °C (Frank 1990). These values are slightly cooler than temperature ranges determined using high importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) and may reflect the northern range of balsam fir that is not included in the Climate Change Atlas data. For the purposes of this report, high importance values were used to set optimal temperature ranges. Growth may also be optimal at cooler temperatures. We set the optimal January temperature range as -16.3 to -7.7 °C, the optimal July temperature range as 17.3 to 20.1 °C, and the optimal May to September temperature range as 13.7 to 16.4 °C.

Table 3.1—Effects of nitrogen deposition on balsam fir

Location	N deposition range ($kg\ ha^{-1}\ yr^{-1}$)	Increased N deposition effects	Citation
Adirondack State Park, NY	< 3.5 to >7.0 (wet)	Increased basal area increment	Bedison and McNeil 2009
Northeastern, Midwestern U.S.	3 to 9	Increased growth and survival	Thomas et al. 2010
Mt. Ascutney, VT	5.4 (bulk) to 21.1	Decreased basal area growth	McNulty et al. 1996

Table 3.2—Abiotic modifying factors for balsam fir

Variable	Units	Suboptimal growth range	Optimal growth range	Weight of evidence[a]
Elevation	m	< 900, > 1400	900 to 1400	4
Aspect		southwestern	northeastern	2
Slope gradient	%	> 6.4	0.0 to 6.4	3.7
January temperature	°C	< -16.3, > -7.7	-16.3 to -7.7	4.3
July temperature	°C	< 17.3, > 20.1	17.3 to 20.1	4.7
May-September temperature	°C	< 13.7, > 16.4	13.7 to 16.4	4.7
Annual precipitation	mm	< 674, > 1317	674 to 1317	4.3
May-September precipitation	mm	< 405, > 586	405 to 586	4.3
Soil pH		< 4.7, > 7.0	4.7 to 7.0	4.3
Clay	%	< 3.8, > 32.5	3.8 to 32.5	3.7
Coarse sand	%	< 61.9, > 91.7	61.9 to 91.7	4
Permeability	$cm\ hr^{-1}$	< 0.8, > 11.1	0.8 to 11.1	3
Depth to bedrock	m	< 0.5	≥ 0.5	3
B-horizon base saturation	%	< 15	≥ 15	2
Soil Ca:Al	mol:mol	< 2	≥ 2	2
Biomass removal		low	high	
Insect pests		abundant	low or absent	
Fungal pathogens		abundant	low or absent	

[a] Refer to Tables 2.2 and 2.3 for description of values.

Annual Precipitation

Reported annual precipitation ranges include 527 to 1896 mm (U.S. Forest Service, n.d.), 330 to 1524 mm (NRCS 2014), and 390 to 1400 mm (Frank 1990). Optimal precipitation was reported as 760 to 1100 mm (Frank 1990). The high importance value range of 674 to 1317 mm (U.S. Forest Service, n.d.) was associated with optimal growth. Values outside of this range were associated with suboptimal growth.

May to September Precipitation

High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to determine thresholds for average May to September precipitation. We associated the precipitation range from 405 to 586 mm with optimal growth and precipitation outside of this range with suboptimal growth.

Soil pH

Reported soil pH ranges include pH 4 to 6 (NRCS 2014), as well as an ideal range of pH 6.5 to 7.0 in the upper organic layers (Frank 1990). We associated soil pH values of 4.7 to 7.0, the high importance value range from the Climate Change Atlas (U.S. Forest Service, n.d.), with optimal growth and values outside of this range with suboptimal growth.

Percent Clay and Percent Coarse Sand

Balsam fir commonly grows on Spodosols, Inceptisols, and Histosols (Frank 1990). High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to set thresholds for percent clay and percent coarse sand. Optimal clay is 3.8 to 32.5 percent; optimal coarse sand is 61.9 to 91.7 percent.

Permeability

Optimal soil permeability from Climate Change Atlas (U.S. Forest Service, n.d.) high importance values range from 0.8 to 11.1 cm hr^{-1}, the permeability rates for moderately slow to moderately rapidly draining clay loams to sandy loams (O'Geen 2012).

Depth to Bedrock

We associated depth to bedrock of <0.5 m with suboptimal growth, based on minimum rooting depth (NRCS 2014), and depths ≥0.5 m with optimal growth.

EXTERNAL INFLUENCES

Insect Pests

The balsam wooly adelgid (*Adelgis picea*) poses the most serious insect threat to balsam fir (Dukes et al. 2009, Frank 1990). Spruce budworm (*Choristoneura fumiferana*) also poses a significant threat (Dukes et al. 2009) to balsam fir and is one of the most destructive insects in northern spruce-fir forests. We assumed that having an abundance of insect pests would correlate with suboptimal growth, while low levels or the absence of insect pests would correlate with optimal growth.

Fungal Pathogens

As with insect pests, we assumed that trees weakened by abundant fungal pathogens would have suboptimal growth. Low levels or the absence of fungal pathogens would correlate with optimal growth.

4 *ACER RUBRUM* (RED MAPLE)

SPECIES RANGE AND CRITICAL LOAD

Red maple, *Acer rubrum* L., grows across southeastern and central Canada, as well as much of the eastern and central United States. Red maple grows and thrives across a wide variety of sites; growth is restricted by extreme cold in Canada and the dry climate in the prairie states. Although red maple can be found from mountain ridges to swamps, best development occurs on moderately well-drained, moist sites at low to intermediate elevations in the mountains of Kentucky and Tennessee. Aspect does not appear to play a strong role in growth (Walters and Yawney 1990).

We assigned a critical load of >11 to 26 kg ha^{-1} yr^{-1} for red maple. Several sources indicate that red maple growth and survival increases with increasing N deposition. Thomas et al. (2010) found increased growth and survival with increased deposition from 3 to 11 kg N ha^{-1} yr^{-1}, while Bedison and McNeil (2009) found increased basal area increment between <3.5 and >7.0 kg N ha^{-1} yr^{-1}. In West Virginia, red maple basal area increased with deposition from 12 to 14 kg N ha^{-1} yr^{-1} (Elias 2008). At a site on Mt. Ascutney in Vermont, maple sprouting increased on sites with high spruce/fir mortality as fertilization increased N input from 5.4 (bulk deposition) to 21.1 kg ha^{-1} yr^{-1} (McNulty et al. 1996), most likely as a direct (fertilization) or indirect (decreased competition) result of N addition. This research indicates that the lower critical load for red maple is >11 kg N ha^{-1} yr^{-1}, while the upper critical load is >21.1 kg N ha^{-1} yr^{-1}. More research is needed to define the upper limit for red maple critical load. In the interim, we have assigned an upper value of 26 kg N ha^{-1} yr^{-1} for red maple. This is based on the high deposition value (>25 kg N ha^{-1} yr^{-1}) in a European study; significant N leaching occurred at all forested plots above this deposition (Dise and Wright 1995). Critical load values and citations are shown in Table 4.1.

ABIOTIC MODIFYING FACTORS

Multiple sources were used to set the ranges of modifying factors for red maple, including the red maple section of the Forest Service silvics handbook (Walters and Yawney 1990), the PLANTS database (NRCS 2014), and high importance value data from the Climate Change Atlas (U.S. Forest Service, n.d.). In general, any factor that inhibits red maple growth would be expected to result in a decreased need for N and thus a lower critical load; optimal growth conditions would result in an increased demand for N and a higher critical load. General values were used for base saturation, Ca:Al, and biomass removal as described in Chapter 2 (pages 13-14). Graphs showing importance values for abiotic modifying factor ranges by species are in Appendix 1. Optimal and suboptimal growth ranges and weight of evidence values are shown in Table 4.2.

Elevation

Elevation effects depend on latitude. We set elevation ranges for the northeastern United States based on basal area dominance at various elevations in the Green Mountains of Vermont as reported by Beckage et al. (2008) as well as elevation ranges from the White Mountains of New Hampshire (Leak and Graber 1974). Growth is expected to be optimal below 600 m in elevation and suboptimal at higher elevations.

Aspect

Shade tolerance and drought tolerance are both intermediate for red maple (NRCS 2014). Because it is not clear which aspect is most favorable for growth, we have not associated aspect with growth for this species.

Slope Gradient

High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to set thresholds for slope. We expect red maple growth to be optimal from 0.0 to 13.0 percent.

Average January, July, and May to September Temperatures

High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to set temperature thresholds. We associated January temperatures from -12.3 to 8.5 °C, July temperatures from 18.7 to 27.2 °C, and May to September temperatures from 15.2 to 25.3 °C with optimal growth. Values outside of these ranges were associated with suboptimal growth.

Table 4.1—Effect of nitrogen deposition on red maple

Location	N deposition range (kg ha^{-1} yr^{-1})	Increased N deposition effects	Interacting factors	Citation
Northeastern, Midwestern U.S.	3 to 11	Increased growth, no change in survival		Thomas et al. 2010
Adirondack State Park, NY	<3.5 to >7.0	Increased basal area increment		Bedison and McNeil 2009
Vermont	5.4 (bulk) to 21.1	Increased seedling and sprouts on high mortality plots		McNulty et al. 1996
West Virginia	12 to 14	Increased basal area	S deposition 20 to 26 kg ha^{-1} yr^{-1}	Elias 2008

Table 4.2—Abiotic modifying factors for red maple

Variable	Units	Suboptimal growth range	Optimal growth range	Weight of evidence[a]
Elevation	m	> 600	≤ 600	3
Aspect		NA	NA	
Slope gradient	%	> 13.0	0.0 to 13.0	4
January temperature	°C	< -12.3, > 8.5	-12.3 to 8.5	4.7
July temperature	°C	< 18.7, > 27.2	18.7 to 27.2	5
May-September temperature	°C	< 15.2, > 25.3	15.2 to 25.3	5
Annual precipitation	mm	< 786, > 1448	786 to 1448	4.7
May-September precipitation	mm	< 410, > 684	410 to 684	4.7
Soil pH		< 4.6, > 7.0	4.6 to 7.0	4.3
Clay	%	< 3.7, > 40.5	3.7 to 40.5	3.3
Coarse sand	%	< 56.1, > 97.7	56.1 to 97.7	3.7
Permeability	cm hr^{-1}	< 0.7, > 12.0	0.7 to 12.0	3
Depth to bedrock	m	< 1.0	≥ 1.0	3
B-horizon base saturation	%	< 15	≥ 15	2
Soil Ca:Al	mol:mol	< 2	≥ 2	2
Biomass removal		low	high	
Insect pests		abundant	low or absent	
Fungal pathogens		abundant	low or absent	

[a] Refer to Tables 2.2 and 2.3 for description of values.

Annual Precipitation

Reported precipitation ranges for red maple include 578 to 2289 mm (U.S. Forest Service, n.d.) and 635 to 2030 mm (NRCS 2014). We associated the high importance value range of 786 to 1448 mm (U.S. Forest Service, n.d.) with optimal growth. Values outside of this range were associated with suboptimal growth.

May to September Precipitation

High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to determine thresholds for average May to September precipitation. We associated the precipitation range from 410 to 684 mm with optimal growth and precipitation outside of of this range with suboptimal growth.

Soil pH

Reported soil pH ranges for red maple include 4.7 to 7.3 (NRCS 2014) and 2.7 to 8.4 (U.S. Forest Service, n.d.). We associated soil pH values of 4.6 to 7.0, high importance values from the Climate Change Atlas (U.S. Forest Service, n.d.), with optimal growth. Values outside of this range were associated with suboptimal growth.

Percent Clay and Percent Coarse Sand

Red maple grows on a wide variety of soils but grows best on moderately drained, moist soils. Dominant soil orders are Entisols, Inceptisols, Ultisols, Alfisols, Spodosols, and Histosols (Walters and Yawney 1990). We used high importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) to set thresholds for percent clay and percent coarse sand. Optimal clay is 3.7 to 40.5 percent; optimal coarse sand is 56.1 to 97.7 percent.

Permeability

Optimal soil permeability from Climate Change Atlas (U.S. Forest Service, n.d.) high importance values range from 0.7 to 12.0 cm hr^{-1}, the rates for moderately slow to moderately rapidly draining clay loams to sandy loams (O'Geen 2012).

Depth to Bedrock

We assigned depth to bedrock values of <1.0 m for suboptimal growth, based on minimum rooting depth (NRCS 2014), and depths ≥1.0 m for optimal growth.

EXTERNAL INFLUENCES

Insect Pests

We assumed that having an abundance of insect pests would correlate with suboptimal growth, while low levels or the absence of insect pests would correlate with optimal growth.

Fungal Pathogens

As with insect pests, we assumed that trees weakened by abundant fungal pathogens would have suboptimal growth. Low levels or the absence of fungal pathogens would correlate with optimal growth.

5 *ACER SACCHARUM* (SUGAR MAPLE)

SPECIES RANGE AND CRITICAL LOAD

Sugar maple, *Acer saccharum* Marsh., grows throughout the central and northern Midwest and eastern United States, as well as southeastern Canada. Sugar maple grows best on fertile, moist, well-drained soils; it grows poorly on nutrient-poor, dry, and shallow soils and is rarely found in swamps or wet soils. It occurs at elevations up to 2,500 feet (762 m) in New England and New York, up to 1,600 feet (488 m) in the upper Midwest, and from 3,000 to 5,500 feet (914 to 1676 m) in the Appalachians (Godman et al. 1990). Bailey et al. (2004) found that stands with soil Ca and Mg below threshold values (<2 percent Ca saturation and <0.5 percent Mg saturation in upper B horizon; <4 percent Ca saturation and <0.6 percent Mg saturation in lower B horizon), when combined with two or more moderate or severe insect defoliations in the past 10-year period, had high sugar maple mortality. All declining stands with low soil Ca and Mg were located on unglaciated upper landscape positions, particularly unglaciated summits, shoulders, and upper backslopes, where weatherable minerals are below the rooting zone and water flow paths are less likely to bring ions released from bedrock into the root zone. In Canadian sugar maples, soil B horizon Ca >28.4 percent was necessary to prevent foliar Ca deficiency; base saturation of 33.4 percent prevented P deficiency (Ouimet et al 2013). In Vermont, Schaberg et al. (2006) found that trees with low foliar Ca and high foliar Al had elevated branch dieback and decreased basal area relative to trees with high Ca and low Al. Foliar Ca and Al were significantly and positively correlated with soil Ca and Al.

We assigned a critical load of 8.5 to 26 kg N ha^{-1} yr^{-1} for sugar maple. Thomas et al. (2010) found increased growth and no change in survival with increased N deposition from 3 to 10.5 kg N ha^{-1} yr^{-1}, while Duchesne et al. (2002) found that sugar maple basal area increment in Quebec was negatively correlated with N and S wet deposition and soil exchangeable acidity over a range of 3.2-9.5 kg N ha^{-1} yr^{-1} and 6.5-15.5 kg S ha^{-1} yr^{-1} deposition. Stand decline rate was positively associated with N and S deposition and soil exchangeable acidity. Research from Boggs et al. (2005) supports a relatively high critical load; sugar maple basal area increased across a deposition gradient of 9 to 15 kg ha^{-1} yr^{-1} wet N deposition (approximately 11 to 17 kg ha^{-1} yr^{-1} wet + dry N) in North Carolina and Virginia. At a site on Mt. Ascutney in Vermont, maple sprouting increased on sites with high spruce/fir mortality as fertilization increased N input from 5.4 (bulk deposition) to 21.1 kg ha^{-1} yr^{-1} (McNulty et al. 1996), most likely as a direct (fertilization) or indirect (decreased competition) result of N addition. At higher levels of fertilization, sugar maples were negatively impacted; sugar maple seedling survival decreased in Michigan as fertilization increased N inputs from 6.8 to 11.8 kg ha^{-1} yr^{-1} to 36.8 to 41.8 kg ha^{-1} yr^{-1}. Sugar maple dieback increased at a base-poor site in Quebec, Canada, when fertilization increased N inputs from 8.5 to 34.5 kg ha^{-1} yr^{-1} (Moore and Houle 2009, 2013), although not significantly. This research indicates that the lower critical load for sugar maple is >8.5 and <9.5 kg N ha^{-1} yr^{-1}, while the upper critical load is >21.1 and <34.5 kg N ha^{-1} yr^{-1}. The results from Duchesne et al. (2002) were not used to set the critical load because the response to N was not analyzed separately. More research is needed to define the upper limit for sugar maple critical load. In the interim, we have assigned a value of 26 kg N ha^{-1} yr^{-1}. This is based on the high deposition value (>25 kg N ha^{-1} yr^{-1}) in a European study; significant N leaching occurred at all forested plots above this deposition (Dise and Wright 1995). Critical load values and citations are shown in Table 5.1.

ABIOTIC MODIFYING FACTORS

Multiple sources were used to set the ranges of modifying factors for sugar maple, including the sugar maple section of the Forest Service silvics handbook (Godman et al. 1990), the PLANTS database (NRCS 2014), and high importance value data from the Climate Change Atlas (U.S. Forest Service, n.d.). In general, any factor that inhibits sugar maple growth would be expected to result in a decreased need for N and thus a lower critical load; optimal growth conditions result in an increased demand for N and a higher critical load. Thus a declining sugar maple stand on an unglaciated summit, shoulder, or backslope in the Appalachian Plateau, as described by Horsley et al. (2000), would have a lower critical load compared to a sugar maple on a fertile site at a

Table 5.1—Effect of nitrogen deposition on sugar maple

Location	N deposition range (kg ha^{-1} yr^{-1})	Increased N deposition effects	Interacting factors	Citation
Northeastern, Midwestern U.S.	3 to 10.5	Increased growth, no change in survival		Thomas et al. 2010
Quebec	3.2 to 9.5 (wet)	Basal area increment negatively correlated with N and S deposition	S deposition 6.5 to 15.5	Duchesne et al. 2002
Vermont	5.4 (bulk) to 21.1	Increased seedling and sprouts on high mortality plots		McNulty et al. 1996
Michigan	6.8-11.8 to 36.8-41.8	Decreased seedling survival		Talhelm et al. 2013
Quebec	8.5 to 34.5	Increased (not significant) dieback, decreased foliar Ca		Moore and Houle 2009
North Carolina and Virginia	9 to 15 (wet)	Increased basal area		Boggs et al. 2005
West Virginia	12 to 14	Decreased basal area	S deposition 20 to 26 kg ha^{-1} yr^{-1}	Elias 2008
Pennsylvania and New York		Declining trees on unglaciated summits, shoulders, upper backslopes		Horsley et al. 2000

Table 5.2—Abiotic modifying factors for sugar maple

Variable	Units	Suboptimal growth range	Optimal growth range	Weight of evidence[a]
Elevation	m	> 800	≤ 800	4
Aspect		southwestern	northeastern	2
Slope gradient	%	< 0.1, > 11.0	0.1 to 11.0	4
January temperature	°C	< -12.9, > 0.5	-12.9 to 0.5	5
July temperature	°C	< 18.2, > 25.1	18.2 to 25.1	5
May-September temperature	°C	< 14.6, > 22.3	14.6 to 22.3	5
Annual precipitation	mm	< 773, > 1352	773 to 1352	5
May-September precipitation	mm	< 406, > 581	406 to 581	5
Soil pH		< 4.8, > 7.1	4.8 to 7.1	4.3
Clay	%	< 4.8, > 37.1	4.8 to 37.1	3.7
Coarse sand	%	< 57.9, > 96.0	57.9 to 96.0	3.7
Permeability	cm hr^{-1}	< 0.6, > 10.2	0.6 to 10.2	3
Depth to bedrock	m	< 1.0	≥ 1.0	3
B-horizon base saturation	%	< 20	≥ 20	3
Soil Ca:Al	mol:mol	< 2	≥ 2	2
Biomass removal		low	high	
Insect pests		abundant	low or absent	
Fungal pathogens		abundant	low or absent	

[a] Refer to Tables 2.2 and 2.3 for description of values.

lower elevation. General values were used for Ca:Al and biomass removal as described in Chapter 2 (pages 13-14). Graphs showing importance values for abiotic modifying factor ranges by species are in Appendix 1. Optimal and suboptimal growth ranges and weight of evidence values are shown in Table 5.2.

Elevation

Elevation effects depend on latitude. We set elevation ranges for the northeastern United States based on basal area dominance at various elevations in the Green Mountains of Vermont as reported by Beckage et al. (2008) as well as elevation ranges from the White

Mountains of New Hampshire (Leak and Graber 1974). Growth is expected to be optimal below approximately 800 m in elevation, and suboptimal at higher elevations.

Aspect

Sugar maple is shade tolerant, with medium drought tolerance (NRCS 2014). Currently northeastern aspects are associated with optimal growth and southwestern aspects with suboptimal growth.

Slope Gradient

High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to set thresholds for slope. Growth for sugar maple is expected to be optimal from 0.1 to 11.0 percent.

Average January, July, and May to September Temperatures

Godman et al. (1990) reports an average January temperature range of -18 to -10 °C and an average July temperature range of 16 to 27 °C. High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to set temperature thresholds. We associated January temperatures from -12.9 to 0.5 °C, July temperatures from 18.2 to 25.1 °C, and May to September temperatures from 14.6 to 22.3 °C with optimal growth, and values outside of these ranges with suboptimal growth.

Annual Precipitation

Reported precipitation ranges include 576 to 2289 mm (U.S. Forest Service, n.d.), 559 to 2030 mm (NRCS 2014), and 510 to 2030 mm, with an ideal value of 1270 mm (Godman et al. 1990). The high importance value range of 773 to 1352 mm (U.S. Forest Service, n.d.) was associated with optimal growth. Values outside of this range were associated with suboptimal growth.

May to September Precipitation

High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to determine thresholds for average May to September precipitation. We associated the precipitation range from 406 to 581 mm with optimal growth and precipitation outside of this range with suboptimal growth.

Soil pH

Reported soil pH ranges include pH 3.7 to 7.9 (NRCS 2014), 4.1 to 8.1 (U.S. Forest Service, n.d.), and 3.7 to 7.3, with an ideal range of pH 5.5 to 7.3. (Godman et al. 1990). We associated soil pH values of 4.8 to 7.1, the high importance value range from the Climate Change Atlas (U.S. Forest Service, n.d.), with optimal growth and values outside of this range with suboptimal growth.

At Hubbard Brook Experimental Forest in New Hampshire, soil pH is 3.4-3.8 in the organic horizons. Sugar maple at high elevations experience high mortality and low foliar Ca. Calcium additions resulted in increased soil pH (Oie = 5.0), increased foliar and root Ca, and increased seedling survival (Juice 2006).

Percent Clay and Percent Coarse Sand

Sugar maple grows on loamy and sandy soils. Dominant soil orders are Mollisols, Alfisols, and Spodosols (Godman et al. 1990). We used high importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) to set thresholds for percent clay and percent coarse sand. Optimal clay is 4.8 to 37.1 percent; optimal coarse sand is 57.9 to 96.0 percent.

Permeability

Optimal soil permeability from Climate Change Atlas (U.S. Forest Service, n.d.) high importance values range from 0.6 to 10.2 cm hr^{-1}, the rates for moderately slow to moderately rapidly draining clay loams to sandy loams (O'Geen 2012).

Depth to Bedrock

We assigned depth to bedrock values of <1.0 m for suboptimal growth, based on minimum rooting depth (NRCS 2014), and depths ≥1.0 m for optimal growth.

Base Saturation

Research indicates that sugar maple on soils with higher base saturation, and thus higher fertility, have increased growth, and decreased mortality (Duchesne et al. 2002, Horsley et al. 2000). Sullivan et al. (2013) found that a B horizon base saturation of 12 percent was the cut-off below which there was a near absence of sugar maple seedling regeneration. Regeneration was highest above 20 percent base saturation. Ouimet et al. (2013) found that B horizon Ca >28.4 percent was necessary to prevent foliar Ca deficiency, indicating that even higher levels of soil base saturation may be necessary for maximum forest health.

EXTERNAL INFLUENCES

Insect Pests

We assumed that abundant levels of insect pests would correlate with suboptimal growth, while low or absent levels of insect pests would correlate with optimal growth.

Fungal Pathogens

As with insect pests, we assumed that trees weakened by an abundance of fungal pathogens would have suboptimal growth. Low or absent levels of fungal pathogens would correlate with optimal growth.

6 *BETULA ALLEGHANIENSIS* (YELLOW BIRCH)

SPECIES RANGE AND CRITICAL LOAD

Yellow birch, *Betula alleghaniensis* Britton, grows in southeastern Canada and in the northeastern and north central United States south to the Appalachian Mountains (Erdmann 1990). In New England, soil drainage is one of the most important factors affecting yellow birch (Post et al. 1969).Yellow birch can grow on a great variety of soils but grows best on well drained, fertile loams and moderately well drained sandy loams in cool, moist climates (Erdmann 1990). In the Green Mountains of Vermont, yellow birch grows well up to 792 m (Beckage et al. 2008); it can be found up to 950 m in the White Mountains of New Hampshire (Leak and Graber 1974). It has better growth at lower elevations and on the northwest aspect. (Erdmann 1990). Yellow birch decline has been observed across the growing region since the 1930s; this may be related to winter thaw-freeze events, which have been increasing over time (Bourque et al. 2005).

We assigned a critical load of 3 to 17 kg ha^{-1} yr^{-1} for yellow birch. Thomas et al. (2010) found no change in growth and decreased survival for yellow birch over a deposition range of 3 to 11 kg N ha^{-1} yr^{-1}. Boggs et al. (2005) found decreased yellow birch basal area across a deposition gradient of 9 to 15 kg ha^{-1} yr^{-1} wet N deposition (approximately 11 to 17 kg ha^{-1} yr^{-1} wet + dry N) in North Carolina and Virginia. Peak natural log of yellow birch basal area occurred at 13 kg ha^{-1} yr^{-1} wet N (approximately 15 kg ha^{-1} yr^{-1} wet + dry N), for a study-based critical load range of 13-17 kg ha^{-1} yr^{-1}. At a site on Mt. Ascutney in Vermont, birch basal area decreased but stump sprouting increased as fertilization increased N input from 5.4 (bulk deposition) to 21.1 kg ha^{-1} yr^{-1} (McNulty et al. 1996). Critical load values and citations are shown in Table 6.1.

ABIOTIC MODIFYING FACTORS

Multiple sources were used to set the ranges of modifying factors for yellow birch, including the yellow birch section of the Forest Service silvics handbook (Erdmann 1990), the PLANTS database (NRCS 2014), and high importance value data from the Climate Change Atlas (U.S. Forest Service, n.d.). In general, any factor that inhibits yellow birch growth would be expected to result in a decreased need for N and thus a lower critical load; optimal growth conditions result in an increased demand for N and a higher critical load. General values were used for base saturation, Ca:Al, and biomass removal as described in Chapter 2 (pages 13-14). Graphs showing importance values for abiotic modifying factor ranges by species are in Appendix 1. Optimal and suboptimal growth ranges and weight of evidence values are shown in Table 6.2.

Elevation

Elevation effects depend on latitude. We set elevation ranges for the northeastern United States based on basal area dominance of yellow birch at various elevations in the Green Mountains of Vermont as reported by Beckage et al. (2008), as well as elevation ranges reported for the White Mountains of New Hampshire (Leak and Graber 1974). Growth is expected to be optimal between approximately 550 and 800 m in elevation.

Aspect

Yellow birch has medium drought and shade tolerance and prefers cool, moist sites. We associated northeastern aspects with optimal growth and southwestern aspects with suboptimal growth.

Slope Gradient

High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to set thresholds for slope. We expect growth for yellow birch to be optimal from 0.6 to 10.3 percent.

Average January, July, and May to September Temperatures

High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to set temperature thresholds. We associated January temperatures from -13.3 to -6.3 °C, July temperatures from 16.5 to 20.4 °C, and May to September temperatures from 13.0 to 16.8 °C with optimal growth, and values outside of these ranges with suboptimal growth.

Table 6.1—Effect of nitrogen deposition on yellow birch

Location	N deposition range (kg ha^{-1} yr^{-1})	Increased N deposition effects	Citation
Northeastern, Midwestern U.S.	3 to 11	No change in growth; decreased survival	Thomas et al. 2010
Mt. Ascutney, VT	5.4 (bulk) to 21.1	Decreased basal area; increased stump sprouting	McNulty et al. 1996
NC and VA	9 to 15 (wet)	Decreased basal area (BA); peak BA at 13 kg ha^{-1} yr^{-1} wet N	Boggs et al. 2005

Table 6.2—Abiotic modifying factors for yellow birch

Variable	Units	Suboptimal growth range	Optimal growth range	Weight of evidence[a]
Elevation	m	< 550, > 800	550 to 800	4
Aspect		southwestern	northeastern	2
Slope gradient	%	< 0.6, > 10.3	0.6 to 10.3	3
January temperature	°C	< -13.3, > -6.3	-13.3 to -6.3	3.7
July temperature	°C	< 16.5, > 20.4	16.5 to 20.4	3.7
May-September temperature	°C	< 13.0, > 16.8	13.0 to 16.8	3.7
Annual precipitation	mm	< 866, > 1558	866 to 1558	3.3
May-September precipitation	mm	< 437, > 695	437 to 695	3.3
Soil pH		< 4.7, > 5.9	4.7 to 5.9	3.3
Clay	%	< 4.5, > 18.8	4.5 to 18.8	2.7
Coarse sand	%	< 61.4, > 87.0	61.4 to 87.0	2.7
Permeability	cm hr^{-1}	< 0.8, > 10.6	0.8 to 10.6	2.3
Depth to bedrock	m	< 0.8	≥ 0.8	3
B-horizon base saturation	%	< 15	≥ 15	2
Soil Ca:Al	mol:mol	< 2	≥ 2	2
Biomass removal		low	High	
Insect pests		abundant	low or absent	
Fungal pathogens		abundant	low or absent	

[a] Refer to Tables 2.2 and 2.3 for description of values.

Annual Precipitation

Reported precipitation ranges include 587 to 2289 mm (U.S. Forest Service, n.d.), 635 to 2030 mm (NRCS 2014), and 640 to 1270 mm (Erdmann 1990). We associated the high importance value range of 866 to 1558 mm (U.S. Forest Service, n.d.) with optimal growth. Values outside of this range were associated with suboptimal growth.

May to September Precipitation

High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to determine thresholds for average May to September precipitation. We associated the precipitation range from 437 to 695 mm with optimal growth and precipitation outside of this range with suboptimal growth.

Soil pH

Reported soil pH ranges include 4 to 8 (NRCS 2014) and 4.5 to 7.6 (U.S. Forest Service, n.d.). We associated the pH range of 4.7 to 5.9, from the Climate Change Atlas (U.S. Forest Service, n.d.) high importance values, with optimal growth. Values outside of this range were associated with suboptimal growth.

Percent Clay and Percent Coarse Sand

Yellow birch grows best on well drained, fertile loams and moderately well drained sandy loams. Dominant soil orders are Alfisols, Inceptisols, and Spodosols (Erdmann 1990). High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to set thresholds for percent clay and percent coarse sand. Optimal clay is 4.5 to 18.8 percent; optimal coarse sand is 61.4 to 87.0 percent.

Permeability

Optimal soil permeability from Climate Change Atlas (U.S. Forest Service, n.d.) high importance values range from 0.8 to 10.6 cm hr^{-1}, the rates for moderately slow to moderately rapidly draining clay loams to sandy loams (O'Geen 2012).

Depth to Bedrock

We assigned depth to bedrock values of <0.8 m for suboptimal growth, based on minimum rooting depth (NRCS 2014), and ≥0.8 m for optimal growth.

EXTERNAL INFLUENCES

Insect Pests

We assumed that abundant insect pests correlate with suboptimal growth, while low or absent insect pests correlate with optimal growth. Birch borer (*Agrilus anxius*) is the primary pest of concern for yellow birch (Erdmann 1990).

Fungal Pathogens

As with insect pests, we assumed that trees weakened by an abundance of fungal pathogens would have suboptimal growth. Low or absent levels of fungal pathogens would correlate with optimal growth. *Nectria galligeno* is the primary pathogen of concern for yellow birch (Erdmann 1990).

7 *BETULA PAPYRIFERA* (PAPER BIRCH)

SPECIES RANGE AND CRITICAL LOAD

Paper birch, *Betula papyrifera* Marsh., grows across a broad swath of Canada and much of the northern and mountainous United States (Safford et al. 1990). Paper birch can grow on a great variety of soils but grows best on well drained, sandy loam soils in cool, moist climates. It grows up to the tree line in southern locations and on cool northern aspects in the northern part of its range (Safford et al. 1990).

We assigned a critical load of 9.5 to 21.1 kg N ha^{-1} yr^{-1} for paper birch. Thomas et al. (2010) found no change in growth and increased survival for paper birch over a N deposition range of 3 to 9.5 kg ha^{-1} yr^{-1}. At a site on Mt. Ascutney in Vermont, birch basal area decreased but stump sprouting increased as fertilization increased N input from 5.4 (bulk deposition) to 21.1 kg ha^{-1} yr^{-1} (McNulty et al. 1996). This research indicates that the critical load for paper birch is above 9.5 kg N ha^{-1} yr^{-1} and below 21.1 kg N ha^{-1} yr^{-1}. Critical load values and citations are shown in Table 7.1.

ABIOTIC MODIFYING FACTORS

Multiple sources were used to set the ranges of modifying factors for paper birch, including the paper birch section of the Forest Service silvics handbook (Safford et al. 1990), the PLANTS database (NRCS 2014), and high importance value data from the Climate Change Atlas (U.S. Forest Service, n.d.). In general, any factor that inhibits paper birch growth would be expected to result in a decreased need for N and thus a lower critical load; optimal growth conditions result in an increased demand for N and a higher critical load. General values were used for base saturation, Ca:Al, and biomass removal as described in Chapter 2 (pages 13-14). Graphs showing importance values for abiotic modifying factor ranges by species are in Appendix 1. Optimal and suboptimal growth ranges and weight of evidence values are shown in Table 7.2.

Elevation

We set elevation ranges for the northeastern United States based on elevation ranges for paper birch in New Hampshire from Leak and Graber (1974). Growth is expected to be optimal between approximately 670 and 1400 m in elevation, and suboptimal when elevation is <670 or >1400 m.

Aspect

Paper birch is both drought intolerant and shade intolerant and prefers cool, moist sites. We associated northeastern aspects with optimal growth and southwestern aspects with suboptimal growth.

Slope Gradient

High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to set thresholds for slope. Growth for paper birch is expected to be optimal from 0.0 to 6.9 percent.

Average January, July, and May to September Temperatures

Paper birch grows in similar areas as quaking aspen, which has an average January temperature range of -30 to -3 ˚C (Perala 1990). Safford et al. (1990) reports an average July temperature range of 13 to 21 ˚C. For the purposes of this report, we set optimal growth ranges using high importance values from the Climate Change Atlas data (U.S. Forest Service, n.d.), which does not include the entire range for paper birch. Optimal growth may also occur at lower temperatures. We associated January temperatures from -16.2 to -8.5 ˚C, July temperatures from 17.2 to 21.7 ˚C, and May to September temperatures from 13.6 to 18.0 ˚C with optimal growth and values outside of these ranges with suboptimal growth.

Annual Precipitation

Reported precipitation ranges for paper birch include 436 to 1896 mm (U.S. Forest Service, n.d.), 305 to 1524 mm (NRCS 2014), and 300 to 1520 (Safford et al. 1990). The high importance value range of 670 to 1299 mm (U.S. Forest Service, n.d.) was associated with optimal growth. Values outside of this range were associated with suboptimal growth.

May to September Precipitation

High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to determine

Table 7.1—Effect of nitrogen deposition on paper birch

Location	N deposition range (kg ha^{-1} yr^{-1})	Increased N deposition effects	Citation
Northeastern, Midwestern U.S.	3 to 9.5	No change in growth; increased survival	Thomas et al. 2010
Mt. Ascutney, VT	5.4 (bulk) to 21.1	Decreased basal area; increased stump sprouting	McNulty et al. 1996

Table 7.2—Abiotic modifying factors for paper birch

Variable	Units	Suboptimal growth range	Optimal growth range	Weight of evidence[a]
Elevation	m	< 670, > 1400	670 to 1400	3
Aspect		southwestern	northeastern	2
Slope gradient	%	> 6.9	0.0 to 6.9	3.3
January temperature	°C	< -16.2, > -8.5	-16.2 to -8.5	4
July temperature	°C	< 17.2, > 21.7	17.2 to 21.7	4.3
May-September temperature	°C	< 13.6, > 18.0	13.6 to 18.0	4.3
Annual precipitation	mm	< 670, > 1299	670 to 1299	3.3
May-September precipitation	mm	< 425, > 579	425 to 579	4
Soil pH		< 4.7, > 7.0	4.7 to 7.0	3.7
Clay	%	< 3.2, > 39.1	3.2 to 39.1	2.7
Coarse sand	%	< 61.3, > 95.8	61.3 to 95.8	3.3
Permeability	cm hr^{-1}	< 0.9, > 11.9	0.9 to 11.9	2.7
Depth to bedrock	m	< 0.6	≥ 0.6	3
B-horizon base saturation	%	< 15	≥ 15	2
Soil Ca:Al	mol:mol	< 2	≥ 2	2
Biomass removal		low	high	
Insect pests		abundant	low or absent	
Fungal pathogens		abundant	low or absent	

[a] Refer to Tables 2.2 and 2.3 for description of values.

thresholds for average May to September precipitation. We associated the precipitation range from 425 to 579 mm with optimal growth and precipitation outside of this range with suboptimal growth.

Soil pH

Soil pH ranges reported for paper birch include 4.2 to 7.4 (NRCS 2014) and 4.5 to 8.1 (U.S. Forest Service, n.d.). We associated the high importance range of pH 4.7 to 7.0 from the Climate Change Atlas (U.S. Forest Service, n.d.) with optimal growth. Values outside of this range were associated with suboptimal growth.

Percent Clay and Percent Coarse Sand

Paper birch grows best on well drained, sandy loams. Dominant soil orders are Spodosols, Inceptisols, and Entisols (Safford et al. 1990). High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to set thresholds for percent clay and percent coarse sand. Optimal clay is 3.2 to 39.1 percent; optimal coarse sand is 61.3 to 95.8 percent.

Permeability

Optimal soil permeability from Climate Change Atlas (U.S. Forest Service, n.d.) high importance values range from 0.9 to 11.9 cm hr^{-1}, the rates for moderately slow to moderately rapidly draining clay loams to sandy loams (O'Geen 2012).

Depth to Bedrock

We assigned depth to bedrock values of <0.6 m for suboptimal growth, based on minimum rooting depth (NRCS 2014), and values ≥0.6 for optimal growth.

EXTERNAL INFLUENCES

Insect Pests

We assumed that abundant insect pests correlate with suboptimal growth, while low or absent insect pests correlate with optimal growth. Birch borer (*Agrilus anxius*) is the primary pest of concern for paper birch (Dukes et al. 2009, Safford et al. 1990).

Fungal Pathogens

As with insect pests, we assumed that trees weakened by abundant fungal pathogens would have suboptimal growth. Low or absent fungal pathogens would correlate with optimal growth.

8 *CASTANEA DENTATA* (AMERICAN CHESTNUT)

SPECIES RANGE AND CRITICAL LOAD

American chestnut, *Castanea dentata*, was at one time a dominant forest tree throughout the north and central eastern United States, from Maine to Georgia and west to the Ohio River Valley. By 1950, most large American chestnut trees had been destroyed by chestnut blight (*Cryphonectria parasitica*). American chestnuts still appear across their former range but are typically killed by chestnut blight before they mature. American chestnut hybrids are being developed in an attempt to restore chestnuts to North American forests (eFloras, n.d.). American chestnuts were historically found on well-drained, acidic soil and were rare over limestone-derived soil. They could be found at elevations up to 2000 m in the southern Appalachians on southern slopes, up to 900 m in the Catskills of New York, and up to 130 m in New Hampshire (Russell 1987). They grow best in well drained, acidic, medium textured soils from pH 4.5 to 6.5, with an optimum pH of 5.5 (Youngsteadt 2014). They are found in regions with a minimum of 150 frost free days over a precipitation range of 889 to 1524 mm (NRCS 2014).

Because American chestnut does not occur as a mature tree in most forest stands, there is little research on its interaction with N deposition. We have assigned a critical load of 3 to 17 kg N ha^{-1} yr^{-1} for American chestnut. This is based on the critical load for oaks (*Quercus* spp.) and American beech (*Fagus grandifolia*), which, with American chestnut, are members of the family Fagaceae. American beech had no change in growth or survival over a deposition range of 3 to 11 kg N ha^{-1} yr^{-1} (Thomas et al. 2010) but had decreased basal area over a deposition range of 9 to 15 wet (11 to 17 wet + dry) N deposition (Boggs et al. 2005). Oaks had no change in growth or increased growth with increasing N deposition from 3 to 11 kg ha^{-1} yr^{-1}, and no change in survival or decreased survival (Thomas et al. 2010). Chestnut oaks had a growth peak at 5 kg N ha^{-1} yr^{-1}; scarlet oaks had a survival peak at 7 kg N ha^{-1} yr^{-1}. For the Fagaceae family, the lower critical load appears to be >3 and <9.5, while the upper critical load is >11 and <17 kg N ha^{-1} yr^{-1}; thus the critical load of 3 to 17 for growth and survival. This critical load should be revised when data specific for American chestnut becomes available. Critical load values and citations are shown in Table 8.1.

ABIOTIC MODIFYING FACTORS

Information from PLANTS database (NRCS 2014), the Climate Change Atlas (U.S. Forest Service, n.d.), and Wang et al. (2013) were used to set the range of modifying factors for American chestnut. In general, any factor that inhibits American chestnut growth would be expected to result in a decreased need for N and thus a lower critical load; optimal growth conditions result in an increased demand for N and a higher critical load. Due to the devastating effects of chestnut blight, the effect of the fungal pathogen may supersede abiotic site factors. In addition, American chestnut is not an important component of Forest Inventory and Analysis sites. For this reason, ranges for abiotic modifying factors were set using Climate Change Atlas data with an importance value threshold of 2 (U.S. Forest Service, n.d.). General values were used for base saturation, Ca:Al, and biomass removal as described in Chapter 2 (pages 13-14). Graphs showing importance values for abiotic modifying factor ranges by species are in Appendix 1. Optimal and suboptimal growth ranges and weight of evidence values are shown in Table 8.2.

Elevation

Elevation effects depend on latitude. We have provided an elevation range for American chestnut in the northeastern United States based on general elevation ranges of co-occurring tree species. Growth is generally expected to be optimal below approximately 550 m and suboptimal above 550 m in elevation.

Aspect

American chestnut appears to have intermediate shade tolerance (Joesting et al. 2008) and medium drought tolerance (NRCS 2014). Because it is not clear which aspect is most favorable for growth, we did not associate aspect with growth for this species.

Slope Gradient

Remaining American chestnut trees in Canada are found on gentle slopes (Tindall et al. 2004). Optimal slope ranges above an importance value of 10 cannot be established with current data. However, the distribution over an importance value of 2 for Climate

Table 8.1—Effect of nitrogen deposition on American chestnut

Location	N deposition range (kg ha^{-1} yr^{-1})	Increased N deposition effects	Species	Citation
Northeastern, Midwestern U.S.	3 to 11	No change in growth or survival	American beech	Thomas et al. 2010
Northeastern, Midwestern U.S.	3 to 11	Increased growth, decreased survival	red oak	Thomas et al. 2010
	3 to 11	No change in growth or survival	white oak, black oak	
	3 to 10.5	No change in growth, decreased survival; survival peak 5 kg ha^{-1} yr^{-1}	chestnut oak	
	5 to 9.5	Increased growth, decreased survival; growth peak at 7 kg ha^{-1} yr^{-1}	scarlet oak	
WV	Up to 12 to 14	Decreased basal area	red oak	Elias 2008
NC and VA	9 to 15 (wet)	Decreased basal area	American beech	Boggs et al. 2005

Table 8.2—Abiotic modifying factors for American chestnut

Variable	Units	Suboptimal growth range	Optimal growth range	Weight of evidence[a]
Elevation	m	> 550	≤ 550	2
Aspect		N/A	N/A	
Slope	%	< 0.8, > 16.1	0.8 to 16.1	2
January temperature	°C	< -5.7, > 1.5	-5.7 to 1.5	3
July temperature	°C	< 19.5, > 23.6	19.5 to 23.6	3
May-September temperature	°C	< 16.6, > 20.9	16.6 to 20.9	3
Annual precipitation	mm	< 956, > 1546	956 to 1546	3.3
May-September precipitation	mm	< 442, > 640	442 to 640	3.3
Soil pH		< 4.5, > 5.6	4.5 to 5.6	2.3
Clay	%	< 13.8, > 40.0	13.8 to 40.0	2.3
Coarse sand	%	< 52.2, > 86.9	52.2 to 86.9	2
Permeability	cm hr^{-1}	< 1.1, > 7.5	1.1 to 7.5	1.7
Depth to bedrock	m	< 0.5	≥ 0.5	3
B-horizon base saturation	%	< 15	≥ 15	2
Soil Ca:Al	mol:mol	< 2	≥ 2	2
Biomass removal		low	high	
Insect pests		abundant	low or absent	
Fungal pathogens		abundant	low or absent	

[a] Refer to Tables 2.2 and 2.3 for description of values.

Change Atlas data (U.S. Forest Service, n.d.) provides a slope range of 0.8 to 16.1 percent.

Average January, July, and May to September Temperatures

American chestnut is prone to frost damage (Gurney et al. 2011) and is not present in much of northern New England. Due to limited presence of mature trees, optimal temperature ranges above an importance value of 10 cannot be established. However, the distribution over an importance value of 2 for Climate Change Atlas data (U.S. Forest Service, n.d.) provides a January temperature range of -5.7 to 1.5 °C, a July temperature range of 19.5 to 23.6 °C, and a May to September temperature range of 16.6 to 20.9 °C.

Annual Precipitation

Wang et al. (2013) report that American chestnut grows in areas from 813 to 2032 mm annual precipitation; the majority of trees are found in areas with 1016 to 1219 mm. The range of 835-2283 mm annual precipitation from the Climate Change Atlas (U.S. Forest Service, n.d.) is similar. The PLANTS database (NRCS 2014) provides a range from 889 to 1524 mm. Due to limited presence of mature trees, optimal temperature ranges above an importance value of 10 cannot be established. However, the distribution over an importance value of 2 for Climate Change Atlas data (U.S. Forest Service, n.d.) provides an annual precipitation range of 956 to 1546 mm.

May to September Precipitation

Distribution over an importance value of 2 for Climate Change Atlas data (U.S. Forest Service, n.d.) provides a May to September precipitation range of 442 to 640 mm. However, American chestnut growth is expected to be suboptimal at all precipitations.

Soil pH

The PLANTS database (NRCS 2014) reports that American chestnut is found on soils with pH 5.5 to 6.5. Surviving American chestnuts in Canada were found on soils of pH 4 to 6 (Tindall et al. 2004). The entire distribution range in the Climate Change Atlas is 4.1 to 6.8, while distribution over an importance value of 2 ranges from 4.5 to 5.6 (U.S. Forest Service, n.d.). We associated soil pH values from pH 4.5 to 5.6 with the optimal growth. Values outside of this range are associated with suboptimal growth.

Percent Clay and Percent Coarse Sand

American chestnut is most common on well-drained, sandy soils (Wang et al. 2013). Distribution over an importance value of 2 for Climate Change Atlas data (U.S. Forest Service, n.d.) provides a range of 13.8 to 40.0 percent clay and 52.2 to 86.9 percent coarse sand. However, American chestnut growth is expected to be suboptimal at all soil textures.

Permeability

Distribution over an importance value of 2 for Climate Change Atlas data (U.S. Forest Service, n.d.) provides a range from 1.1 to 7.5 cm hr^{-1}, the rate for moderately slow to moderately rapidly draining sandy loams (O'Geen 2012).

Depth to Bedrock

We associated depth to bedrock of <0.5 m with suboptimal growth, based on minimum rooting depth (NRCS 2014), and depths ≥0.5 m with optimal growth.

EXTERNAL INFLUENCES

Insect Pests

In a study of mycorrhizal inoculation and fertilization of American chestnut and American chestnut/Chinese chestnut hybrids, gypsy moth (*Lymantria dispar*) performance was highest on fertilized hybrid trees and lowest on unfertilized American chestnut seedlings (Rieske et al. 2003). We assumed that abundant levels of insect pests correlate with suboptimal growth, while low levels or the absence of insect pests correlate with optimal growth.

Fungal Pathogens

As with insect pests, we assumed that trees weakened by abundant fungal pathogens would have suboptimal growth. In the case of American chestnut, since chestnut blight is nearly universally present, growth conditions are almost always suboptimal. The presence of fungal pathogens would correlate with suboptimal growth, while the absence of fungal pathogens would correlate with optimal growth.

9 *FAGUS GRANDIFOLIA* (AMERICAN BEECH)

SPECIES RANGE AND CRITICAL LOAD

American beech, *Fagus grandifolia* Ehrh., grows across much of the eastern United States and southeastern Canada. American beech grows best in loamy, high humus, dry-mesic soils, although it can also grow on poorly drained soils. The largest trees are found on alluvial bottomlands of the Ohio and Mississippi River Valleys. It occurs at elevations up to 980 m in New England and up to 1830 m in the southern part of its range (Tubbs and Houston 1990). Across its range, American beech is affected in varying degrees by beech bark disease, a moderately lethal, relatively slow acting disease (Lovett et al. 2006).

We assigned a critical load for growth of 11 to 17 kg N ha^{-1} yr^{-1} for American beech based on the results from several studies. Thomas et al. (2010) found no change in growth or survival with increased deposition from 3 to 11 kg N ha^{-1} yr^{-1} deposition; the minimum critical load, based on this study, is ≥11 kg N ha^{-1} yr^{-1}. Boggs et al. (2005) found decreased American beech basal area growth at high depositions along a gradient from 9 to 15 kg N ha^{-1} yr^{-1} wet deposition (approximately 11 to 17 kg N ha^{-1} yr^{-1} wet + dry) in North Carolina and Virginia. American beech basal area growth was highest at 13 kg N ha^{-1} yr^{-1} wet (approximately 15 kg N ha^{-1} yr^{-1} wet + dry). The maximum critical load, based on this study, is 17 kg N ha^{-1} yr^{-1}. Elias (2008) found decreased basal area for American beech with N deposition of 12 to 14 kg ha^{-1} yr^{-1} and S deposition of 20-26 kg ha^{-1} yr^{-1} in West Virginia, making the critical load range for this study <14 kg N ha^{-1} yr^{-1}. A summary of studies used to set the critical load for American beech is provided in Table 9.1.

ABIOTIC MODIFYING FACTORS

Multiple sources were used to set the ranges of modifying factors for American beech, including the American beech section of the Forest Service silvics handbook (Tubbs and Houston 1990), the PLANTS database (NRCS 2014), and the Climate Change Atlas (U.S. Forest Service, n.d). In general, any factor that inhibits American beech growth would be expected to decrease the need for N and thus lower the critical load; optimal growth conditions would result in an increased demand for N and a higher critical load. General values were used for base saturation, Ca:Al, and biomass removal as described in Chapter 2 (pages 13-14). Graphs showing importance values for abiotic modifying factor ranges by species are in Appendix 1. Optimal and suboptimal growth ranges and weight of evidence values are shown in Table 9.2.

Elevation

Elevation effects depend on latitude. We set elevation ranges for the northeastern United States based on basal area dominance at various elevations in the Green Mountains of Vermont and elevation ranges from the White Mountains of New Hampshire. Beech was present between 549 and 792 m in the northern hardwoods-boreal ecotone of the Green Mountains, with the greatest basal area at lower elevations (Beckage et al. 2008). In the White Mountains of New Hampshire, beech was found between approximately 610 and 750 m (Leak and Graber 1974). Growth is expected to be suboptimal above 750 m and optimal below 750 m.

Aspect

According to PLANTS database (NRCS 2014), beech are both drought tolerant and shade tolerant. Tubbs and Houston (1990) report that more beech trees are found on cooler northern slopes in middle-range latitudes. For this reason, northeastern aspects are associated with optimal growth and southwestern aspects are associated with suboptimal growth.

Slope Gradient

We used high importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) to set thresholds for slope. Growth for American beech is expected to be optimal from 0.6 to 12.1 percent.

Average January, July, and May to September Temperatures

High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to determine temperature thresholds. We associated January temperatures from -11.6 to 0.7 °C; July temperatures from 17.7 to 24.8 °C; and May to September

Table 9.1—Effect of nitrogen deposition on American beech

Location	N deposition range (kg ha^{-1} yr^{-1})	Increased N deposition effects	Interacting factors	Citation
Northeastern U.S., Midwestern U.S.	3 to 11	No change in growth or mortality	N/A	Thomas et al. 2010
North Carolina and Virginia	9 to 15 (wet)	Decreased basal area	N/A	Boggs et al. 2005
West Virginia	12 to 14	Decreased basal area	S deposition 20 to 26 kg ha^{-1} yr^{-1}	Elias 2008

Table 9.2—Abiotic modifying factors for American beech

Variable	Units	Suboptimal growth range	Optimal growth range	Weight of evidence[a]
Elevation	m	> 750	≤ 750	4
Aspect		southwestern	northeastern	2
Slope gradient	%	< 0.6, > 12.1	0.6 to 12.1	3.7
January temperature	°C	< -11.6, > 0.7	-11.6 to 0.7	4.7
July temperature	°C	< 17.7, > 24.8	17.7 to 24.8	4.7
May-September temperature	°C	< 14.3, > 22.0	14.3 to 22.0	4.7
Annual precipitation	mm	< 883, > 1418	883 to 1418	4.3
May-September precipitation	mm	< 429, > 621	429 to 621	4.3
Soil pH		< 4.6, > 6.8	4.6 to 6.8	4
Clay	%	< 4.7, > 33.5	4.7 to 33.5	3
Coarse sand	%	< 54.4, > 93.2	54.4 to 93.2	3.3
Permeability	cm hr^{-1}	< 0.6, > 7.5	0.6 to 7.5	3
Depth to bedrock	m	< 0.8	≥ 0.8	3
B-horizon base saturation	%	< 15	≥ 15	2
Soil Ca:Al	mol:mol	< 2	≥ 2	2
Biomass removal		low	high	
Insect pests		abundant	low or absent	
Fungal pathogens		abundant	low or absent	

[a] Refer to Tables 2.2 and 2.3 for description of values.

temperatures from 14.3 to 22.0 °C with optimal growth and temperatures outside of this range with suboptimal growth. General ranges were verified using reported habitat preferences for American beech (Tubbs and Houston 1990).

Annual Precipitation

Precipitation ranges in the literature include 720 to 2283 mm (U.S. Forest Service, n.d.), 711 to 2032 mm (NRCS 2014), and 760 to 1270 mm (Tubbs and Houston 1990). We associated the high importance value range of 883 to 1418 mm from Climate Change Atlas data (U.S. Forest Service, n.d.) with optimal growth. Values outside of this range were associated with suboptimal growth.

May to September Precipitation

High importance values from the Climate Change Atlas data (U.S. Forest Service, n.d.) were used to determine thresholds for average May to September precipitation. We associated the precipitation range from 429 to 621 mm with optimal growth and precipitation outside of this range with suboptimal growth.

Soil pH

Tubbs and Houston (1990) reported that American beech is typically found on soils with pH of 4.1 to 6 and rarely on soils over pH 7.0. NRCS (2014) provides a pH range of 4.1 to 7.2. Climate Change Atlas data

(U.S. Forest Service, n.d.) have a high importance value range of pH 4.6 to 6.8; we associated these values with optimal growth and values outside of this range with suboptimal growth.

Percent Clay and Percent Coarse Sand

American beech grows best on loamy soils and is most often found on Oxisols, Alfisols, and Spodosols (Tubbs and Houston 1990). We used high importance value ranges from Climate Change Atlas data (U.S. Forest Service, n.d.) to set thresholds for percent clay and percent coarse sand. Optimal clay is 4.7 to 33.5 percent; optimal sand is 54.4 to 93.2 percent.

Permeability

High importance values from Climate Change Atlas data (U.S. Forest Service, n.d.) indicate optimal soil permeability ranges from 0.6 to 7.5 cm hr^{-1}, the range for a moderately slow draining clay loam to moderately rapidly draining sandy loam (O'Geen 2012).

Depth to Bedrock

We associated depth to bedrock of <0.8 m with suboptimal growth, based on minimum rooting depth (NRCS 2014), and ≥0.8 m with optimal growth.

EXTERNAL INFLUENCES

Insect Pests

We assumed that abundant insect pests correlate with suboptimal growth, and low levels or the absence of insect pests correlate with optimal growth. Infestation of beech with beech scale (*Cryptococcus fagisuga)* leaves beech trees vulnerable to *Neonectria* fungi, which subsequently causes beech bark disease (Lovett et al. 2006). In a Connecticut study, populations of beech scale were higher on trees with higher bark nitrogen content (Wargo 1988).

Fungal Pathogens

Larger trees have a higher mortality rate as a result of beech bark disease (and invasion by *Neonectria spp.*) than smaller trees (Morin et al. 2007). Researchers found that mature American beech trees with higher bark N content had more severe symptoms of beech bark disease than younger trees with lower bark N (Latty el al. 2003). As with insect pests, we assumed that trees weakened by abundant levels of fungal pathogens would exhibit suboptimal growth. Absent or low levels of fungal pathogens would correlate with optimal growth.

10 *FRAXINUS AMERICANA* (WHITE ASH)

SPECIES RANGE AND CRITICAL LOAD

White ash, *Fraxinus americana* L., grows in much of central and eastern United States and in southeastern Canada. It prefers fertile, well-drained sandy to clay loam soils of pH 5 to 7.5 with high nitrogen content and moderate to high calcium content (Schlesinger 1990). In Pennsylvania, ash dieback was highest on upper slope positions with relatively low base cation status (Royo and Knight 2012). White ash can be found in areas with January temperatures from -14 to 12 °C and July temperatures from 18 to 27 °C; precipitation generally ranges from 760 to 1520 mm yr^{-1}. White ash grows up to 600 m in the Adirondacks and up to 1050 m in the Cumberland Mountains (Schlesinger 1990).

We assigned a critical load of >11 to 18 kg ha^{-1} yr^{-1} for white ash. Thomas et al. (2010) found a significant increase in growth and no change in survival with increased N deposition from 3 to 11 kg N ha^{-1} yr^{-1}. Dietz and Moorcroft (2011) found increased mortality for northern mid successional hardwoods with increasing N deposition; visual inspection of supplementary material indicate that mortality was lowest from approximately 5 to 16 kg ha^{-1} yr^{-1} wet N deposition (7 to 18 kg ha^{-1} yr^{-1} wet + dry N). We used the low end of the range from Thomas et al. (2010) and the upper end of the range from Dietz and Moorcroft (2011) to set the critical load. Critical load values and citations are shown in Table 10.1.

ABIOTIC MODIFYING FACTORS

Multiple sources were used to set the ranges of modifying factors for white ash, including the white ash section of the Forest Service silvics handbook (Schlesinger 1990), the PLANTS database (NRCS 2014), and high importance value data from the Climate Change Atlas (U.S. Forest Service, n.d.). In general, any factor that inhibits white ash growth would be expected to result in a decreased need for N and thus a lower critical load; optimal growth conditions result in an increased demand for N and a higher critical load. General values were used for base saturation, Ca:Al, and biomass removal as described in Chapter 2 (pages 13-14). Graphs showing importance values for abiotic modifying factor ranges by species are in Appendix 1. Optimal and suboptimal growth ranges and weight of evidence values are shown in Table 10.2.

Elevation

We set elevation ranges for the northeastern United States based on basal area dominance of hardwood trees at various elevations in the Green Mountains of Vermont as reported by Beckage et al. (2008). We generally expect growth to be optimal below 610 m and suboptimal at higher elevations.

Aspect

White ash trees are shade intolerant and have low drought tolerance (NRCS 2014). We have currently associated northeastern exposures with optimal growth and southwestern exposures with suboptimal growth. However, it may be that aspect does not have a strong influence on white ash growth.

Slope Gradient

We used high importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) to set thresholds for slope. Growth for white ash is expected to be optimal from 0.1 to 7.3 percent.

Average January, July, and May to September Temperatures

Schlesinger (1990) reports an average January temperature range of -14 to 12 °C and an average July temperature range of 18 to 27 °C. High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to set temperature thresholds. We associated January temperatures from -8.7 to 0.3 °C, July temperatures from 19.6 to 25.6 °C, and May to September temperatures from 16.4 to 22.6 °C with optimal growth, and values outside of these ranges with suboptimal growth.

Annual Precipitation

Reported precipitation ranges include 465 to 2289 mm (U.S. Forest Service, n.d.), 711 to 2030 mm (NRCS 2014), and 760 to 1520 mm (Schlesinger 1990). We associated the high importance value range of 785

Table 10.1—Effect of nitrogen deposition on white ash

Location	N deposition range ($kg\ ha^{-1}\ yr^{-1}$)	Increased N deposition effects	Citation
Northeastern, Midwestern U.S.	3 to 11	Increased growth, no change in survival	Thomas et al. 2010
Eastern and Central U.S.	5 to 16 (wet NO_3)	Increased mortality probability	Dietze and Moorcroft 2011

Table 10.2—Abiotic modifying factors for white ash

Variable	Units	Suboptimal growth range	Optimal growth range	Weight of evidence[a]
Elevation	m	> 610	≤ 610	2
Aspect		southwestern	northeastern	2
Slope	%	< 0.1, > 7.3	0.1 to 7.3	4
January temperature	°C	< -8.7, > 0.3	-8.7 to 0.3	4.7
July temperature	°C	< 19.6, > 25.6	19.6 to 25.6	4.7
May-September temperature	°C	< 16.4, > 22.6	16.4 to 22.6	4.7
Annual precipitation	mm	< 785, > 1264	785 to 1264	4.7
May-September precipitation	mm	< 393, > 552	393 to 552	5
Soil pH		< 5.0, > 7.2	5.0 to 7.2	4
Clay	%	< 6.9, > 41.8	6.9 to 41.8	3.7
Coarse sand	%	< 54.9, > 97.9	54.9 to 97.9	3.7
Permeability	$cm\ hr^{-1}$	< 0.4, > 6.7	0.4 to 6.7	3.3
Depth to bedrock	m	< 1.0	≥ 1.0	3
B-horizon base saturation	%	< 15	≥ 15	2
Soil Ca:Al	mol:mol	< 2	≥ 2	2
Biomass removal		low	high	
Insect pests		abundant	low or absent	
Fungal pathogens		abundant	low or absent	

[a] Refer to Tables 2.2 and 2.3 for description of values.

to 1264 mm (U.S. Forest Service, n.d.) with optimal growth. Values outside of this range were associated with suboptimal growth.

May to September Precipitation

High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to determine thresholds for average May to September precipitation. We associated the precipitation range from 393 to 552 mm with optimal growth, and precipitation outside of this range with suboptimal growth.

Soil pH

Reported soil pH ranges include 4.7 to 7.5 (NRCS 2014), 5.0 to 7.5 (Schlesinger 1990), and 2.7 to 8.4 (U.S. Forest Service, n.d.). We associated soil pH values of 5.0 to 7.2, high importance values from the Climate Change Atlas (U.S. Forest Service, n.d.), with optimal growth and values outside of this range with suboptimal growth.

Percent Clay and Percent Coarse Sand

White ash can be found on sandy and clay loam soils. It is most common on fertile soils with a high nitrogen and calcium content. Dominant soil orders are Inceptisols, Alfisols, and Spodosols (Schlesinger 1990). We used high importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) to set thresholds for percent clay and percent coarse sand. Optimal clay is 6.9 to 41.8 percent; optimal coarse sand is 54.9 to 97.9 percent.

Permeability

Optimal soil permeability from Climate Change Atlas (U.S. Forest Service, n.d.) high importance values range from 0.4 to 6.7 cm hr^{-1}, the rates for moderately slow to moderately rapidly draining clay loams to sandy loams (O'Geen 2012).

Depth to Bedrock

We associated depth to bedrock of <1.0 m with suboptimal growth and ≥1.0 m for optimal growth. These are based on minimum rooting depth values for white ash (NRCS 2014).

EXTERNAL INFLUENCES

Insect Pests

We assumed that an abundance of insect pests correlate with suboptimal growth, while low or absent levels of insect pests correlate with optimal growth. Emerald ash borers (*Agrilus planipennis*) present the biggest threat to white ash trees (Dukes et al. 2009) and have killed millions of trees across the eastern United States and Canada (U.S. Forest Service and Michigan State University, n.d.).

Fungal pathogens

As with insect pests, we assumed that trees weakened by abundant fungal pathogens would have suboptimal growth. Low or absent levels of fungal pathogens would correlate with optimal growth.

Bacterial Pathogens

Ash yellows is a disease caused by *Candidatus phytoplasma fraxini*, wall-less microbes that block phloem tubes, causing slow growth and decline in affected ash trees. Ash yellows is thought to be transmitted by leaf hoppers and other insects and can be exacerbated by drought and competition. It can be difficult to diagnose because many symptoms are nonspecific (Pokorny and Sinclair 1994). We presume trees affected by ash yellows would have suboptimal growth.

11 *FRAXINUS PENNSYLVANICA* (GREEN ASH)

SPECIES RANGE AND CRITICAL LOAD

Green ash, *Fraxinus pennsylvanica Marsh.*, a riverside and bottomlands tree, is found in much of central and eastern United States and Canada. It tolerates a wide variety of soils, including land subject to flooding, but prefers fertile, moist, well-drained soil (Kennedy 1990). Green ash can be found in areas with January temperatures from -18 to 13 °C and July temperatures from 18 to 27 °C; precipitation generally ranges from 380 to 1520 mm yr^{-1} (Kennedy 1990).

We assigned a critical load of >11 to 18 kg N ha^{-1} yr^{-1} for green ash; this is based on the critical load for white ash. Thomas et al. (2010) found a significant increase in growth and no change in survival with increased N deposition from 3 to 11 kg N ha^{-1} yr^{-1}. Dietz and Moorcroft (2011) found increased mortality for northern mid successional hardwoods with increasing N deposition; visual inspection of supplementary material indicate that mortality was lowest from 5 to 16 kg ha^{-1} yr^{-1} wet N deposition (7 to 18 kg ha^{-1} yr^{-1} wet + dry N). We used the low end of the range from Thomas et al. (2010) and the upper end of the range from Dietz and Moorcroft (2011) to set the critical load. Critical load values and citations are shown in Table 11.1.

ABIOTIC MODIFYING FACTORS

Multiple sources were used to set the ranges of modifying factors for green ash, including the green ash section of the Forest Service silvics handbook (Kennedy 1990), the PLANTS database (NRCS 2014), and high importance value data from the Climate Change Atlas (U.S. Forest Service, n.d.). In general, any factor that inhibits green ash growth would be expected to result in a decreased need for N and thus a lower critical load; optimal growth conditions result in an increased demand for N and a higher critical load. General values were used for base saturation, Ca:Al, and biomass removal as described in Chapter 2 (pages 13-14). Graphs showing importance values for abiotic modifying factor ranges by species are in Appendix 1. Optimal and suboptimal growth ranges and weight of evidence values are shown in Table 11.2.

Elevation

Elevation effects depend on latitude. Green ash growth is expected to be optimal at low elevations in the northeastern United States. We have set an approximate elevation threshold of 330 m for optimal growth.

Aspect

According to NRCS (2014), green ash trees are shade tolerant and have moderate drought tolerance. We have currently associated northeastern exposures with optimal growth and southwestern exposures with suboptimal growth. However, it may be that aspect does not have a strong influence on green ash growth.

Slope Gradient

We used high importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) to set thresholds for slope. Growth for green ash is expected to be optimal from 0.0 to 3.8 percent.

Average January, July, and May to September Temperatures

Kennedy (1990) reported an average January temperature range for green ash of -18 to 13 °C and an average July temperature range of 18 to 27 °C. We used high importance values from the Climate Change Atlas (U.S. Forest Service, n.d.), which are similar to these ranges, to set temperature thresholds. We associated January temperatures from -15.5 to 6.4 °C, July temperatures from 20.8 to 27.7 °C, and May to September temperatures from 16.9 to 25.6 °C with optimal growth and values outside of these ranges with suboptimal growth.

Annual Precipitation

Reported precipitation ranges for green ash include 430 to 2289 mm (U.S. Forest Service, n.d.), 381 to 1803 mm (NRCS 2014), and 380 to 1520 mm (Kennedy 1990). We associated the high importance value range of 469 to 1416 mm (U.S. Forest Service, n.d.) with optimal growth. Values outside of this range were associated with suboptimal growth.

Table 11.1—Effect of nitrogen deposition on green ash

Location	N deposition range ($kg\ ha^{-1}\ yr^{-1}$)	Increased N deposition effects	Interacting factors	Citation
Northeastern, Midwestern U.S.	3 to 11	Increased growth, no change in survival		Thomas et al. 2010
Eastern and Central U.S.	5 to 16 (wet NO_3)	Decreased mortality probability		Dietze and Moorcroft 2011

Table 11.2—Abiotic modifying factors for green ash

Variable	Units	Suboptimal growth range	Optimal growth range	Weight of evidence[a]
Elevation	m	> 330	≤ 330	2
Aspect		southwestern	northeastern	2
Slope gradient	%	> 3.8	0.0 to 3.8	4
January temperature	°C	< -15.5, > 6.4	-15.5 to 6.4	4.3
July temperature	°C	< 20.8, > 27.7	20.8 to 27.7	5
May-September temperature	°C	< 16.9, > 25.6	16.9 to 25.6	5
Annual precipitation	mm	< 469, > 1416	469 to 1416	4.3
May-September precipitation	mm	< 318, > 579	318 to 579	4.3
Soil pH		< 5.5, > 7.8	5.5 to 7.8	4.3
Clay	%	< 11.1, > 49.0	11.1 to 49.0	3.7
Coarse sand	%	< 79.5, > 100.0	79.5 to 100.0	4
Permeability	$cm\ hr^{-1}$	< 0.2, > 8.6	0.2 to 8.6	3.3
Depth to bedrock	m	< 1.0	≥ 1.0	3
B-horizon base saturation	%	< 15	≥ 15	2
Soil Ca:Al	mol:mol	< 2	≥ 2	2
Biomass removal		low	high	3
Insect pests		abundant	low or absent	
Fungal pathogens		abundant	low or absent	
Elevation		abundant	low or absent	

[a] Refer to Tables 2.2 and 2.3 for description of values.

May to September precipitation

High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to determine thresholds for average May to September precipitation. We associated the precipitation range from 318 to 579 mm with optimal growth and precipitation outside of this range with suboptimal growth.

Soil pH

Reported soil pH ranges include pH 4.7 to 8.1 (NRCS 2014) and 5.0 to 8.0 (Kennedy 1990). We associated the Climate Change Atlas (U.S. Forest Service, n.d.) high importance value range of 5.5 to 7.8 with optimal growth. Values outside of this range were associated with suboptimal growth.

Percent Clay and Percent Coarse Sand

Green ash can tolerate a wide range of soils, but grows best on fertile, moist, well drained soils. Dominant soil orders are Inceptisols and Entisols (Kennedy 1990). We used high importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) to set thresholds for percent clay and percent coarse sand. Optimal clay is 11.1 to 49.0 percent; optimal coarse sand is 79.5 to 100.0 percent.

Permeability

Optimal soil permeability from Climate Change Atlas (U.S. Forest Service, n.d.) high importance values range from 0.2 to 8.6 $cm\ hr^{-1}$, the rates for slowly to moderately rapidly draining sandy clays to sandy loams (O'Geen 2012).

Depth to Bedrock

We associated depth to bedrock of <1.0 m for suboptimal growth and values ≥1.0 m for optimal growth. These are based on minimum rooting depth values for green ash as reported in PLANTS database (NRCS 2014).

EXTERNAL INFLUENCES

Insect Pests

We assumed that abundant insect pests correlate with suboptimal growth, while low or absent insect pests correlate with optimal growth. Emerald ash borers (*Agrilus planipennis*) present a significant health threat to green ash trees (Dukes et al. 2009). The larvae of emerald ash borers feed on the inner bark of ash trees and disrupt the flow of nutrients and water. Millions of trees have died across the eastern United States and Canada as a result of this insect (U.S. Forest Service and Michigan State University, n.d.).

Fungal Pathogens

As with insect pests, we assumed that trees weakened by an abundance of fungal pathogens would have suboptimal growth. Low or absent levels of fungal pathogens would correlate with optimal growth.

Bacterial Pathogens

Ash yellows is a disease caused by *Candidatus phytoplasma fraxini*, microbes that lack rigid cell walls. The microbes block phloem tubes, resulting in slow growth and decline in affected ash trees. Ash yellows is thought to be transmitted by leaf hoppers and other insects, and can be exacerbated by drought and competition. It can be difficult to diagnose, as many symptoms are nonspecific (Pokorny and Sinclair 1994). Trees affected by ash yellows would be presumed to have a suboptimal growth.

12 *JUGLANS CINEREA* (BUTTERNUT)

SPECIES RANGE AND CRITICAL LOAD

Butternut, *Juglans cinerea* (L.), grows in the northeastern and north central United States, as well as a small part of southern Canada, over a precipitation range of 630-2030 mm per year and an average temperature range of 4 to 16 °C. Butternut grows best on well-drained, stream-side soils and is rarely found on dry, compact, or infertile soils. It can be found at elevations up to 1500 m in the South (Rink 1990). However, in the Great Smoky Mountains of Tennessee and North Carolina, butternut was found most often from 400 to 700 m in elevation in floodplain forests. Butternut populations in the Great Smoky Mountains and elsewhere have declined dramatically as a result of butternut canker caused by the fungus *Ophiognomonia clavigignenti-juglandacearum* (Parks et al. 2013).

We assigned a critical load of 7 to 18 kg ha^{-1} yr^{-1} for butternut. This is based solely on the northern mid-successional hardwood forest type in Dietze and Moorcroft (2011); visual inspection of supplementary material indicate that mortality was lowest from 5 to 16 kg ha^{-1} yr^{-1} wet N deposition (approximately 7 to 18 kg/ha/N wet + dry deposition). Critical load citations and values are shown in Table 12.1. The critical load should be revised when species specific information becomes available.

ABIOTIC MODIFYING FACTORS

Multiple sources were used to set the ranges of modifying factors for butternut, including the butternut section of the Forest Service silvics handbook (Rink 1990), the PLANTS database (NRCS 2014), and the Climate Change Atlas (U.S. Forest Service, n.d.). In general, any factor that inhibits butternut growth would be expected to result in a decreased need for N and thus a lower critical load; optimal growth conditions result in an increased demand for N and a higher critical load. Butternut is not an important component of Forest Inventory and Analysis sites. For this reason, ranges for abiotic modifying factors were set using Climate Change Atlas data with an importance value threshold of 3 (U.S. Forest Service, n.d.). General values were used for base saturation, Ca:Al, and biomass removal as described in Chapter 2 (pages 13-14). Graphs showing importance values for abiotic modifying factor ranges by species are in Appendix 1. Optimal and suboptimal growth ranges and weight of evidence values are shown in Table 12.2.

Elevation

We set elevation ranges for the northeastern United States based on basal area dominance of hardwood trees at various elevations in the Green Mountains of Vermont as reported by Beckage et al. (2008). We generally expect growth to be optimal below 610 m and suboptimal at higher elevations.

Aspect

Butternut has low drought tolerance and is shade intolerant (NRCS 2014). Because it is not clear which aspect is most favorable for growth, we have not associated aspect with growth for this species.

Slope Gradient

We used an importance value threshold of 3 from the Climate Change Atlas (U.S. Forest Service, n.d.) to set optimal growth ranges for slope. Growth for butternut is expected to be optimal from 0.7 to 11.5 percent.

Average January, July, and May to September Temperatures

Because butternut was not an important component of sites included in the Climate Change Atlas (U.S. Forest Service, n.d.), optimal growth was established using a high importance value threshold of 3, which resulted in a January temperature range from -11.8 to -1.8 °C, a July temperature range from 20.0 to 25.1 °C, and a May to September temperature range from 16.9 to 22.1 °C.

Annual Precipitation

Annual precipitation for butternut was reported to range from 666 to 1525 mm (U.S. Forest Service, n.d.), 635 to 2032 mm (NRCS 2014), and 630 to 2030 mm (Rink 1990). We associated the range of 731 to 1139 mm, determined using an importance value threshold of 3 (U.S. Forest Service, n.d.), with optimal growth.

Table 12.1—Effect of nitrogen deposition on butternut

Location	N deposition range ($kg\ ha^{-1}\ yr^{-1}$)	Increased N deposition effects	Citation
Eastern and Central U.S.	5 to 16 (wet NO_3)	Decreased mortality probability	Dietze and Moorcroft 2011

Table 12.2—Abiotic modifying factors for butternut

Variable	Units	Suboptimal growth range	Optimal growth range	Weight of evidence[a]
Elevation	M	> 610	≤ 610	2
Aspect		N/A	N/A	
Slope gradient	%	< 0.7, > 11.5	0.7 to 11.5	2
January temperature	°C	< -11.8, > -1.8	-11.8 to -1.8	3
July temperature	°C	< 20.0, > 25.1	20.0 to 25.1	3
May-September temperature	°C	< 16.9, > 22.1	16.9 to 22.1	3
Annual precipitation	mm	< 731, > 1139	731 to 1139	3
May-September precipitation	mm	< 441, > 543	441 to 543	3
Soil pH		< 5.2, > 7.3	5.2 to 7.3	2
Clay	%	< 6.6, > 42.0	6.6 to 42.0	2
Coarse sand	%	< 71.3, > 98.3	71.3 to 98.3	2
Permeability	$cm\ hr^{-1}$	< 0.7, > 6.7	0.7 to 6.7	1.5
Depth to bedrock	M	< 1.0	≥ 1.0	3
B-horizon base saturation	%	< 15	≥ 15	2
Soil Ca:Al	mol:mol	< 2	≥ 2	2
Biomass removal		low	high	
Insect pests		abundant	low or absent	
Fungal pathogens		abundant	low or absent	

[a] Refer to Tables 2.2 and 2.3 for description of values.

May to September Precipitation

The Climate Change Atlas (U.S. Forest Service, n.d.) provides a range from 441 to 543 mm for average May to September precipitation using an importance value threshold of 3. We associated this range with optimal growth.

Soil pH

We associated soil pH values from 5.2 to 7.3, set using an importance value threshold of 3 in the Climate Change Atlas (U.S. Forest Service, n.d.), with optimal growth and values outside of this range with suboptimal growth. PLANTS database (NRCS 2014) reports a pH range of 6 to 7 for butternut.

Percent Clay and Percent Coarse Sand

Butternut grows best on well-drained riparian soils and is most often found on Alfisols and Entisols (Rink 1990). We used a Climate Change Atlas (U.S. Forest Service, n.d.) importance value threshold of 3 to set optimal ranges for soil texture. Clay ranges from 6.6 to 42 percent; coarse sand ranges from 71.3 to 98.3 percent.

Permeability

Optimal soil permeability from Climate Change Atlas (U.S. Forest Service, n.d.), set using an importance value threshold of 3, ranges from 0.7 to 6.7 $cm\ hr^{-1}$, the rates for moderately slow to moderately rapidly draining clay loams to fine sandy and silty loams (O'Geen 2012).

Depth to Bedrock

We have assigned depth of bedrock values of <1.0 m for suboptimal growth, based on minimum rooting depth (NRCS 2014), and ≥1.0 m for optimal growth.

EXTERNAL INFLUENCES

Insect Pests

We assumed that abundant insect pests correlate with suboptimal growth, while low levels or the absence of insect pests correlate with optimal growth.

Fungal Pathogens

We assumed that trees weakened by abundant fungal pathogens would have suboptimal growth. Low levels or absent fungal pathogens would correlate with optimal growth. Butternut canker, caused by the fungus *Ophiognomonia clavigignenti-juglandacearum*, is the primary fungal threat to butternut (Parks et al. 2013; Rink 1990). *Melanconium oblongum* is a secondary fungal pathogen of butternut that colonizes stressed branches (Rink 1990). Because butternut canker is a persistent threat to butternut, growth conditions may always be suboptimal.

13 *PICEA MARIANA* (BLACK SPRUCE)

SPECIES RANGE AND CRITICAL LOAD

Black spruce, *Picea mariana* (Mill.) B.S.P., grows in northern New England and across much of Canada to the tree line. Black spruce grows in cold, humid to subhumid climates with average annual temperatures of -11 to 7 °C. Precipitation ranges from 150 to 1520 mm yr^{-1}, although most black spruce grow in areas with precipitation between 380 to 760 mm per year. Black spruce is usually found over moist organic soils, such as acidic peat swamps, but it can grow on a wide variety of soils, including clay, loam, sand, and shallow soils. It grows from sea level to 1830 m and is most common between 150 and 760 m (Viereck and Johnston 1990).

We assigned a critical load of 5.4 to 21.1 kg N ha^{-1} yr^{-1} for black spruce. This critical load is based on the critical load for red spruce. Thomas et al. (2010) found very slight decreases in growth (-0.1 percent growth decrease per kg ha^{-1} yr^{-1}) and no change in survival with increased deposition from 3 to 10 kg N ha^{-1} yr^{-1} in a multi-state gradient study. At a site on Mt. Ascutney in Vermont, live red spruce basal area decreased as fertilization increased N input from 5.4 (bulk deposition) to 21.1 kg ha^{-1} yr^{-1} (McNulty et al. 1996, 2005). These studies indicate the lower critical load for spruce is >5.4 and <10 kg N ha^{-1} yr^{-1}, while the upper critical load for spruce is less than 21.1 kg ha^{-1} yr^{-1}. The range may be narrowed with further research. A summary of critical load citations and values are shown in Table 13.1.

ABIOTIC MODIFYING FACTORS

Multiple sources were used to set the ranges of modifying factors for black spruce, including the black spruce section of the Forest Service silvics handbook (Viereck and Johnston 1990), the PLANTS database (NRCS 2014), and high importance value data from the Climate Change Atlas (U.S. Forest Service, n.d.). We assumed that in most situations, factors that result in decreased black spruce growth or survival also result in decreased need for N and thus a lower critical load; optimal growth conditions result in an increased demand for N and a higher critical load. General values were used for base saturation, Ca:Al, and biomass removal as described in Chapter 2 (pages 13-14). Graphs showing importance values for abiotic modifying factor ranges by species are in Appendix 1. Optimal and suboptimal growth ranges and weight of evidence values are shown in Table 13.2.

Elevation

We set elevation ranges for the northeastern United States based on elevation ranges reported in Viereck and Johnston (1990). Growth is expected to be optimal from 150 to 760 m, and suboptimal outside of this range.

Aspect

Black spruce is shade tolerant and has low drought tolerance (NRCS 2014). We associated northeastern aspects with optimal growth and southwestern aspects with suboptimal growth.

Slope Gradient

High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to set thresholds for slope. We expect growth for black spruce to be optimal from 0 to 3.1 percent.

Average January, July, and May to September Temperatures

Climate Change Atlas data (U.S. Forest Service, n.d.) do not cover much of the range of black spruce, which extends well into northern Canada. Optimal values reported here apply to the range of black spruce in the United States. Black spruce grows in regions with January temperatures from -30 to -6 °C (Viereck and Johnston 1990) and July temperatures from 10 to 27 °C; most black spruce grow in regions with July temperatures between 16 and 24 °C (Viereck and Johnston 1990). In the United States, black spruce can have high importance on plots with January temperatures of -16.8 to -9.1, July temperatures of 17.9 to 19.8, and May to September temperatures of 14.1 to 16.0. We associated these temperatures with optimal growth; temperatures outside of these ranges were associated with suboptimal growth.

Table 13.1—Effect of nitrogen deposition on black spruce

Location	N deposition range ($kg\ ha^{-1}\ yr^{-1}$)	Increased N deposition effects	Citation
Northeastern, Midwestern U.S.	3 to 10	Slightly decreased growth, no change in survival	Thomas et al. 2010
Vermont	5.4 (bulk) to 21.1	Decreased red spruce basal area with fertilization	McNulty et al. 1996, 2005

Table 13.2—Abiotic modifying factors for black spruce

Variable	Units	Suboptimal growth range	Optimal growth range	Weight of evidence[a]
Elevation	m	< 150, > 760	150 to 760	3
Aspect		southwestern	northeastern	2
Slope gradient	%	> 3.1	0.0 to 3.1	3
January temperature	°C	< -16.8, > -9.1	-16.8 to -9.1	3.7
July temperature	°C	< 17.9, > 19.8	17.9 to 19.8	4
May-September temperature	°C	< 14.1, > 16.0	14.1 to 16.0	4
Annual precipitation	mm	< 624, > 1035	624 to 1035	3.7
May-September precipitation	mm	< 405, > 495	405 to 495	4
Soil pH		< 4.7, > 7.3	4.7 to 7.3	3.3
Clay	%	< 4.0, > 52.4	4.0 to 52.4	2.3
Coarse sand	%	< 63.7, > 94.8	63.7 to 94.8	3
Permeability	$cm\ hr^{-1}$	< 0.8, > 11.2	0.8 to 11.2	1.7
Depth to bedrock	m	< 0.4	≥ 0.4	3
B-horizon base saturation	%	< 15	≥ 15	2
Soil Ca:Al	mol:mol	< 2	≥ 2	2
Biomass removal		low	high	
Insect pests		abundant	low or absent	
Fungal pathogens		abundant	low or absent	

[a] Refer to Tables 2.2 and 2.3 for description of values.

Annual Precipitation

Literature values for black spruce precipitation range were 499 to 1800 mm (U.S. Forest Service, n.d.), 127 to 1524 mm (NRCS 2014), and 150 to 1520 mm (Viereck and Johnston 1990). Optimal precipitation ranges were 380 to 760 mm (Viereck and Johnston 1990) and a high importance value range of 624 to 1035 mm (U.S. Forest Service, n.d.). We associated the high importance value range with optimal growth. Values outside of this range were associated with suboptimal growth. These values apply to black spruce in the United States.

May to September Precipitation

High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to determine thresholds for average May to September precipitation. We associated the precipitation range from 405 to 495 mm with optimal growth and precipitation outside of this range with suboptimal growth. These values apply to black spruce in the United States.

Soil pH

We associated soil pH values of 4.7 to 7.3 from the Climate Change Atlas high importance values (U.S. Forest Service, n.d.) with optimal growth and values outside of this range with suboptimal growth. PLANTS database (NRCS 2014) reports a pH range of 4.7 to 6.5 for black spruce.

Percent Clay and Percent Coarse Sand

Black spruce grows best on dark colored peats in the Lake States and Canada and in central Canada on the better drained glacial deposits, river terraces, and outwash plains (Viereck and Johnston 1990). Common soil orders are Histosols, Spodosols, Inceptisols, and Entisols. We used high importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) to set thresholds for percent clay and percent coarse sand. Optimal clay is 4.0 to 52.4 percent; optimal coarse sand is 63.7 to 94.8 percent.

Permeability

Optimal soil permeability from Climate Change Atlas (U.S. Forest Service, n.d.) high importance values range from 0.8 to 11.2 cm hr^{-1}, the rates for moderately slow to moderately rapidly draining clay loams to sandy loams (O'Geen 2012).

Depth to Bedrock

We have assigned depth to bedrock values of <0.4 m for suboptimal growth, based on NRCS (2014) minimum rooting depth, and ≥ 0.4 m for optimal growth.

EXTERNAL INFLUENCES

Insect pests

We assumed that abundant levels of insect pests correlate with suboptimal growth, while low levels or the absence of insect pests correlate with optimal growth.

Fungal Pathogens

We assumed that trees weakened by abundant fungal pathogens would have suboptimal growth. Low levels or the absence of fungal pathogens would correlate with optimal growth.

14 *PICEA RUBENS* (RED SPRUCE)

SPECIES RANGE AND CRITICAL LOAD

Red spruce, *Picea rubens Sarg.*, grows in the northeastern United States, along the Appalachian Mountains, and in southeastern Canada. Red spruce grows in cool, moist climates; it is typically found on acidic (pH 4.0 to 5.5) and shallow till soils in the northeastern states. It grows from sea level to 4,500 feet (1372 m) in the northern part of its range and from 3,200 feet to 6,200 feet (975 to 1890 m) in the southern part of its range (Blum 1990).

We assigned a critical load of 5.4 to 21.1 kg N ha^{-1} yr^{-1} for red spruce. Bedison and McNeil (2009) found increased basal area increment of red spruce along a wet N deposition gradient of <3 to >7 kg N ha^{-1} yr^{-1} (approximately 5 to 9 kg ha^{-1} yr^{-1} wet + dry N deposition) in Adirondack State Park, New York, while Thomas et al. (2010) found a very slight decrease in growth (-0.1 % growth decrease per kg ha^{-1} yr^{-1}) and no change in survival with increased deposition from 3 to 10 kg N ha^{-1} yr^{-1} in a multi-state gradient study. At a site on Mt. Ascutney in Vermont, live red spruce basal area decreased as fertilization increased N input from 5.4 (bulk deposition) to 21.1 kg ha^{-1} yr^{-1} (McNulty et al. 1996, 2005). These studies indicate the lower critical load for red spruce is >5 and <10 kg N ha^{-1} yr^{-1}, while the upper critical load for red spruce is <21.1 kg ha^{-1} yr^{-1}. The range may be narrowed with further research. Critical load citations and values are shown in Table 14.1.

ABIOTIC MODIFYING FACTORS

Multiple sources were used to set the ranges of modifying factors for red spruce, including the red spruce section of the Forest Service silvics handbook (Blum 1990), the PLANTS database (NRCS 2014), and high importance value data from the Climate Change Atlas (U.S. Forest Service, n.d.). We assumed that in most situations, factors that result in decreased red spruce growth or survival also result in decreased need for N and thus a lower critical load; optimal growth conditions result in an increased demand for N and a higher critical load. General values were used for base saturation, Ca:Al, and biomass removal as described in Chapter 2 (pages 13-14). Graphs showing importance values for abiotic modifying factor ranges by species are in Appendix 1. Optimal and suboptimal growth ranges and weight of evidence values are shown in Table 14.2.

Elevation

We set elevation ranges for the northeastern United States based on basal area dominance at various elevations in the Green Mountains of Vermont as reported by Beckage et al. (2008), as well as on elevation ranges reported for the White Mountains of New Hampshire (Leak and Graber 1974). Growth is expected to be optimal between elevations of about 610 and 1200 m and suboptimal at elevations <610 m and >1200 m.

Aspect

Red spruce is shade tolerant and has medium drought tolerance (NRCS 2014). We associated northeastern aspects with optimal growth and southwestern aspects with suboptimal growth.

Slope Gradient

We used high importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) to set thresholds for slope. Growth for red spruce is expected to be optimal from 0.6 to 8.9 percent.

Average January, July, and May to September Temperatures

Blum (1990) reports an average January temperature range of -18 to -1 °C. July temperatures can range from 11 to 27 °C (Blum 1990). High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to set temperature thresholds. We associated January temperatures from -13.1 to -7.3 °C, July temperatures from 16.5 to 19.5 °C, and May to September temperatures from 13.1 to 15.9 °C with optimal growth and values outside of these ranges with suboptimal growth.

Table 14.1—Effect of nitrogen deposition on red spruce

Location	N deposition range (kg ha^{-1} yr^{-1})	Increased N deposition effects	Citation
Northeastern and Midwestern U.S.	3-10	Slightly decreased growth, no change in survival	Thomas et al. 2010
Adirondacks, NY	<3 to >7	Increased basal area increment along deposition gradient	Bedison and McNeil 2009
Vermont	5.4 (bulk) to 21.1	Decreased red spruce basal area with fertilization	McNulty et al. 1996, 2005

Table 14.2—Abiotic modifying factors for red spruce

Variable	Units	Suboptimal growth range	Optimal growth range	Weight of evidence[a]
Elevation	m	< 610, > 1200	610 to 1200	4
Aspect		southwestern	northeastern	2
Slope gradient	%	< 0.6, > 8.9	0.6 to 8.9	2.7
January temperature	°C	< -13.1, > -7.3	-13.1 to -7.3	3.3
July temperature	°C	< 16.5, > 19.5	16.5 to 19.5	4
May-September temperature	°C	< 13.1, > 15.9	13.1 to 15.9	4
Annual precipitation	mm	< 923, > 1470	923 to 1470	3.3
May-September precipitation	mm	< 438, > 671	438 to 671	3.3
Soil pH		< 4.7, > 5.9	4.7 to 5.9	3.3
Clay	%	< 4.1, > 18.9	4.1 to 18.9	2.7
Coarse sand	%	< 61.8, > 77.8	61.8 to 77.8	3
Permeability	cm hr^{-1}	< 0.6, > 7.1	0.6 to 7.1	2
Depth to bedrock	m	< 0.3	≥ 0.3	3
B-horizon base saturation	%	< 15	≥ 15	2
Soil Ca:Al	mol:mol	< 2	≥ 2	2
Biomass removal		low	high	
Insect pests		abundant	low or absent	
Fungal pathogens		abundant	low or absent	

[a] Refer to Tables 2.2 and 2.3 for description of values.

Annual Precipitation

Reported precipitation ranges include 834 to 2062 mm (U.S. Forest Service, n.d.), 711 to 1321 mm (NRCS 2014), and 910 to 1320 mm (Blum 1990). The high importance value range of 923 to 1470 mm (U.S. Forest Service, n.d.) was associated with optimal growth. We associated values outside of this range with suboptimal growth.

May to September Precipitation

High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to determine thresholds for average May to September precipitation. We associated the precipitation range from 438 to 671 mm with optimal growth and precipitation outside of this range with suboptimal growth.

Soil pH

Reported soil pH ranges for red spruce include 4.0 to 5.5 (Blum 1990), 4.0 to 5.8 (NRCS 2014), and 4.5 to 7.1 (U.S. Forest Service, n.d.). We associated soil pH values of 4.7 to 5.9, the high importance value range from the Climate Change Atlas (U.S. Forest Service, n.d.), with optimal growth and values outside of this range with suboptimal growth.

Percent Clay and Percent Coarse Sand

Red spruce grows on a variety of forest soils. Dominant soil orders are Spodosols, Inceptisols, and Histosols (Blum 1990). High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to set thresholds for percent clay and percent coarse sand. Optimal clay is 4.1 to 18.9 percent; optimal coarse sand is 61.8 to 77.8 percent.

Permeability

Optimal soil permeability from Climate Change Atlas (U.S. Forest Service, n.d.) high importance values range from 0.6 to 7.1 cm hr^{-1}, the rates for moderately slow to moderately rapidly draining clay loams to sandy loams (O'Geen 2012).

Depth to Bedrock

We assigned depth to bedrock values of <0.3 m for suboptimal growth, based on NRCS (2014) minimum rooting depth, and ≥0.3 m for optimal growth.

EXTERNAL INFLUENCES

Insect Pests

We assumed that abundant insect pests correlate with suboptimal growth, while low levels or the absence of insect pests correlate with optimal growth. Spruce budworm (*Choristoneura fumiferana*) is one of the most detrimental pests to red spruce (Blum 1990, Dukes et al. 2009).

Fungal Pathogens

As with insect pests, we assumed that trees weakened by abundant fungal pathogens would have suboptimal growth. Low or absent fungal pathogens would correlate with optimal growth.

15 *PINUS RESINOSA* (RED PINE)

SPECIES RANGE AND CRITICAL LOAD

Red pine, *Pinus resinosa* Ait., grows in southeastern Canada, and in the northeastern and north central United States (Rudolf 1990). Red pine usually grows on dry soils low in fertility. Although it does not grow on alkaline surface soils, it will grow on acid soils overlying limestone or calcareous soils. It prefers cool to warm summers with average temperatures between 16 to 21˚C, and cold winters with temperatures between -18 and -4 ˚C. Precipitation is low to moderate and ranges between 510 to 1010 mm yr^{-1} over much most of its range. Red pine typically occurs between 210 and 400 m in New England and between 945 and 1290 m in the south (Rudolf 1990).

We assigned a critical load of 3 to 10 kg ha^{-1} yr^{-1} for red pine. Thomas et al. (2010) found significantly decreased growth and no change in survival for red pine over a deposition range of 3 to 10 kg N ha^{-1} yr^{-1}. Critical load citations and values are shown in Table 15.1.

ABIOTIC MODIFYING FACTORS

Multiple sources were used to set the ranges of modifying factors for red pine, including the red pine section of the Forest Service silvics handbook (Rudolf 1990), the PLANTS database (NRCS 2014), and high importance value data from the Climate Change Atlas (U.S. Forest Service, n.d.). In general, any factor that inhibits red pine growth would be expected to result in a decreased need for N and thus a lower critical load; optimal growth conditions result in an increased demand for N and a higher critical load General values were used for base saturation, Ca:Al, and biomass removal as described in Chapter 2 (pages 13-14). Graphs showing importance values for abiotic modifying factor ranges by species are in Appendix 1. Optimal and suboptimal growth ranges and weight of evidence values are shown in Table 15.2.

Elevation

Elevation effects depend on latitude. We set elevation ranges for the northeastern United States based on elevations reported in the Forest Service silvics handbook (Rudolf 1990). Red pine growth is expected to be optimal between elevations of 210 and 820 m.

Aspect

Red pine is intolerant of shade and moderately drought tolerant (NRCS 2014). We associated southwestern aspects with optimal growth and northeastern aspects with suboptimal growth.

Slope Gradient

We used high importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) to set thresholds for slope. Growth for red pine is expected to be optimal from 0 to 3.7 percent.

Average January, July, and May to September Temperatures

Rudolph (1990) reports an average January temperature range of -18 to -4 ˚C and an average July temperature range of 16 to 21 ˚C. High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to set temperature thresholds. We associated January temperatures from -12.7 to -5.3 ˚C, July temperatures from 19.2 to 22.6 ˚C, and May to September temperatures from 15.5 to 19.4 ˚C with optimal growth and values outside of these ranges with suboptimal growth.

Annual Precipitation

Reported precipitation ranges include 542 to 1476 mm (U.S. Forest Service, n.d.), 381 to 1524 mm (NRCS 2014), and 510 to 1520 mm, with a main range of 510 to 1010 mm (Rudolf 1990). The high importance value range of 724 to 942 mm (U.S. Forest Service, n.d.) was associated with optimal growth. Values outside of this range were associated with suboptimal growth.

May to September Precipitation

High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to determine thresholds for average May to September precipitation. We associated the precipitation range from 388 to 508 mm with optimal growth and precipitation outside of this range with suboptimal growth.

Table 15.1—Effect of nitrogen deposition on red pine

Location	N deposition range ($kg\ ha^{-1}\ yr^{-1}$)	Increased N deposition effects	Citation
Northeastern and Midwestern U.S.	3 to 10	Significantly decreased growth; no change in survival	Thomas et al. 2010

Table 15.2—Abiotic modifying factors for red pine

Variable	Units	Suboptimal growth range	Optimal growth range	Weight of evidence[a]
Elevation	m	< 210, > 820	210 to 820	3
Aspect		northeastern	southwestern	2
Slope gradient	%	> 3.7	0.0 to 3.7	3
January temperature	°C	< -12.7, > -5.3	-12.7 to -5.3	3.7
July temperature	°C	< 19.2, > 22.6	19.2 to 22.6	3.7
May-September temperature	°C	< 15.5, > 19.4	15.5 to 19.4	3.7
Annual precipitation	mm	< 724, > 942	724 to 942	4
May-September precipitation	mm	< 388, > 508	388 to 508	4
Soil pH		< 5.4, > 7.3	5.4 to 7.3	3.3
Clay	%	< 3.3, > 32.5	3.3 to 32.5	2.3
Coarse sand	%	< 62.3, > 96.9	62.3 to 96.9	3
Permeability	$cm\ hr^{-1}$	< 1.0, > 13.0	1.0 to 13.0	1.7
Depth to bedrock	m	< 1.0	≥ 1.0	3
B-horizon base saturation	%	< 15	≥ 15	2
Soil Ca:Al	mol:mol	< 2	≥ 2	2
Biomass removal		low	high	
Insect pests		abundant	low or absent	
Fungal pathogens		abundant	low or absent	

[a] Refer to Tables 2.2 and 2.3 for description of values.

Soil pH

Reported soil pH ranges include 4.5 to 6.0 (NRCS 2014, Rudolf 1990). Pot experiments indicate that ideal growth occurs at pH 5.5, with growth inhibitions at pH 7.5 (Liu et al. 2009). We associated soil pH values of 5.4 to 7.3, from the high importance value range in the Climate Change Atlas (U.S. Forest Service, n.d.), with optimal growth and values outside of this range with suboptimal growth. Further research may be needed to verify the upper end of the range.

Percent Clay and Percent Coarse Sand

Red pine is commonly found on dry soils with low fertility. Dominant soil orders are Entisols, Spodosols, Alfisols, and Inceptisols. High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to set thresholds for percent clay and percent coarse sand. Optimal clay is 3.3 to 32.5 percent; optimal coarse sand is 62.3 to 96.9 percent.

Permeability

Optimal soil permeability from Climate Change Atlas (U.S. Forest Service, n.d.) high importance values range from 1.0 to 13.0 $cm\ hr^{-1}$, the rates for moderately slow to rapidly draining clay loams to loamy sands (O'Geen 2012).

Depth to Bedrock

We have assigned depth to bedrock values of <1.0 m for suboptimal growth, based on minimum rooting depth (NRCS 2014), and ≥1.0 m for optimal growth.

EXTERNAL INFLUENCES

Insect pests

We assumed that an abundance of insect pests correlates with suboptimal growth, while low or absent levels of insect pests correlate with optimal growth.

Fungal Pathogens

As with insect pests, we assumed that trees weakened by abundant fungal pathogens would have suboptimal growth. Low or absent levels of fungal pathogens would correlate with optimal growth.

16 *PINUS RIGIDA* (PITCH PINE)

SPECIES RANGE AND CRITICAL LOAD

Pitch pine, *Pinus rigida* Mill., grows in southeastern New England and south along the Appalachian Mountain range. Pitch pine usually grows on shallow sandy or gravelly soils low in fertility with a pH range of 3.5 to 5.1 (Little and Garrett 1990). It prefers a humid climate with warm summers and cool winters. Precipitation is moderate and ranges between 940 to 1420 mm yr^{-1} over much of its range. Pitch pine typically occurs below 610 m in New York and between 430 and 1370 m in the south. In hilly sections, pitch pine occurs on southern and western exposures (Little and Garrett 1990).

We assigned a critical load of 3 to 10 kg ha^{-1} yr^{-1} for pitch pine, based on red pine response to N deposition in Thomas et al (2010). Thomas et al. (2010) found significantly decreased growth and no change in survival for red pine over a deposition range of 3 to 10 kg N ha^{-1} yr^{-1}. Critical load citations and values are shown in Table 16.1.

ABIOTIC MODIFYING FACTORS

Multiple sources were used to set the ranges of modifying factors for pitch pine, including the pitch pine section of the Forest Service silvics handbook (Little and Garrett 1990) and high importance value data from the Climate Change Atlas (U.S. Forest Service, n.d.). In general, any factor that inhibits pitch pine growth would be expected to result in a decreased need for N and thus a lower critical load; optimal growth conditions result in an increased demand for N and a higher critical load. General values were used for base saturation, Ca:Al, and biomass removal as described in Chapter 2 (pages 13-14). Graphs showing importance values for abiotic modifying factor ranges by species are in Appendix 1. Optimal and suboptimal growth ranges and weight of evidence values are shown in Table 16.2.

Elevation

Elevation effects depend on latitude. We set elevation ranges for the northeastern United States based on elevations reported in Little and Garrett (1990). Pitch pine growth is expected to be optimal below 610 m in elevation.

Aspect

Pitch pine occurs on southern and western exposures in hilly sections (Little and Garrett 1990). We associated southwestern aspects with optimal growth and northeastern aspects with suboptimal growth.

Slope Gradient

High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to set thresholds for slope. We expect growth for pitch pine to be optimal from 0.0 to 5.6 percent.

Average January, July, and May to September Temperatures

High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to set temperature thresholds. We associated January temperatures from -2.5 to -0.3 °C, July temperatures from 21.6 to 24.4°C, and May to September temperatures from 18.3 to 21.2 °C with optimal growth and values outside of these ranges with suboptimal growth.

Annual Precipitation

Reported precipitation ranges for pitch pine include 815 to 2289 mm (U.S. Forest Service, n.d.) and 940 to 1420 mm (Little and Garett 1990). We set the high importance value range of 1045 to 1203 mm (U.S. Forest Service, n.d.) with optimal growth. Values outside of this range were associated with suboptimal growth.

May to September Precipitation

High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to determine thresholds for average May to September precipitation. We associated the precipitation range from 435 to 525 mm with optimal growth and precipitation outside of this range with suboptimal growth.

Table 16.1—Effect of nitrogen deposition on pitch pine

Location	N deposition range ($kg\ ha^{-1}\ yr^{-1}$)	Increased N deposition effects	Citation
Northeastern, Midwestern U.S.	3 to 10 (for red pine)	Significantly decreased growth; no change in survival	Thomas et al. 2010

Table 16.2—Abiotic modifying factors for pitch pine

Variable	Units	Suboptimal growth range	Optimal growth range	Weight of evidence[a]
Elevation	m	> 610	≤ 610	3
Aspect		northeastern	southwestern	2
Slope gradient	%	> 5.6	0.0 to 5.6	2.3
January temperature	°C	< -2.5, > -0.3	-2.5 to -0.3	3.7
July temperature	°C	< 21.6, > 24.4	21.6 to 24.4	3.7
May-September temperature	°C	< 18.3, > 21.2	18.3 to 21.2	3.7
Annual precipitation	mm	< 1045, > 1203	1045 to 1203	3.7
May-September precipitation	mm	< 435, > 525	435 to 525	3.7
Soil pH		< 4.5, > 4.9	4.5 to 4.9	3
Clay	%	< 2.4, > 16.9	2.4 to 16.9	2
Coarse sand	%	< 60.0, > 87.9	60.0 to 87.9	2.7
Permeability	$cm\ hr^{-1}$	< 5.8, > 15.9	5.8 to 15.9	1.3
Depth to bedrock	m	< 1.0	≥ 1.0	3
B-horizon base saturation	%	< 15	≥ 15	2
Soil Ca:Al	mol:mol	< 2	≥ 2	2
Biomass removal		low	high	
Insect pests		abundant	low or absent	
Fungal pathogens		abundant	low or absent	

[a] Refer to Tables 2.2 and 2.3 for description of values.

Soil pH

Little and Garrett (1990) report that pitch pine is typically found on soils with pH of 3.5 to 5.1. We associated soil pH values of 4.5 to 4.9, the high importance value range from the Climate Change Atlas (U.S. Forest Service, n.d.), with optimal growth and values outside of this range with suboptimal growth.

Percent Clay and Percent Coarse Sand

Pitch pine growth is typically restricted to shallow, coarse, sandy soils. Dominant soil orders are Spodosols, Alfisols, Entisols, and Ultisols (Little and Garett 1990). High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to set thresholds for percent clay and percent coarse sand. Optimal clay is 2.4 to 16.9 percent; optimal coarse sand is 60.0 to 87.9 percent.

Permeability

Optimal soil permeability from Climate Change Atlas (U.S. Forest Service, n.d.) high importance values range from 5.8 to 15.9 cm hr^{-1}, rates for moderately to rapidly draining very fine sandy loams to loamy sand (O'Geen 2012).

Depth to Bedrock

Because pitch pine does not have an extensive entry in the PLANTS database (NRCS 2014), we assigned depth to bedrock values based on red pine. Depth to bedrock of <1.0 m is associated with suboptimal growth, while values ≥ 1.0 m are associated with optimal growth.

EXTERNAL INFLUENCES

Insect Pests

We assumed that having an abundance of insect pests correlates with suboptimal growth, while low or absent levels of insect pests correlate with optimal growth.

Fungal Pathogens

As with insect pests, we assumed that trees weakened by abundant fungal pathogens would have suboptimal growth. Low or absent levels of fungal pathogens would correlate with optimal growth.

17 *PINUS STROBUS* (EASTERN WHITE PINE)

SPECIES RANGE AND CRITICAL LOAD

Eastern white pine, *Pinus strobus* L., grows in southeastern Canada and in the northeastern and north central United States south to the Appalachian Mountains (Wendel and Smith 1990). Eastern white pine can grow on a great variety of soils, but competes best on well drained, sandy soils with low to medium quality. It grows poorly on heavy clay soils and poorly drained bottomlands. July temperatures in the white pine growing region range from 18 to 23 °C; precipitation ranges from 510 to 2030 mm. White pine grows from sea level to 460 m or sometimes higher in the north, and from 370 to 1070 m in the Appalachians (Wendel and Smith 1990).

We assigned a critical load of 5 to 9.5 kg N ha^{-1} yr^{-1} for eastern white pine, based on Thomas et al. (2010), which found slightly increased growth and slightly decreased survival for eastern white pine over a deposition range of 5 to 9.5 kg N ha^{-1} yr^{-1}. Critical load citations and values are shown in Table 17.1.

ABIOTIC MODIFYING FACTORS

Multiple sources were used to set the ranges of modifying factors for eastern white pine, including the eastern white pine section of the Forest Service silvics handbook (Wendel and Smith 1990), the PLANTS database (NRCS 2014), and high importance value data from the Climate Change Atlas (U.S. Forest Service, n.d.). In general, any factor that inhibits eastern white pine growth would be expected to result in a decreased need for N and thus a lower critical load; optimal growth conditions result in an increased demand for N and a higher critical load. General values were used for base saturation, Ca:Al, and biomass removal as described in Chapter 2 (pages 13-14). Graphs showing importance values for abiotic modifying factor ranges by species are in Appendix 1. Optimal and suboptimal growth ranges and weight of evidence values are shown in Table 17.2.

Elevation

Elevation effects depend on latitude. We set elevation ranges for the northeastern United States based on elevations reported in the Forest Service silvics handbook (Wendel and Smith 1990). Eastern white pine growth is expected to be optimal below 460 m and suboptimal at higher elevations.

Aspect

Eastern white pine has intermediate shade tolerance and no drought tolerance (NRCS 2014). In Pennsylvania and the southern Appalachians, white pine is found on northerly aspects (Wendel and Smith 1990). We associated northeastern aspects with optimal growth and southwestern aspects with suboptimal growth.

Slope Gradient

We used high importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) to set thresholds for slope. Growth for eastern white pine is expected to be optimal from 0.2 to 10.4 percent.

Average January, July, and May to September Temperatures

According to Wendel and Smith (1990), eastern white pine prefers cool, humid climates. Average July temperatures range from 18 to 23 °C. High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to set temperature thresholds. We associated January temperatures from -9.6 to 1.9 °C, July temperatures from 19.3 to 23.8 °C, and May to September temperatures from 15.8 to 21.4 °C with optimal growth, and values outside of these ranges with suboptimal growth.

Annual Precipitation

Precipitation ranges for eastern white pine include 556 to 2289 mm (U.S. Forest Service, n.d.), 508 to 2030 mm (NRCS 2014), and 510 to 2030 mm (Wendel and Smith 1990). We associated the Climate Change Atlas high importance value range of 814 to 1364 mm with optimal growth. Values outside of this range were associated with suboptimal growth.

May to September Precipitation

High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to determine thresholds for average May to September precipitation.

Table 17.1—Effect of nitrogen deposition on eastern white pine

Location	N deposition range (kg ha^{-1} yr^{-1})	Increased N deposition effects	Citation
Northeastern, Midwestern U.S.	5 to 9.5	Slightly increased growth; slightly decreased survival	Thomas et al. 2010

Table 17.2—Abiotic modifying factors for eastern white pine

Variable	Units	Suboptimal growth range	Optimal growth range	Weight of evidence[a]
Elevation	m	> 460	≤ 460	3
Aspect		southwestern	northeastern	2
Slope gradient	%	< 0.2, > 10.4	0.2 to 10.4	3.7
January temperature	°C	< -9.6, > 1.9	-9.6 to 1.9	4
July temperature	°C	< 19.3, > 23.8	19.3 to 23.8	4.3
May-September temperature	°C	< 15.8, > 21.4	15.8 to 21.4	4.3
Annual precipitation	mm	< 814, > 1364	814 to 1364	3.7
May-September precipitation	mm	< 417, > 590	417 to 590	3.7
Soil pH		< 4.9, > 7.1	4.9 to 7.1	3
Clay	%	< 2.6, > 32.8	2.6 to 32.8	2.7
Coarse sand	%	< 57.1, > 95.3	57.1 to 95.3	3
Permeability	cm hr^{-1}	< 0.8, > 13.2	0.8 to 13.2	2
Depth to bedrock	m	< 1.0	≥ 1.0	3
B-horizon base saturation	%	< 15	≥ 15	2
Soil Ca:Al	mol:mol	< 2	≥ 2	2
Biomass removal		low	high	
Insect pests		abundant	low or absent	
Fungal pathogens		abundant	low or absent	

[a] Refer to Tables 2.2 and 2.3 for description of values.

We associated the precipitation range from 417 to 590 mm with optimal growth and precipitation outside of this range with suboptimal growth.

Soil pH

Reported soil pH ranges for eastern white pine include 4 to 6.5 (NRCS 2014) and 4.1 to 7.8 (U.S. Forest Service, n.d.). We associated soil pH values of 4.9 to 7.1, from Climate Change Atlas high importance values (U.S. Forest Service, n.d.), with optimal growth. Values outside of this range were associated with suboptimal growth.

Percent Clay and Percent Coarse Sand

Eastern white pine competes best on well drained sandy soils with low to medium site quality. The species can be found on Inceptisols, Ultisols, Spodosols, Entisols, and Alfisols (Wendel and Smith 1990). We used high importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) to set thresholds for percent clay and percent coarse sand. Optimal clay is 2.6 to 32.8 percent; optimal coarse sand is 57.1 to 95.3 percent.

Permeability

Optimal soil permeability from Climate Change Atlas (U.S. Forest Service, n.d.) high importance values range from 0.8 to 13.2 cm hr^{-1}, the rates for moderately slow to rapidly draining clay loams to loamy sands (O'Geen 2012).

Depth to Bedrock

We assigned depth to bedrock values of <1.0 m for suboptimal growth, based on minimum rooting depth (NRCS 2014), and values ≥1.0 m for optimal growth. Rooting restrictions at <50 cm in Maine resulted in reductions in sapwood area and diameter breast height for white pine (Granger 2004) and may predispose white pine to decline. This indicates that at least 50 cm of unrestricted rooting should be available to white pine, and depths of 1.0 m may be deeper than necessary.

EXTERNAL INFLUENCES

Insect Pests

We assumed that an abundance of insect pests correlate with suboptimal growth, while low or absent levels of insect pests correlate with optimal growth.

Fungal Pathogens

As with insect pests, we assumed that trees weakened by abundant fungal pathogens would have suboptimal growth. Low or absent levels of fungal pathogens would correlate with optimal growth. White pine blister rust (*Cronartium ribicola*) is the most damaging fungal disease of white pine (Wendel and Smith 1990). Wet weather, especially in the spring, may exacerbate fungal diseases (University of New Hampshire 2012).

18 *POPULUS GRANDIDENTATA* (BIGTOOTH ASPEN)

SPECIES RANGE AND CRITICAL LOAD

Bigtooth aspen, *Populus grandidentata* Michx., grows in southeastern Canada and northeastern and north central United States (Laidly 1990). Although aspen can grow on a variety of soils, it grows best in moist, well drained, loamy and sandy soils that are high in organic matter and nutrients (Laidly 1990). Good soil aeration is important to bigtooth aspen growth. It grows in regions with a January average temperature range of -18 to 2 °C and a July temperature range of 16 to 26 °C, with 510 to 1270 mm annual precipitation. It is most abundant on floodplains and lower slopes between 150 and 610 m (Laidly 1990).

We assigned a critical load of 3 to 11 kg N $ha^{-1} yr^{-1}$ for bigtooth aspen. Thomas et al. (2010) found no change in growth but steadily decreasing survival for bigtooth aspen between 3 and 11 kg N $ha^{-1} yr^{-1}$. Critical load values and citations for bigtooth aspen are shown in table 18.1.

ABIOTIC MODIFYING FACTORS

Multiple sources were used to set the ranges of modifying factors for bigtooth aspen, including the bigtooth aspen section of the Forest Service silvics handbook (Laidly 1990), the PLANTS database (NRCS 2014), and high importance value data from the Climate Change Atlas (U.S. Forest Service, n.d.). In general, any factor that inhibits aspen growth would be expected to result in a decreased need for N and thus a lower critical load; optimal growth conditions result in an increased demand for N and a higher critical load. General values were used for base saturation, Ca:Al, and biomass removal as described in Chapter 2 (pages 13-14). Graphs showing importance values for abiotic modifying factor ranges by species are in Appendix 1. Optimal and suboptimal growth ranges and weight of evidence values are shown in Table 18.2.

Elevation

We set elevation ranges for the northeastern United States based on elevation limits described in the Forest Service silvics handbook (Laidly 1990). For this species, we associated elevations from 150 to 610 m with optimal growth and elevations outside of this range with suboptimal growth.

Aspect

Because aspen is both drought intolerant and shade intolerant, it is not clear which aspect is most favorable to growth. For this reason we have not associated aspect with growth for this species.

Slope Gradient

We used high importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) to set thresholds for slope. Growth for bigtooth aspen is expected to be optimal from 0 to 4.3 percent.

Average January, July, and May to September Temperatures

Reported temperature ranges include a January temperature range of -18 to 2 °C and a July temperature range of 16 to 26 °C (Laidly 1990). High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) are within this range, and we used them to set optimal values. Optimal January temperature is set as -13.0 to -4.9 °C, the July temperature range is 19.3 to 22.3 °C, and the May to September temperature range is 15.6 to 19.2 °C. Temperatures outside of these ranges are associated with suboptimal growth.

Annual Precipitation

The Climate Change Atlas (U.S. Forest Service, n.d.) provides a range from 475 to 1579 mm for annual precipitation for bigtooth aspen, with a high importance value range of 725 to 1005 mm. This range is associated with optimal growth and is similar to the optimal range of 799 to 1069 reported in Laidly (1990). We associated 725 to 1005 mm of precipitation with optimal growth. Values outside of this range were associated with suboptimal growth.

May to September Precipitation

High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to determine thresholds for average May to September precipitation.

Table 18.1—Effect of nitrogen deposition on bigtooth aspen

Location	N deposition range ($kg\ ha^{-1}\ yr^{-1}$)	Increased N deposition effects	Species	Citation
Northeastern, Midwestern U.S.	3 to 11	No change in growth; decreased survival	Bigtooth aspen	Thomas et al. 2010

Table 18.2—Abiotic modifying factors for bigtooth aspen

Variable	Units	Suboptimal growth range	Optimal growth range	Weight of evidence[a]
Elevation	m	< 150, > 610	150 to 610	3
Aspect		N/A	N/A	
Slope gradient	%	> 4.3	0.0 to 4.3	3
January temperature	°C	< -13.0, > -4.9	-13.0 to -4.9	3.7
July temperature	°C	< 19.3, > 22.3	19.3 to 22.3	3.7
May-September temperature	°C	< 15.6, > 19.2	15.6 to 19.2	3.7
Annual precipitation	mm	< 725, > 1005	725 to 1005	3.7
May-September precipitation	mm	< 386, > 499	386 to 499	4
Soil pH		< 5.4, > 7.3	5.4 to 7.3	3
Clay	%	< 3.1, > 31.8	3.1 to 31.8	2.3
Coarse sand	%	< 71.7, > 95.1	71.7 to 95.1	2.7
Permeability	$cm\ hr^{-1}$	< 1.0, > 13.0	1.0 to 13.0	2
Depth to bedrock	m	< 0.8	≥ 0.8	3
B-horizon base saturation	%	< 15	≥ 15	2
Soil Ca:Al	mol:mol	< 2	≥ 2	2
Biomass removal		low	high	
Insect pests		abundant	low or absent	
Fungal pathogens		abundant	low or absent	

[a] Refer to Tables 2.2 and 2.3 for description of values.

We associated the precipitation range from 386 to 499 mm with optimal growth and precipitation outside of this range with suboptimal growth.

Soil pH

Neither NRCS (2014) nor Laidly (1990) report a pH range associated with bigtooth aspen. Quaking aspen, a close relative, has a reported pH range of 4.3 to 9.0 (NRCS 2014). We associated soil pH values of 5.4 to 7.3, the high importance values from the Climate Change Atlas (U.S. Forest Service, n.d.), with optimal growth and values outside of this range with suboptimal growth.

Percent Clay and Percent Coarse Sand

Bigtooth aspen grows best on moist, fertile sands and sandy loams and is most often found on Spodosols, Alfisols, and Inceptisols (Laidly 1990). We used high importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) to set thresholds for percent clay and percent coarse sand. Optimal clay is 3.1 to 31.8 percent; optimal coarse sand is 71.7 to 95.1 percent.

Permeability

Optimal soil permeability from Climate Change Atlas (U.S. Forest Service, n.d.) high importance values range from 1.0 to 13.0 cm hr^{-1}, the rates for moderately slow to rapidly draining clay loams to loamy sands (O'Geen 2012).

Depth to Bedrock

We assigned depth to bedrock values of <0.8 m for suboptimal growth, based on minimum rooting depth for quaking aspen (NRCS 2014), and ≥0.8 m for optimal growth.

EXTERNAL INFLUENCES

Insect Pests

We assumed that an abundance of insect pests correlates with suboptimal growth, while low levels or the absence of insect pests correlate with optimal growth.

Fungal Pathogens

As with insect pests, we assumed that trees weakened by abundant fungal pathogens would have suboptimal growth. Low levels or the absence of fungal pathogens would correlate with optimal growth. Hypoxylon canker is the one of the most lethal fungal diseases of aspen in North America; moisture stress, clone variety, and stand density are among the factors influencing canker incidence and mortality. Fertilization with N, P, K did not have a significant effect on canker incidence (Ostry 2013).

19 *POPULUS TREMULOIDES* (QUAKING ASPEN)

SPECIES RANGE AND CRITICAL LOAD

Quaking (or trembling) aspen, *Populus tremuloides* Michx., grows across a broad swath of Canada and the northern United States and can be found in mountainous regions through most of the United States, extending down into the mountains of Mexico. Although aspen can grow on a variety of soils, it grows best in moist, well drained, loamy soils that are high in organic matter and nutrients (Perala 1990). In a Canadian study across multiple sites, moist, nutrient rich soil resulted in the highest aspen site index (Chen et al. 2002). Growth on sandy soils lacking moisture and nutrients is usually poor; heavy, clayey soils also limit aspen growth. It occurs at elevations up to 910 m in the north and as high as 3050 m in Arizona. Growth is best on aspects where moisture conditions are most favorable; this varies across the county. In the southwestern United States, northern aspects are more favorable, while in Alaska and western Canada, southwestern and western aspects are more favorable (Perala 1990).

Recent research indicates that quaking aspen dieback in multiple regions in North America is the result of drought stress and various secondary factors, including insect and fungal infestations (Frey et al. 2004, Worrall 2013). Increasing temperatures and decreasing growing season precipitation resulted in decreased suitable habitat, especially in marginal areas such as shallow soils over bedrock. In the western United States, factors that can exacerbate moisture stress include low elevations, upper slope positions, southwestern aspects, poor climatic suitability, stand stocking, age, and poor soils (Worrall et al. 2013). Increased ozone (O_3) has also been found to depress growth of some aspen clones (Moran and Kubiske 2013, Wang et al. 1986). It may be hard to differentiate the effects of multiple atmospheric pollutants on aspen growth and mortality.

We assigned a critical load of 5 to 9 kg N ha^{-1} yr^{-1} for aspen. Thomas et al. (2010) found decreased survival and increased growth for quaking aspen over a deposition range of 3 to 11 N kg ha^{-1} yr^{-1}; peak growth occurred around 7 kg N ha^{-1} yr^{-1}. The critical load for growth, when accounting for variability, is 5 to 9 kg N ha^{-1} yr^{-1}. The critical load source is shown in Table 19.1.

ABIOTIC MODIFYING FACTORS

Multiple sources were used to set the ranges of modifying factors for aspen, including the aspen section of the Forest Service silvics handbook (Perala 1990), the PLANTS database (NRCS 2014), and high importance value data from the Climate Change Atlas (U.S. Forest Service, n.d.). In general, any factor that inhibits aspen growth would be expected to result in a decreased need for N and thus a lower critical load; optimal growth conditions result in an increased demand for N and a higher critical load. General values were used for base saturation, soil Ca:Al, and biomass removal as described in Chapter 2 (pages 13-14). Graphs showing importance values for abiotic modifying factor ranges by species are in Appendix 1. Optimal and suboptimal growth ranges and weight of evidence values are shown in Table 19.2.

Elevation

We set elevation ranges for the northeastern United States based on elevation limits described in the Forest Service silvics handbook (Perala 1990). Growth is expected to be optimal below 910 m in the northeastern United States and suboptimal at higher elevations.

Aspect

Because aspen is both drought intolerant and shade intolerant, it is not clear which aspect is most favorable to growth. For this reason, we did not associate aspect with growth for this species.

Slope Gradient

We used high importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) to set thresholds for slope. Growth for quaking aspen is expected to be optimal from 0.0 to 3.5 percent.

Average January, July, and May to September Temperatures

Quaking aspen grows in areas with an average January temperature range of -30 to -3 °C and an average July temperature range of 16 to 23 °C (Perala 1990). The Climate Change Atlas data (U.S. Forest Service, n.d.) does not include the entire range for quaking aspen. The optimal temperature thresholds in this report, set

Table 19.1—Effect of nitrogen deposition on quaking aspen

Location	N deposition range ($kg\ ha^{-1}\ yr^{-1}$)	Increased N deposition effects	Citation
Northeastern, Midwestern U.S.	3 to 11	Increased growth, with peak at 7 $kg\ N\ ha^{-1}\ yr^{-1}$; decreased survival	Thomas et al. 2010

Table 19.2—Abiotic modifying factors for quaking aspen

Variable	Units	Suboptimal growth range	Optimal growth range	Weight of evidence[a]
Elevation	m	> 910	≤ 910	3
Aspect		N/A	N/A	
Slope gradient	%	> 3.5	0.0 to 3.5	4
January temperature	°C	< -16.8, > -6.8	-16.8 to -6.8	4
July temperature	°C	< 18.6, > 22.0	18.6 to 22.0	4.3
May-September temperature	°C	< 14.8, > 18.4	14.8 to 18.4	5
Annual precipitation	mm	< 544, > 895	544 to 895	5
May-September precipitation	mm	< 373, > 514	373 to 514	4.3
Soil pH		< 4.9, > 7.7	4.9 to 7.7	4.3
Clay	%	< 3.6, > 38.8	3.6 to 38.8	4.3
Coarse sand	%	< 65.4, > 95.8	65.4 to 95.8	3.7
Permeability	$cm\ hr^{-1}$	< 0.8, > 12.2	0.8 to 12.2	3.7
Depth to bedrock	m	< 0.8	≥ 0.8	3
B-horizon base saturation	%	< 15	≥ 15	2
Soil Ca:Al	mol:mol	< 2	≥ 2	2
Biomass removal		low	high	
Insect pests		abundant	low or absent	
Fungal pathogens		abundant	low or absent	

[a] Refer to Tables 2.2 and 2.3 for description of values.

using high importance values from the Climate Change Atlas, apply to quaking aspen in the eastern United States. We associated January temperatures from -16.8 to -6.8 °C, July temperatures from 18.6 to 22.0 °C, and May to September temperatures from 14.8 to 18.4 °C with optimal growth and values outside of these ranges with suboptimal growth.

Annual Precipitation

Reported precipitation ranges for quaking aspen include 427 to 1800 mm (U.S. Forest Service, n.d.), 178 to 1524 mm (NRCS 2014), and 410 to 1020 mm (Perala 1990). The high importance value range of 544 to 895 mm (U.S. Forest Service, n.d.) was associated with optimal growth. Values outside of this range were associated with suboptimal growth.

Stand factors can influence the effect of precipitation on aspen mortality. For example, Bell et al. (2014) found that stands with high aspen density and low stand age were more susceptible to mortality as a result of decreasing winter precipitation.

May to September Precipitation

High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to determine thresholds for average May to September precipitation. We associated the precipitation range from 373 to 514 mm with optimal growth and precipitation outside of this range with suboptimal growth.

Soil pH

Reported soil pH values for quaking aspen include 4.3 to 9.0 (NRCS 2014) and 4.5 to 8.1 (U.S Forest Service, n.d.). We associated soil pH values of 4.9 to 7.7, the high importance value range from the Climate Change Atlas (U.S. Forest Service, n.d.), with optimal growth and values outside of this range with suboptimal growth.

Percent Clay and Percent Coarse Sand

Quaking aspen growth is best on soils that are well drained, loamy, and high in organic matter, calcium, magnesium, potassium, and nitrogen. Dominant soil orders are Alfisols, Spodosols, and Inceptisols (Perala 1990). We used high importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) to set thresholds for percent clay and percent coarse sand. Optimal clay is 3.6 to 38.8 percent; optimal coarse sand is 65.4 to 95.8 percent.

Permeability

Optimal soil permeability from Climate Change Atlas (U.S. Forest Service, n.d.) high importance values range from 0.8 to 12.2 cm hr^{-1}, the rates for moderately slow to moderately rapidly draining clay loams to sandy loams (O'Geen 2012).

Depth to Bedrock

We assigned depth to bedrock values of <0.8 m for suboptimal growth, based on minimum rooting depth (NRCS 2014), and ≥0.8 m for optimal growth.

EXTERNAL INFLUENCES

Insect pests

We assumed an abundance of insect pests correlates with suboptimal growth, while low levels or the absence of insect pests correlate with optimal growth. Increased nitrogen content in leaves may increase insect pest populations. In the great lakes, forest tent caterpillar *(Malacosoma disstria* Hübner) pupal weight was positively correlated with higher nitrogen content in quaking aspen leaves (Hemming and Lindroth 1995).

Fungal Pathogens

As with insect pests, we assumed that trees weakened by an abundance of fungal pathogens would have suboptimal growth. Low or absent levels of fungal pathogens would correlate with optimal growth. Hypoxylon canker is one of the most lethal fungal diseases of aspen in North America; moisture stress, clone variety, and stand density are among the factors influencing canker incidence and mortality. Fertilization with N, P, K did not have a significant effect on canker incidence (Ostry 2013).

20 *QUERCUS ALBA* (WHITE OAK)

SPECIES RANGE AND CRITICAL LOAD

White oak, *Quercus alba* L., is found in most of the eastern United States, as well as in extremely southern parts of eastern Canada. It grows on sandy plains, gravelly ridges, fertile uplands, and well drained loams, growing well on all but the driest and shallowest soils. Average temperatures range from 7 to 21 °C, while precipitation ranges from 760 to 2030 mm yr^{-1} (Rogers 1990). White oak can be found below 150 m in the north, and as a scrub tree at 1350 m in the southern Appalachians, with best growth in lower slopes and coves with northerly or easterly aspects. White oak is more abundant, but smaller, on west and south facing slopes. Oak wilt and golden oak scale are the most serious threat to white oak health (Rogers 1990).

We assigned a critical load of 11 to 18 kg ha^{-1} yr^{-1} for white oak. Thomas et al. (2010) found no change in growth or survival for white oak between 3 to 11 kg N ha^{-1} yr^{-1}. Elias (2008) found decreased basal area for oak with N deposition between 12 and 14 kg ha^{-1} yr^{-1}, while Dietz and Moorcroft (2011) found increased mortality for northern mid successional hardwoods with increasing N deposition; visual inspection of supplementary material indicate that mortality was lowest from 5 to 16 kg ha^{-1} yr^{-1} wet N deposition (7 to 18 kg ha^{-1} yr^{-1} wet + dry N).We used the upper end of the range from Thomas et al. (2010) and the upper end of the range from Dietz and Moorcroft (2011) to set the critical load. Critical load values and citations are shown in Table 20.1.

ABIOTIC MODIFYING FACTORS

Multiple sources were used to set the ranges of modifying factors for white oak, including the white oak section of the Forest Service silvics handbook (Rogers 1990), the PLANTS database (NRCS 2014), and high importance value data from the Climate Change Atlas (U.S. Forest Service, n.d.). In general, any factor that inhibits white oak growth would be expected to result in a decreased need for N and thus a lower critical load; optimal growth conditions result in an increased demand for N and a higher critical load. General values were used for base saturation, Ca:Al, and biomass removal as described in Chapter 2 (pages 13-14). Graphs showing importance values for abiotic modifying factor ranges by species are in Appendix 1. Optimal and suboptimal growth ranges and weight of evidence values are shown in Table 20.2.

Elevation

We based optimal elevation for white oak on information from Rogers (1990). Growth is expected to be optimal below 150 m in elevation and suboptimal at higher elevations.

Aspect

According to Rogers (1990), white oak trees grow best on northern and eastern exposures. They have intermediate shade tolerance and medium drought tolerance (NRCS 2014). We associated northeastern exposures with optimal growth and southwestern exposures with suboptimal growth.

Slope Gradient

We used high importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) to set thresholds for slope. Growth for white oak is expected to be optimal from 0.1 to 9.4 percent.

Average January, July, and May to September Temperatures

High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to set temperature thresholds. We associated January temperatures from -9.7 to 3.8 °C, July temperatures from 21.5 to 26.5 °C, and May to September temperatures from 18.0 to 23.7 °C with optimal growth, and values outside of these ranges with suboptimal growth.

Annual precipitation

Reported precipitation ranges include 465 to 2289 mm (U.S. Forest Service, n.d.), 762 to 2030 mm (NRCS 2014), and 760 to 2030 mm, with an ideal value of 1020 mm (Rogers 1990). We associated the high importance value range of 808 to 1450 mm (U.S. Forest Service, n.d.) with optimal growth. Values outside of this range were associated with suboptimal growth.

Table 20.1—Effect of nitrogen deposition on white oak

Location	N deposition range (kg ha^{-1} yr^{-1})	Increased N deposition effects	Interacting factors	Citation
Northeastern and Midwestern U.S.	3 to 11	No change in growth or survival		Thomas et al. 2010
West Virginia	12 to 14	Decreased basal area	S deposition 20-26 kg ha^{-1} yr^{-1}	Elias 2008
Eastern and Central U.S.	5 to 18 (wet NO_3) (5 to 16 lowest mortality)	Increased mortality probability		Dietze and Moorcroft 2011

Table 20.2—Abiotic modifying factors for white oak

Variable	Units	Suboptimal growth range	Optimal growth range	Weight of evidence[a]
Elevation	m	> 150	≤ 150	3
Aspect		southwestern	northeastern	2
Slope gradient	%	< 0.1, > 9.4	0.1 to 9.4	3.7
January temperature	°C	< -9.7, > 3.8	-9.7 to 3.8	5
July temperature	°C	< 21.5, > 26.5	21.5 to 26.5	5
May-September temperature	°C	< 18.0, > 23.7	18.0 to 23.7	5
Annual precipitation	mm	< 808, > 1450	808 to 1450	4.7
May-September precipitation	mm	< 433, > 578	433 to 578	4.7
Soil pH		< 4.7, > 6.9	4.7 to 6.9	4.3
Clay	%	< 11.4, > 42.7	11.4 to 42.7	3.7
Coarse sand	%	< 50.0, > 99.5	50.0 to 99.5	3.3
Permeability	cm hr^{-1}	< 0.5, > 7.5	0.5 to 7.5	3.3
Depth to bedrock	m	< 1.2	≥ 1.2	3
B-horizon base saturation	%	< 15	≥ 15	2
Soil Ca:Al	mol:mol	< 2	≥ 2	2
Biomass removal		low	high	
Insect pests		abundant	low or absent	
Fungal pathogens		abundant	low or absent	

[a] Refer to Tables 2.2 and 2.3 for description of values.

May to September Precipitation

High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to determine thresholds for average May to September precipitation. We associated the precipitation range from 433 to 578 mm with optimal growth, and precipitation outside of this range with suboptimal growth.

Soil pH

Reported soil pH ranges include pH 4.5 to 6.8 (NRCS 2014) and 2.7 to 8 (U.S. Forest Service, n.d.). We associated the high importance value range of pH 4.7 to 6.9 (U.S. Forest Service, n.d.) with optimal growth, and values outside of this range with suboptimal growth.

Percent Clay and Percent Coarse Sand

White oak can be found growing on a variety of soils, including sandy plains, gravelly ridges, and well-drained loamy soils. Dominant soil orders are Alfisols and Ultisols (Rogers 1990). We used high importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) to set thresholds for percent clay and percent coarse sand. Optimal pecent clay is 11.4 to 42.7 percent; optimal coarse sand is 50.0 to 99.5 percent.

Permeability

Optimal soil permeability from Climate Change Atlas (U.S. Forest Service, n.d.) high importance values range from 0.5 to 7.5 cm hr^{-1}, rates for moderately slow to moderately rapidly draining clay loams to sandy loams (O'Geen 2012).

Depth to Bedrock

We associated depth to bedrock of <1.2 m with suboptimal growth, and ≥1.2 m for optimal growth, based on minimum rooting depth from PLANTS database (NRCS 2014).

EXTERNAL INFLUENCES

Insect Pests

We assumed that an abundance of insect pests correlates with suboptimal growth, while low or absent levels of insect pests correlate with optimal growth.

Fungal Pathogens

As with insect pests, we assumed that trees weakened by abundant fungal pathogens would have suboptimal growth. Low or absent levels of fungal pathogens would correlate with optimal growth.

21 *QUERCUS PRINUS* (CHESTNUT OAK)

SPECIES RANGE AND CRITICAL LOAD

Chestnut oak, *Quercus prinus* L., is frequently found growing on dry, infertile ridges in the Appalachian region of the eastern United States, although it grows best on fertile, well drained soils along streams. Chestnut oak grows from sea level in the north to 1400 m in the southern Appalachians and is most common on south and west facing slopes. Precipitation is typically between 1020 to 1220 mm yr^{-1}, although it can range from 810 to 2030 mm yr^{-1} (McQuilkin 1990).

We assigned a critical load of 3 to10.5 N kg ha^{-1} yr^{-1} for chestnut oak. Thomas et al. (2010) found no change in growth and decreased survival with increased N deposition from 3 to 10.5 kg N ha^{-1} yr^{-1}. Survival was highest around 5 kg N ha^{-1} yr^{-1}; the critical load based on survival alone would be approximately 3 to 7 kg ha^{-1} yr^{-1}. The upper end of the range is supported by results from Elias (2008), who found decreased basal area for oak with N deposition between 12 and 14 kg ha^{-1} yr^{-1}. Critical load values and citations are shown in Table 21.1.

ABIOTIC MODIFYING FACTORS

Multiple sources were used to set the ranges of modifying factors for chestnut oak, including the chestnut oak section of the Forest Service silvics handbook (McQuilkin 1990) and high importance value data from the Climate Change Atlas (U.S. Forest Service, n.d.). In general, any factor that inhibits chestnut oak growth would be expected to result in a decreased need for N and thus a lower critical load; optimal growth conditions result in an increased demand for N and a higher critical load. General values were used for base saturation, Ca:Al, and biomass removal as described in Chapter 2 (pages 13-14). Graphs showing importance values for abiotic modifying factor ranges by species are in Appendix 1. Optimal and suboptimal growth ranges and weight of evidence values are shown in Table 21.2.

Elevation

Elevation effects depend on latitude. Chestnut oak growth is expected to be optimal at low elevations in the northeastern United States. We set an approximate elevation threshold of 330 m for optimal growth.

Aspect

According to McQuilkin (1990), chestnut oak are most common on southern and western exposures. In a study in West Virginia, chestnut oak growth increased on southwestern aspects and decreased on northeastern aspects (Fekedulegn et al. 2003). We associated southwestern exposures with optimal growth and northeastern exposures with suboptimal growth.

Slope Gradient

High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to set thresholds for slope. We expect growth of chestnut oak to be optimal from 1.3 to 15.9 percent.

Average January, July, and May to September Temperatures

High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to set temperature thresholds. We associated January temperatures from -4.6 to 3.3 °C, July temperatures from 20.2 to 25.1 °C, and May to September temperatures from 17.6 to 22.7 °C with optimal growth, and values outside of these ranges with suboptimal growth.

Annual Precipitation

Annual precipitation is reported to range from 758 to 2289 mm (U.S. Forest Service, n.d.) and 810 to 2030 mm (McQuilkin 1990), with an ideal range of 1020 to 1220 mm (McQuilkin 1990). We associated the high importance value range of 920 to 1591 mm (U.S. Forest Service, n.d.), which includes the reported ideal range, with optimal growth. Values outside of this range were associated with suboptimal growth.

May to September Precipitation

High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to determine thresholds for average May to September precipitation. We associated the precipitation range from 429 to 643 mm with optimal growth and precipitation outside of this range with suboptimal growth.

Table 21.1—Effect of nitrogen deposition on chestnut oak

Location	N deposition range ($kg\ ha^{-1}\ yr^{-1}$)	Increased N deposition effects	Interacting factors	Citation
Northeastern, Midwestern U.S.	3 to 10.5	No change in growth, increased mortality		Thomas et al. 2010
West Virginia	12 to 14	Decreased basal area	S deposition 20-26 $kg\ ha^{-1}\ yr^{-1}$	Elias 2008

Table 21.2—Abiotic modifying factors for chestnut oak

Variable	Units	Suboptimal growth range	Optimal growth range	Weight of evidence[a]
Elevation	m	> 330	≤ 330	2
Aspect		northeastern	southwestern	2
Slope gradient	%	< 1.3, > 15.9	1.3 to 15.9	3
January temperature	°C	< -4.6, > 3.3	-4.6 to 3.3	4
July temperature	°C	< 20.2, > 25.1	20.2 to 25.1	4.3
May-September temperature	°C	< 17.6, > 22.7	17.6 to 22.7	4
Annual precipitation	mm	< 920, > 1591	920 to 1591	3.7
May-September precipitation	mm	< 429, > 643	429 to 643	4
Soil pH		< 4.5, > 5.9	4.5 to 5.9	3.7
Clay	%	< 14.2, > 44.3	14.2 to 44.3	3
Coarse sand	%	< 53.1, > 90.1	53.1 to 90.1	3
Permeability	$cm\ hr^{-1}$	< 1.0, > 7.5	1.0 to 7.5	2.7
Depth to bedrock	m	< 0.8	≥ 0.8	3
B-horizon base saturation	%	< 15	≥ 15	2
Soil Ca:Al	mol:mol	< 2	≥ 2	2
Biomass removal		low	high	
Insect pests		abundant	low or absent	
Fungal pathogens		abundant	low or absent	

[a] Refer to Tables 2.2 and 2.3 for description of values.

Soil pH

We used high importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) to determine pH ranges for chestnut oak. We associated soil pH values of 4.5 to 5.9 with optimal growth and values outside of this range with suboptimal growth.

Percent Clay and Percent Coarse Sand

Chestnut oak is typically found growing on dry upland sites; dominant soil orders are Ultisols and Inceptisols (McQuilkin 1990). We used high importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) to set thresholds for percent clay and percent coarse sand. Optimal clay is 14.2 to 44.3 percent; optimal coarse sand is 53.1 to 90.1 percent.

Permeability

Optimal soil permeability from Climate Change Atlas (U.S. Forest Service, n.d.) high importance values range from 1.0 to 7.5 $cm\ hr^{-1}$, the rates for moderately slow to moderately rapidly draining clay loams to sandy loams (O'Geen 2012).

Depth to Bedrock

We assigned depth to bedrock values of <0.8 m for suboptimal growth and ≥0.8 for optimal growth. This is an approximate threshold because depth to bedrock was not given in the PLANTS database (NRCS 2014).

EXTERNAL INFLUENCES

Insect Pests

We assumed that an abundance of insect pests correlates with suboptimal growth. Low or absent levels of insect pests correlate with optimal growth.

Fungal Pathogens

As with insect pests, we assumed that trees weakened by abundant fungal pathogens would have suboptimal growth. Low or absent levels of fungal pathogens would correlate with optimal growth.

22 *QUERCUS RUBRA* (NORTHERN RED OAK)

SPECIES RANGE AND CRITICAL LOAD

Northern red oak, *Quercus rubra L.*, is found in much of central and eastern United States, as well southern parts of eastern Canada. Although it can be found on clay to loamy sand soils, red oak grows best on deep, well drained loam to silty clay loam soils (Sander 1990). Average temperatures range from 4 to 16 °C, while precipitation ranges from 760 to 2030 mm yr^{-1}. Red oak can be found up to 1070 m in West Virginia and up to 1680 m in the southern Appalachians, with best growth in lower or middle slopes with northerly or easterly aspects. Oak wilt and gypsy moth infestations can have a major impact on red oak health and mortality (Sander 1990).

We assigned a critical load of 3 to 14 kg N ha^{-1} yr^{-1} for red oak. Thomas et al. (2010) found a significant increase in growth and a small decrease in survival with increased N deposition from 3 to 11 kg N ha^{-1} yr^{-1}. Seedling growth decreased as ambient N deposition increased from approximately 2.4 kg ha^{-1} yr^{-1} wet N deposition to approximately 10 kg ha^{-1} yr^{-1} wet N at a site in Illinois (BassiriRad et al. 2015). Elias (2008) found decreased basal area for red oak with N deposition between 12 and 14 kg N ha^{-1} yr^{-1}.We used the low end of the range from Thomas et al. (2010) and the upper end of the range from Elias (2008) to set the critical load. Critical load values and citations are shown in Table 22.1.

ABIOTIC MODIFYING FACTORS

We used multiple sources to set the ranges of modifying factors for red oak, including the red oak section of the Forest Service silvics handbook (Sander 1990), the PLANTS database (NRCS 2014), and high importance value data from the Climate Change Atlas (U.S. Forest Service, n.d.). In general, any factor that inhibits red oak growth would be expected to result in a decreased need for N and thus a lower critical load; optimal growth conditions result in an increased demand for N and a higher critical load. General values were used for base saturation, Ca:Al, and biomass removal as described in Chapter 2 (pages 13-14). Graphs showing importance values for abiotic modifying factor ranges by species are in Appendix 1.

Optimal and suboptimal growth ranges and weight of evidence values are shown in Table 22.2.

Elevation

We set elevation ranges for the northeastern United States based on basal area dominance of hardwood trees at various elevations in the Green Mountains of Vermont as reported by Beckage et al. (2008). We generally expect growth to be optimal below 610 m and suboptimal at higher elevations.

Aspect

According to NRCS (2014), red oaks are shade intolerant and have little drought tolerance. They are most common on northern and eastern exposures (Sander 1990). However, Fekedulegn et al. (2003) did not find a difference in red oak growth between northeastern and southwestern aspect. We have currently associated northeastern exposures with optimal growth and southwestern exposures with suboptimal growth. However, it may be that aspect does not have a strong influence on red oak growth.

Slope Gradient

We used high importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) to set thresholds for slope. Growth for red oak is expected to be optimal from 0.0 to 9.0 percent.

Average January, July, and May to September Temperatures

High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to set temperature thresholds. We associated January temperatures from -13.2 to 0.5 °C, July temperatures from 19.7 to 25.4 °C, and May to September temperatures from 16.2 to 22.4 °C with optimal growth and values outside of these ranges with suboptimal growth.

Annual Precipitation

Reported precipitation ranges include 565 to 2289 mm (U.S. Forest Service, n.d.), 762 to 2030 mm (NRCS 2014), and 760 to 2030 mm (Sander 1990).

Table 22.1—Effect of nitrogen deposition on red oak

Location	N deposition range (kg ha^{-1} yr^{-1})	Increased N deposition effects	Interacting factors	Citation
Illinois, Indiana	2.4 to 10.1 (wet)	Decreased seedling growth		BassiriRad et al. 2015
Northeastern, Midwestern U.S.	3 to 11	Increased growth, small decrease in survival		Thomas et al. 2010
West Virginia	12 to 14	Decreased basal area	S deposition 20 to 26 kg ha^{-1} yr^{-1}	Elias 2008

Table 22.2—Abiotic modifying factors for red oak

Variable	Units	Suboptimal growth range	Optimal growth range	Weight of evidence[a]
Elevation	m	> 610	≤ 610	2
Aspect		southwestern	northeastern	2
Slope gradient	%	> 9.0	0.0 to 9.0	3.7
January temperature	°C	< -13.2, > 0.5	-13.2 to 0.5	4
July temperature	°C	< 19.7, > 25.4	19.7 to 25.4	4.3
May-September temperature	°C	< 16.2, > 22.4	16.2 to 22.4	4.3
Annual precipitation	mm	< 699, > 1264	699 to 1264	4
May-September precipitation	mm	< 398, > 565	398 to 565	4.3
Soil pH		< 4.8, > 7.2	4.8 to 7.2	4
Clay	%	< 4.0, > 35.9	4.0 to 35.9	3
Coarse sand	%	< 58.6, > 99.0	58.6 to 99.0	3.3
Permeability	cm hr^{-1}	< 0.6, > 12.4	0.6 to 12.4	2.7
Depth to bedrock	m	< 0.9	≥ 0.9	3
B-horizon base saturation	%	< 15	≥ 15	2
Soil Ca:Al	mol:mol	< 2	≥ 2	2
Biomass removal		low	high	
Insect pests		abundant	low or absent	
Fungal pathogens		abundant	low or absent	

[a] Refer to Tables 2.2 and 2.3 for description of values.

We associated the high importance value range of 699 to 1264 mm (U.S. Forest Service, n.d.) with optimal growth. Values outside of this range were associated with suboptimal growth.

Red oak appears to be moderately responsive to changes in precipitation. Drought years resulted in small decreases in growth for red oak in West Virginia (Fekedulegn et al. 2003). In Pennsylvania, red oaks on sites with higher soil pH and base saturation had better basal area growth recovery following drought than red oaks on sites with lower soil base saturation and pH (Demchik and Sharpe 2000).

May to September Precipitation

High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to determine thresholds for average May to September precipitation. We associated the precipitation range from 398 to 565 mm with optimal growth, and precipitation outside of this range with suboptimal growth.

Soil pH

Reported soil pH ranges for red oak include 4.3 to 7.3 (NRCS 2014) and 2.7 to 7.9 (U.S. Forest Service, n.d.). We used high importance values from the Climate

Change Atlas (U.S. Forest Service, n.d.) to associate soil pH values of 4.8 to 7.2 with optimal growth. Values outside of this range were associated with suboptimal growth.

Percent Clay and Percent Coarse Sand

Red oak grows best on deep, well drained loam and silty clay loam. Dominant soil orders are Spodosols, Alfisols, Inceptisols, Mollisols, Ultisols, and Entisols. We used high importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) to set thresholds for percent clay and percent coarse sand. Optimal clay is 4.0 to 35.9 percent; optimal coarse sand is 58.6 to 99.0 percent.

Permeability

Optimal soil permeability from Climate Change Atlas (U.S. Forest Service, n.d.) high importance values range from 0.6 to 12.4 cm hr^{-1}, the rates for moderately slow to moderately rapidly draining clay loams to sandy loams (O'Geen 2012).

Depth to Bedrock

Based on PLANTS database (NRCS 2014) minimum rooting depths, we associated depth to bedrock of <0.9 m with suboptimal growth and ≥0.9 m for optimal growth.

EXTERNAL INFLUENCES

Insect Pests

We assumed that abundant levels of insect pests correlate with suboptimal growth, while low or absent levels of insect pests correlate with optimal growth. Gypsy moths (*Lymantria dispar* (L.)) are the most serious pest of red oak trees (Lovett et al. 2006, Sander 1990).

Fungal Pathogens

As with insect pests, we assumed that trees weakened by abundant fungal pathogens would have suboptimal growth, and low or absent levels of fungal pathogens would correlate with optimal growth.

23 *THUJA OCCIDENTALIS* (NORTHERN WHITE-CEDAR)

SPECIES RANGE AND CRITICAL LOAD

Northern white-cedar, *Thuja occidentalis* L., grows in southeastern Canada, the northeastern United States, and the Lake States. Growth is best in humid climates with adequate rainfall over organic or calcareous mineral soils; northern white-cedar does not develop well on extremely wet or dry sites (Johnston 1990). Growth and health are positively correlated with Ca and Mg and negatively correlated with acidity and Al (Boulfroy et. al. 2012, Kell 2009). Precipitation generally ranges from 710 to 1170 mm yr^{-1}, average January temperatures range from -12 to -4 ˚C, and average July temperatures range from 16 to 22 ˚C. Northern white-cedar grows from sea level to 600 m, though it is most common between 150 and 600 m (Johnston 1990).

We assigned a critical load of 3 to 8.5 kg N ha^{-1} yr^{-1} for northern white-cedar. Thomas et al. (2010) found slightly decreased growth and no change in survival over a deposition range of 3 to 8.5 kg N ha^{-1} yr^{-1}; growth appeared to peak at 5.5 kg N ha^{-1} yr^{-1}. Critical load values and citations are shown in Table 23.1.

ABIOTIC MODIFYING FACTORS

We used multiple sources to set the ranges of modifying factors for northern white-cedar, including the northern white-cedar section of the Forest Service silvics handbook (Johnston 1990), the PLANTS database (NRCS 2014), and high importance value data from the Climate Change Atlas (U.S. Forest Service, n.d.). In general, any factor that inhibits northern white-cedar growth would be expected to result in a decreased need for N and thus a lower critical load; optimal growth conditions result in an increased demand for N and a higher critical load. General values were used for base saturation, Ca:Al, and biomass removal as described in Chapter 2 (pages 13-14). Graphs showing importance values for abiotic modifying factor ranges by species are in Appendix 1. Optimal and suboptimal growth ranges and weight of evidence values are shown in Table 23.2.

Elevation

We set elevation ranges for the northeastern United States based on elevations for northern white-cedar reported in Johnston (1990). Northern white-cedar is expected to have optimal growth between 150 and 600 m in elevation.

Aspect

Northern white-cedar is generally drought intolerant (NRCS 2014), although this varies by site; drought resistance is low to moderate on imperfectly drained sites and high on calcareous sites (Boulfroy et al. 2012). Shade tolerance is intermediate (NRCS 2014). We have associated southwestern aspects with suboptimal growth and northeastern aspects with optimal growth.

Slope Gradient

We used high importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) to set thresholds for slope. Growth for northern white-cedar is expected to be optimal from 0.0 to 3.4 percent.

Average January, July, and May to September Temperatures

Johnston (1990) reports an average January temperature range of -12 to -4 ˚C and an average July temperature range of 16 to 22 ˚C. High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to set temperature thresholds. We associated January temperatures from -16.3 to -7.5 ˚C, July temperatures from 17.9 to 21.1 ˚C, and May to September temperatures from 14.1 to 17.4 ˚C with optimal growth, and values outside of these ranges with suboptimal growth. The low optimal average temperature from the Climate Change Atlas is cooler that the low average January temperature reported in the Forest Service silvics handbook.

Annual Precipitation

Precipitation ranges for northern white-cedar include 499 to 1800 mm (U.S. Forest Service, n.d.), 889 to 1397 mm (NRCS 2014), and 510 to 1400 (Johnston

Table 23.1—Effect of nitrogen deposition on northern white-cedar

Location	N deposition range ($kg\ ha^{-1}\ yr^{-1}$)	Increased N deposition effects	Citation
Northeastern, Midwestern U.S.	3 to 8.5	Decreased growth and no change in survival	Thomas et al. 2010

Table 23.2—Abiotic modifying factors for northern white-cedar

Variable	Units	Suboptimal growth range	Optimal growth range	Weight of evidence[a]
Elevation	m	< 150, > 600	150 to 600	3
Aspect		southwestern	northeastern	2
Slope gradient	%	> 3.4	0.0 to 3.4	3.7
January temperature	°C	< -16.3, > -7.5	-16.3 to -7.5	4
July temperature	°C	< 17.9, > 21.1	17.9 to 21.1	4.3
May-September temperature	°C	< 14.1, > 17.4	14.1 to 17.4	4.3
Annual precipitation	mm	< 658, > 1124	658 to 1124	4.3
May-September precipitation	mm	< 389, > 499	389 to 499	4.3
Soil pH		< 5.2, > 7.3	5.2 to 7.3	3.7
Clay	%	< 4.2, > 25.8	4.2 to 25.8	3
Coarse sand	%	< 65.1, > 91.5	65.1 to 91.5	3.7
Permeability	$cm\ hr^{-1}$	< 0.6, > 12.5	0.6 to 12.5	2
Depth to bedrock	m	< 0.7	≥ 0.7	3
B-horizon base saturation	%	< 15	≥ 15	2
Soil Ca:Al	mol:mol	< 2	≥ 2	2
Biomass removal		low	high	
Insect pests		abundant	low or absent	
Fungal pathogens		abundant	low or absent	

[a] Refer to Tables 2.2 and 2.3 for description of values.

1990). We associated the high importance value range of 658 to 1124 mm (U.S. Forest Service, n.d.) with optimal growth. Values outside of this range were associated with suboptimal growth.

May to September Precipitation

High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to determine thresholds for average May to September precipitation. We associated the precipitation range from 389 to 499 mm with optimal growth and precipitation outside of this range with suboptimal growth.

Soil pH

Reported soil pH values for northern white-cedar include 5.2 to 7.0 (NRCS 2014) and 5.5 to 7.2 (Johnston 1990). We associated soil pH values of 5.2 to 7.3, the high importance value range from the Climate Change Atlas (U.S. Forest Service, n.d.), with optimal growth. We associated values outside of this range with suboptimal growth.

Percent Clay and Percent Coarse Sand

Northern white-cedar is most often found on cool, moist, nutrient rich sites with high organic matter or calcareous mineral soils. Dominant soil orders are Histosols, Inceptisols, and Entisols (Johnston 1990). We used high importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) to set thresholds for percent clay and percent coarse sand. Optimal clay is 4.2 to 25.8 percent; optimal coarse sand is 65.1 to 91.5 percent.

Permeability

Optimal soil permeability from Climate Change Atlas (U.S. Forest Service, n.d.) high importance values range from 0.6 to 12.5 cm hr^{-1}, the rate for moderately slow to moderately rapidly draining clay loams to sandy loams (O'Geen 2012).

Depth to Bedrock

We assigned depth to bedrock values of <0.7 m for suboptimal growth, based on minimum rooting depth (NRCS 2014), and ≥0.7 m for optimal growth.

EXTERNAL INFLUENCES

Insect Pests

Northern white-cedar does not have significant insect pests; for this reason, we assumed that insect pests do not significantly affect the growth of this species.

Fungal Pathogens

Northern white-cedar does not have significant fungal pathogens; for this reason, we assumed that fungal pathogens do not significantly affect the growth of this species.

24 *TSUGA CANADENSIS* (EASTERN HEMLOCK)

SPECIES RANGE AND CRITICAL LOAD

Eastern hemlock, *Tsuga candensis* (L.) Carrière, grows in the northeastern and central-eastern United States, as well as southeastern Canada. Eastern hemlock grows best in moist sandy loams, loamy sands, and silty loams with good drainage. It occurs at elevations up to 730 m in New England, 300 to 910 m in New York and Pennsylvania, and from 610 to 1520 m in the southern Appalachians (Godman and Lancaster 1990). Eastern hemlock populations in the southern part of the range are often subject to infestation of hemlock wooly adelgid (*Adelgis tsugae*), which can result in tree death in 4-5 years (Lovett et al. 2006), although tree decline may occur much more gradually (Eschtruth et al. 2006, 2013).

We assigned a critical load of >11 to 23 kg ha^{-1} yr^{-1} for eastern hemlock. Thomas et al. (2010) found no change in growth or survival with increased N deposition from 3 to 11 kg N ha^{-1} yr^{-1}. For late successional conifers, Dietze and Moorcroft (2011) found that decreased probability of mortality was correlated with increased N deposition between 6 to 23 kg ha^{-1} yr^{-1} NO_3 wet; visual inspection of supplementary material indicate that mortality was lowest from approximately 10 to 21 kg ha^{-1} yr^{-1} NO_3 wet (12 to 23 kg ha^{-1} yr^{-1} wet + dry N). Critical load citations and values are shown in Table 24.1.

ABIOTIC MODIFYING FACTORS

Multiple sources were used to set the ranges of modifying factors for eastern hemlock, including the eastern hemlock section of the Forest Service silvics handbook (Godman and Lancaster 1990), the PLANTS database (NRCS 2014), and high importance value data from the Climate Change Atlas (U.S. Forest Service, n.d.). In general, any factor that inhibits eastern hemlock growth would be expected to result in a decreased need for N and thus a lower critical load; optimal growth conditions result in an increased demand for N and a higher critical load. General values were used for base saturation, Ca:Al, and biomass removal as described in Chapter 2 (pages 13-14). Graphs showing importance values for abiotic modifying factor ranges by species are in Appendix 1. Optimal and suboptimal growth ranges and weight of evidence values are shown in Table 24.2.

Elevation

We set elevation ranges for the northeastern United States based on elevation ranges in Godman and Lancaster (1990) for New England. Eastern hemlock growth is expected to be optimal below 730 m, and suboptimal at higher elevations.

Aspect

Because eastern hemlock is drought intolerant and shade tolerant, we associated southwestern aspects with suboptimal growth, and northeastern aspects with optimal growth.

Slope Gradient

We used high importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) to set thresholds for slope. Growth for eastern hemlock is expected to be optimal from 0.5 to 8.2 percent.

Average January Temperature

High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to determine average January temperature ranges. We associated the temperature range from -10.3 to -3.2 °C with optimal growth and temperatures outside of this range with suboptimal growth. This is within the range from the eastern hemlock section in Godman and Lancaster (1990), which provides an average January temperature range of -12 to 6 °C. Although hemlock growth has been positively associated with warmer winters (Tardif et al. 2001), warmer winters also bring an increased risk of hemlock wooly adelgid. Cold winter temperatures are associated with decreased hemlock wooly adelgid populations and decreased hemlock mortality (Eschtruth 2013, Paradis et al. 2008). All hemlock wooly adelgid are likely to die with an average mean winter temperature of -5 °C (Paradis et al. 2008).

Average July Temperature

High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to determine

Table 24.1—Effect of nitrogen deposition on eastern hemlock

Location	N deposition range (kg ha^{-1} yr^{-1})	Increased N deposition effects	Citation
Northeastern, Midwestern U.S.	3 to 11	No change in growth or survival	Thomas et al. 2010
Eastern and Central U.S.	6 to 23 (wet NO_3) (12 to 23 wet+ dry N lowest mortality)	Decreased mortality probability	Dietze and Moorcroft

Table 24.2—Abiotic modifying factors for eastern hemlock

Variable	Units	Suboptimal growth range	Optimal growth range	Weight of evidence[a]
Elevation	m	> 730	≤ 730	3
Aspect		southwestern	northeastern	2
Slope gradient	%	< 0.5, > 8.2	0.5 to 8.2	3
January temperature	°C	< -10.3, > -3.2	-10.3 to -3.2	4
July temperature	°C	< 18.9, > 22.2	18.9 to 22.2	4.3
May-September temperature	°C	< 15.4, > 19.0	15.4 to 19.0	4.3
Annual precipitation	mm	< 866, > 1314	866 to 1314	4
May-September precipitation	mm	< 417, > 597	417 to 597	4
Soil pH		< 4.9, > 6.7	4.9 to 6.7	3.7
Clay	%	< 3.4, > 26.2	3.4 to 26.2	3
Coarse sand	%	< 55.6, > 94.0	55.6 to 94.0	3
Permeability	cm hr^{-1}	< 0.7, > 12.2	0.7 to 12.2	2.3
Depth to bedrock	m	< 0.7	≥ 0.7	3
B-horizon base saturation	%	< 15	≥ 15	2
Soil Ca:Al	mol:mol	< 2	≥ 2	2
Biomass removal		low	high	
Insect pests		abundant	low or absent	
Fungal pathogens		abundant	low or absent	

[a] Refer to Tables 2.2 and 2.3 for description of values.

the range for average July temperature. We associated the July temperature range from 18.9 to 22.2 °C with optimal growth and temperatures outside of this range with suboptimal growth. Average July temperature is used to delimit preferred growth climate for eastern hemlock, but does not necessarily describe optimum growth temperatures. Optimum July temperature for photosynthesis, in a simulated field environment in Wisconsin, was found to be 17 °C. Optimum temperatures for photosynthesis were lower in May (Adams and Loucks 1971). High summer temperatures (21 °C) in August in Massachusetts resulted in carbon storage near zero (Hadley and Schedlbauer 2002); storage was highest in the cooler months of April and May.

Average May to September Temperature

High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to determine thresholds for average May to September temperature. We associated the temperature range from 15.4 to 19.0 °C with optimal growth and temperatures outside of this range with suboptimal growth.

Annual Precipitation

Annual precipitation ranges for eastern hemlock include 720 to 2289 mm (U.S. Forest Service, n.d.), 813 to 1397 mm (NRCS 2014), and 740 to 1520 mm (Godman and Lancaster 1990). We associated the Climate Change Atlas (U.S. Forest Service, n.d.)

high importance value range of 866 to 1314 mm with optimal growth. Values outside of this range were associated with suboptimal growth.

May to September Precipitation

High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to determine thresholds for average May to September precipitation. We associated the precipitation range from 417 to 597 mm with optimal growth and precipitation outside of this range with suboptimal growth.

Soil pH

Soil pH ranges reported for eastern hemlock include 4.1 to 7.6 (U.S. Forest Service, n.d.) and 4.2 to 5.7 (NRCS 2014). We associated soil pH values of 4.9 to 6.7, the high importance value range from the Climate Change Atlas (U.S. Forest Service, n.d.), with optimal growth and values outside of this range with suboptimal growth.

Percent Clay and Percent Coarse Sand

Eastern hemlock is found on moist to very moist sandy loams, loamy sands, and silt loams with good drainage. Spodosols are the dominant soil order for this species (Godman and Lancaster 1990). We used high importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) to set thresholds for percent clay and percent coarse sand. Optimal clay is 3.4 to 26.2 percent; optimal coarse sand is 55.6 to 94.0 percent.

Permeability

Optimal soil permeability from Climate Change Atlas (U.S. Forest Service, n.d.) high importance values range from 0.7 to 12.2 cm hr^{-1}, the rates for moderately slow to moderately rapidly draining clay loams to sandy loams (O'Geen 2012).

Depth to Bedrock

We assigned depth to bedrock values of <0.7 m for suboptimal growth, based on minimum rooting depth (NRCS 2014), and values ≥0.7 for optimal growth.

EXTERNAL INFLUENCES

Insect Pests

Research indicates that increased N may increase the palatability of certain tree species to insect pests. McClure (1991) found that trees fertilized with nitrogen had higher rates of hemlock wooly adelgid infestation and reduced health compared to unfertilized trees. Reduced vigor and growth could result in lower nutrient demands. The range of hemlock wooly adelgid will likely increase with warmer temperatures (Dukes et al. 2009, Paradis et al 2008). Drought increases the risk of mortality for trees infested with hemlock wooly adelgid, while cold winter temperatures reduce insect populations and tree mortality (Eschtruth et al. 2013). We assumed that an abundance of insect pests would correlate with suboptimal growth, while low or absent levels of pests would correlate with optimal growth.

Fungal Pathogens

As with insect pests, we assumed that trees weakened by abundant fungal pathogens would have suboptimal growth. Low or absent levels of fungal pathogens would correlate with optimal growth.

25 *ULMUS AMERICANA* (AMERICAN ELM)

SPECIES RANGE AND CRITICAL LOAD

American elm, *Ulmus americana* L., grows in the eastern and central United States, as well as in south central and southeastern Canada, over a precipitation range of 380 to 1520 mm yr^{-1} (Bey 1990). Temperature spans a wide range; July average temperatures range from 16 to 27 °C, while January average temperatures range from -16 to 16 °C. American elm grows best on rich, well-drained soil and grows poorly on dry soils, soils high in organic matter, and soils with a high water table (Bey 1990). It is most commonly found on flats and bottomlands, but can be found up to 760 m in West Virginia. American elm is highly susceptible to Dutch elm disease (*Ophiostoma ulmi/novi-ulmi*) (Dukes et al. 2009), an introduced fungal pathogen that is spread through feeding by European and native elm bark beetles (*Scolytus multistriatus and Hylurgopinus rufipes,* respectively) (Bey 1990).

We assigned a critical load of 7 to 18 kg N ha^{-1} yr^{-1} for American elm. This range is based solely on the northern mid successional hardwood forest type in Dietze and Moorcroft (2011); visual inspection of supplementary material indicates that mortality was lowest from 5 to 16 kg ha^{-1} yr^{-1} wet N deposition (approximately 7 to 18 kg/ha/N wet + dry deposition). This critical load should be revised when American elm specific data becomes available. Critical load citations and values are shown in table 25.1.

ABIOTIC MODIFYING FACTORS

We used multiple sources to set the ranges of modifying factors for American elm, including the American elm section of the Forest Service silvics handbook (Bey 1990) and high importance value data from the Climate Change Atlas (U.S. Forest Service, n.d.). In general, any factor that inhibits American elm growth would be expected to result in a decreased need for N and thus a lower critical load; optimal growth conditions result in an increased demand for N and a higher critical load. General values were used for base saturation, Ca:Al, and biomass removal as described in Chapter 2 (pages 13-14). Graphs showing importance values for abiotic modifying factor ranges by species are in Appendix 1. Optimal and suboptimal growth ranges and weight of evidence values are shown in Table 25.2.

Elevation

We set elevation ranges for the northeastern United States based on elevation in the Forest Service silvics handbook (Bey 1990). Growth is generally expected to be optimal below approximately 550 m and suboptimal above 550 m in elevation.

Aspect

American elm has intermediate shade and drought tolerance (Bey 1990). Because it is not clear which aspect is most favorable for growth, we have not associated aspect with growth for this species.

Slope Gradient

We used high importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) to set thresholds for slope. Growth for American elm is expected to be optimal from 0.0 to 5.4 percent.

Average January, July, and May to September Temperatures

High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to set temperature thresholds. We associated January temperatures from -13.1 to -0.1 °C, July temperatures from 20.9 to 27.0 °C, and May to September temperatures from 17.2 to 23.4 °C with optimal growth and values outside of these ranges with suboptimal growth. These are within temperature ranges reported in Bey (1990).

Annual Precipitation

The distribution range from the Climate Change Atlas (U.S. Forest Service, n.d.) provides a range of 436 to 1774 mm annual precipitation. The range for high importance value stands is 600 to 1139 mm. According to Bey (1990), the range for American elm is 380 to 1520 mm annually, with 760 to 1270 mm over the central part of the range. We have associated the high importance value range, from 600 to 1139 mm, with optimal growth. Values outside of this range were associated with suboptimal growth.

Table 25.1—Effect of nitrogen deposition on American elm

Location	N deposition range ($kg\ ha^{-1}\ yr^{-1}$)	Increased N deposition effects	Citation
Eastern and Central U.S.	5 to 16 (wet NO_3)	Decreased mortality probability	Dietze and Moorcroft

Table 25.2—Abiotic modifying factors for American elm

Variable	Units	Suboptimal growth range	Optimal growth range	Weight of evidence[a]
Elevation	m	> 550	≤ 550	3
Aspect		N/A	N/A	
Slope gradient	%	> 5.4	0.0 to 5.4	4
January temperature	°C	< -13.1, > -0.1	-13.1 to -0.1	4.3
July temperature	°C	< 20.9, > 27.0	20.9 to 27.0	4.7
May-September temperature	°C	< 17.2, > 23.4	17.2 to 23.4	4.7
Annual precipitation	Mm	< 600, > 1139	600 to 1139	4.3
May-September precipitation	Mm	< 386, > 576	386 to 576	4.3
Soil pH		< 5.4, > 7.6	5.4 to 7.6	4.3
Clay	%	< 13.0, > 42.1	13.0 to 42.1	3.7
Coarse sand	%	< 75.4, > 100.0	75.4 to 100.0	4
Permeability	$cm\ hr^{-1}$	< 0.3, > 6.2	0.3 to 6.2	3.3
Depth to bedrock	m	< 1.0	≥ 1.0	3
B-horizon base saturation	%	< 15	≥ 15	2
Soil Ca:Al	mol:mol	< 2	≥ 2	2
Biomass removal		low	high	
Insect pests		abundant	low or absent	
Fungal pathogens		abundant	low or absent	

[a] Refer to Tables 2.2 and 2.3 for description of values.

May to September Precipitation

High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) were used to determine thresholds for average May to September precipitation. We associated the precipitation range from 386 to 576 mm with optimal growth and precipitation outside of this range with suboptimal growth.

Soil pH

High importance values from the Climate Change Atlas (U.S. Forest Service, n.d.), supported by information from Bey (1990), which provides an American elm pH range of 5.5 to 8.0, were used to set pH values. We associated soil pH values of 5.4 to 7.6, from the high importance value range, with optimal growth and values outside of this range with suboptimal growth.

Percent Clay and Percent Coarse Sand

American elm grows best on rich, well-drained soils, and is most often found on Alfisols, Inceptisols, Mollisols, and Ultisols (Bey 1990). We used high importance values from the Climate Change Atlas (U.S. Forest Service, n.d.) to set thresholds for percent clay and percent coarse sand. Optimal clay is 13.0 to 42.1 percent; optimal coarse sand is 75.4 to 100 percent.

Permeability

Optimal soil permeability from Climate Change Atlas (U.S. Forest Service, n.d.) high importance values range from 0.3 to 6.2 cm hr^{-1}, the rate for moderately slow to moderately draining clay loams to fine sandy loams (O'Geen 2012). Permeability outside of this range is associated with suboptimal growth.

Depth to Bedrock

We associated bedrock depth of <1.0 m with suboptimal growth and ≥1.0 m with optimal growth. Rooting depth varies with soil conditions. In heavy, wet, soils the root system is typically within approximately 1 m of the surface. On medium textured soils, roots can penetrate up to 3 m, while on dry soils the roots may extend up to approximately 6 m (Bey 1990).

EXTERNAL INFLUENCES

Insect Pests

We assumed that an abundance of insect pests correlates with suboptimal growth, while low levels or the absence of insect pests correlate with optimal growth. Winter moth (*Ophorophtera brumata*) is one of many pests of concern (Dukes et al. 2009).

Fungal Pathogens

As with insect pests, we assumed that trees weakened by abundant fungal pathogens would have suboptimal growth. Low levels or the absence of fungal pathogens would correlate with optimal growth. Because Dutch elm disease is a persistent threat to American elm, growth may always be suboptimal.

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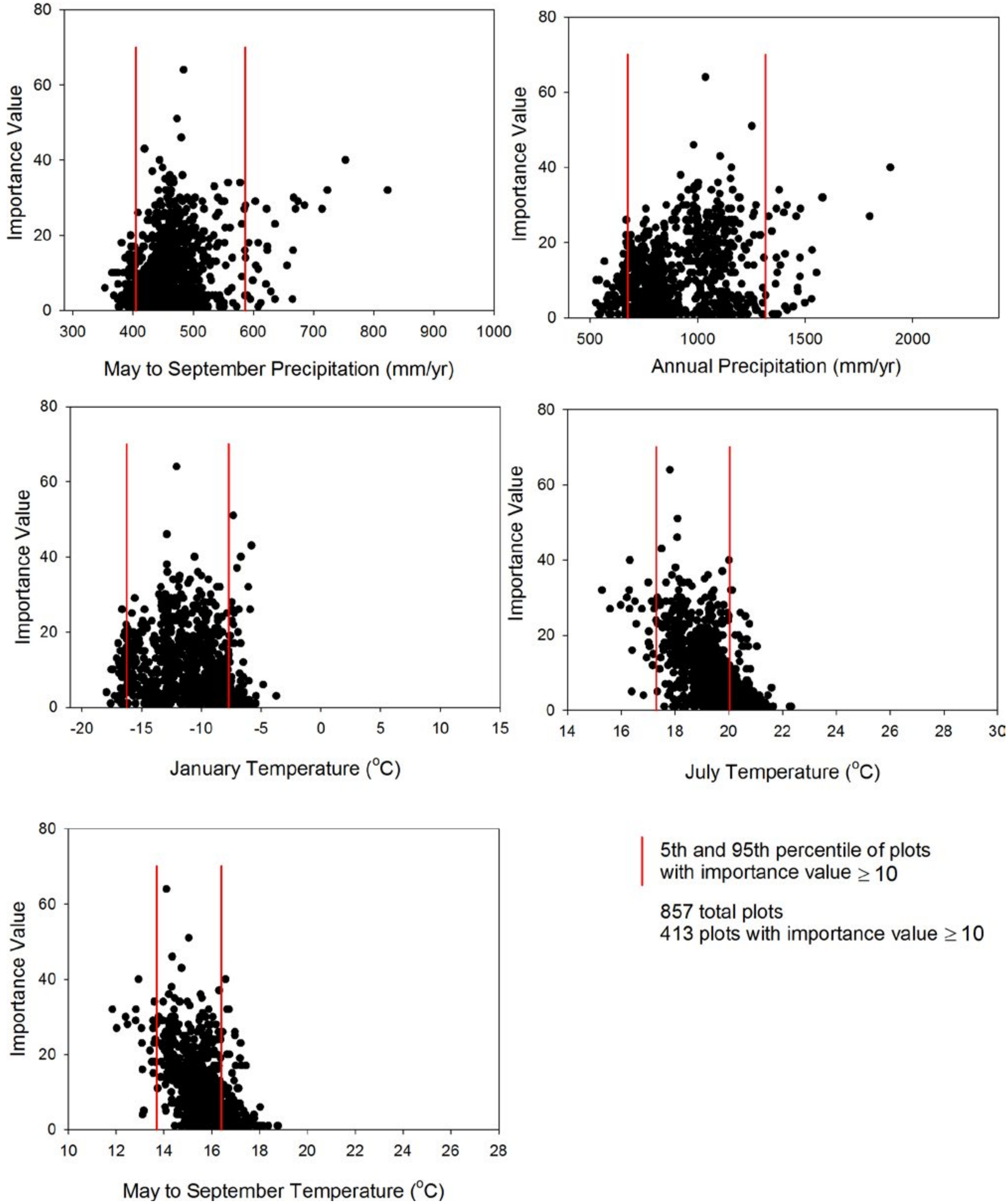
APPENDIX 1

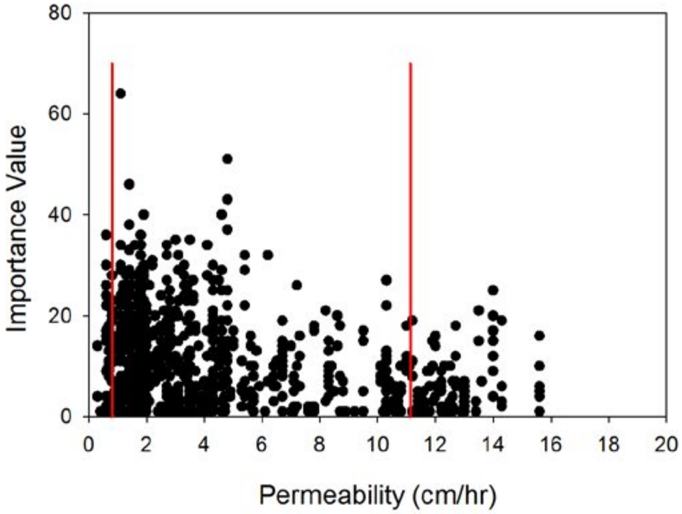
Importance Values Versus Climate and Soil Characteristics for Each Species

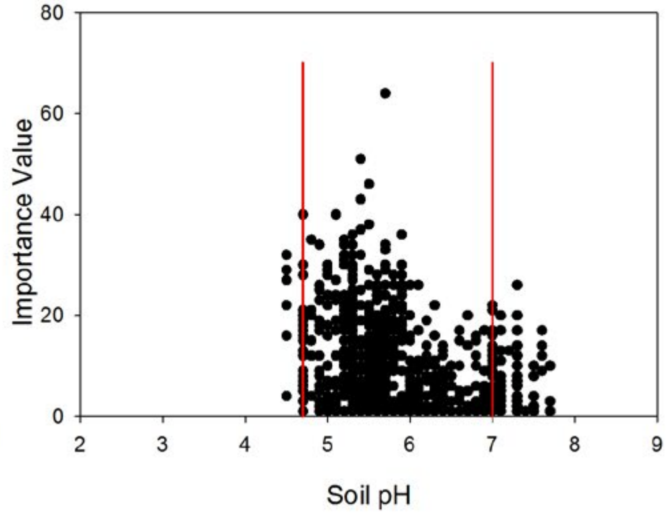
Data from the Climate Change Atlas (U.S. Forest Service, n.d.)

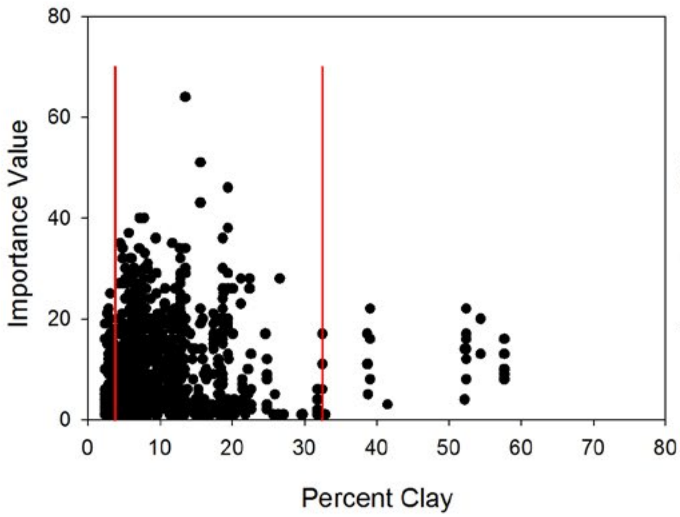
Abies balsamea (balsam fir)
Climate Parameters

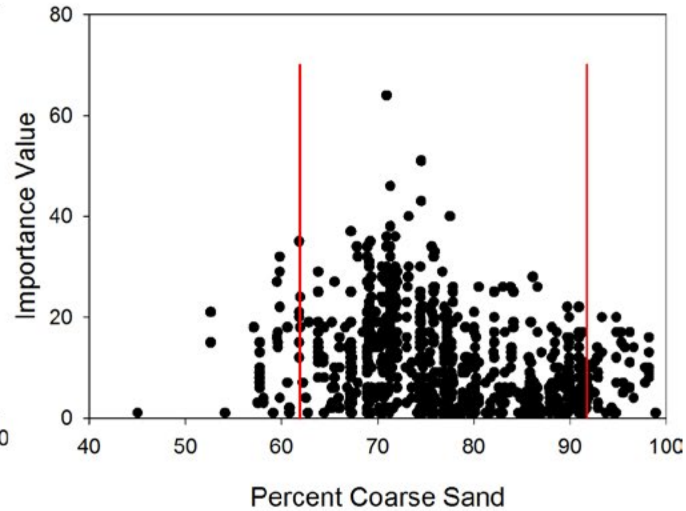


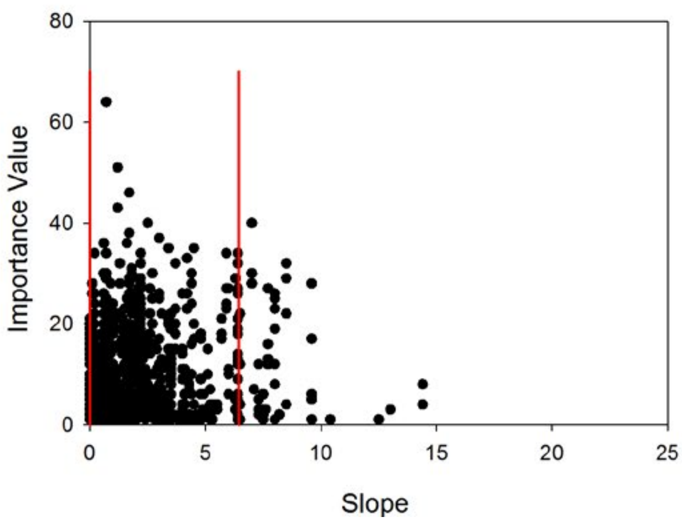
Abies balsamea (balsam fir)
Soil and Topographic Parameters







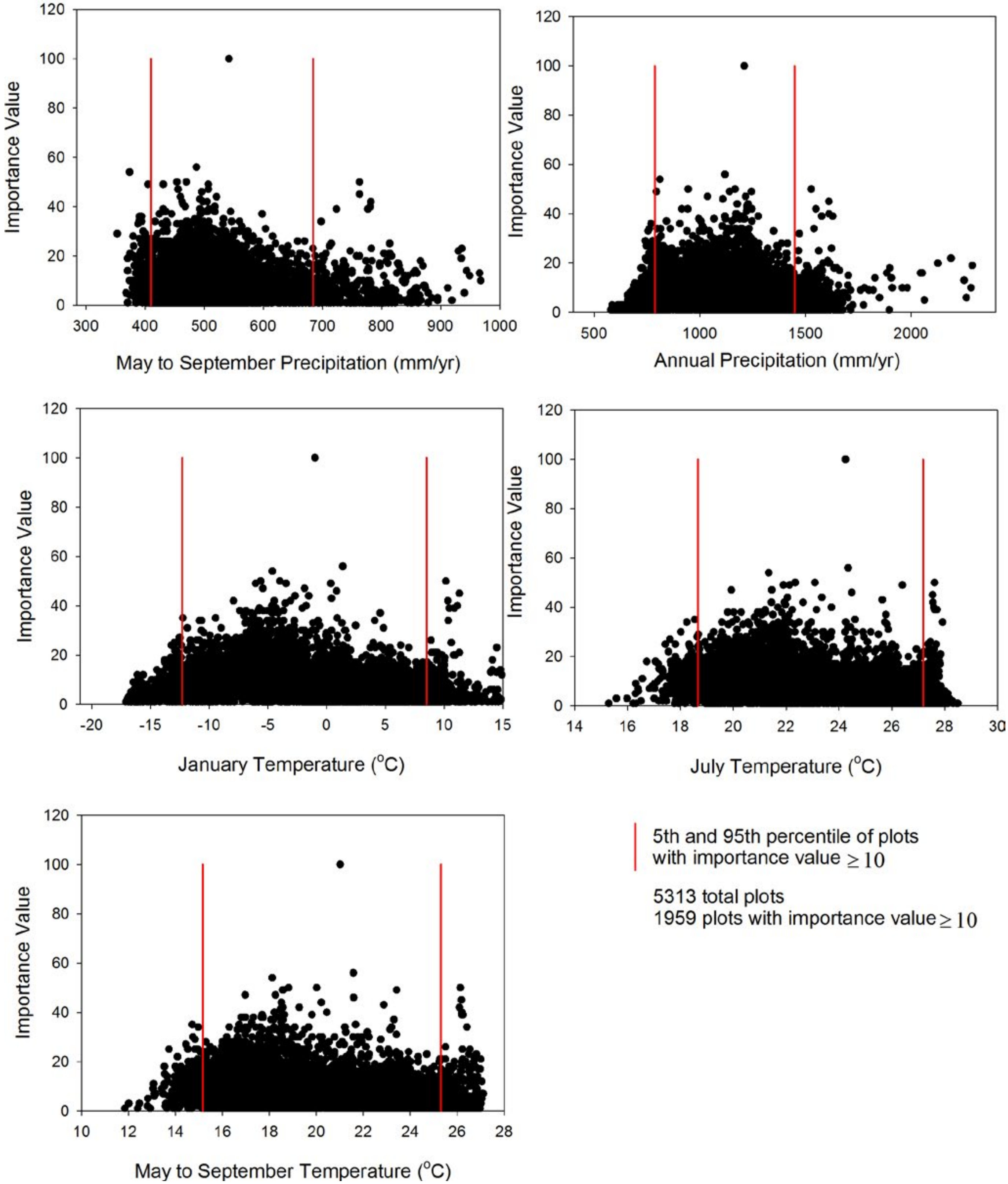




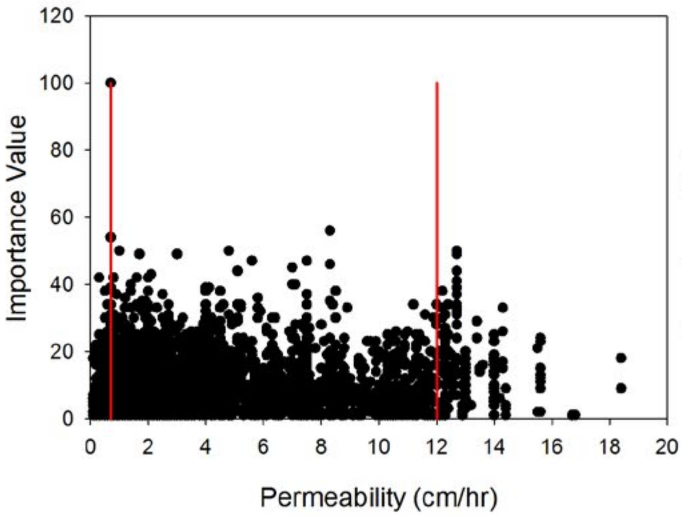
5th and 95th percentile of plots with importance value ≥ 10

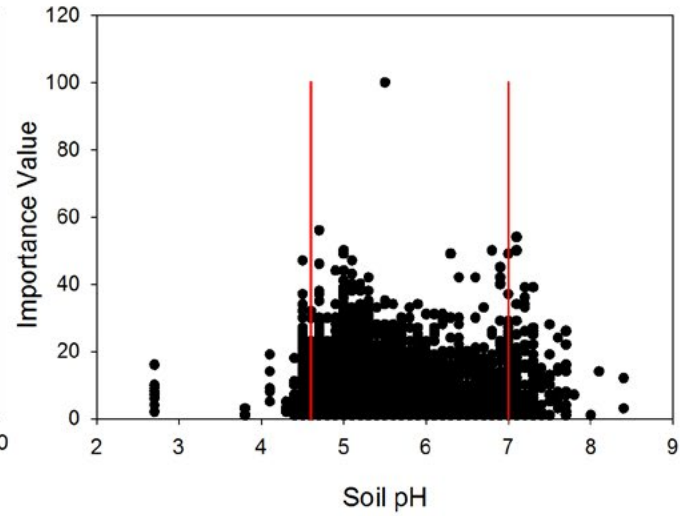
857 total plots
413 plots with importance value ≥ 10

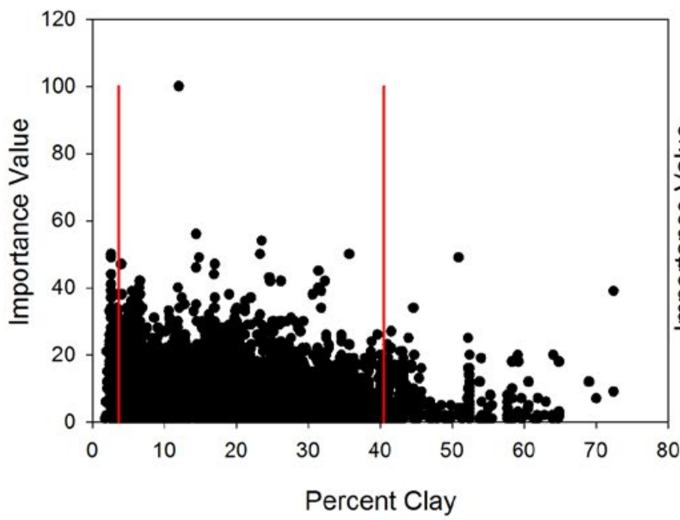
Acer rubrum - red maple - climate parameters

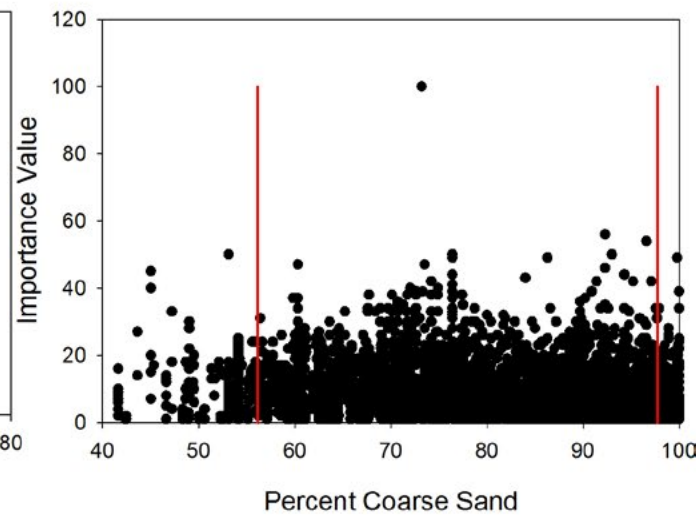


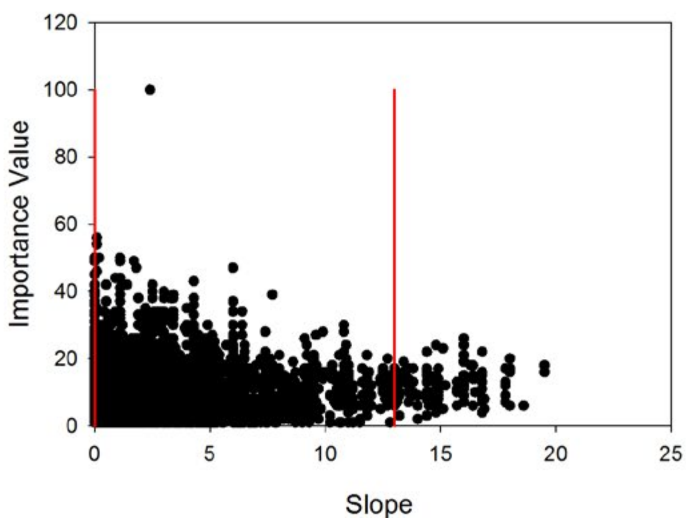
Acer rubrum - red maple - soil and topographic parameters







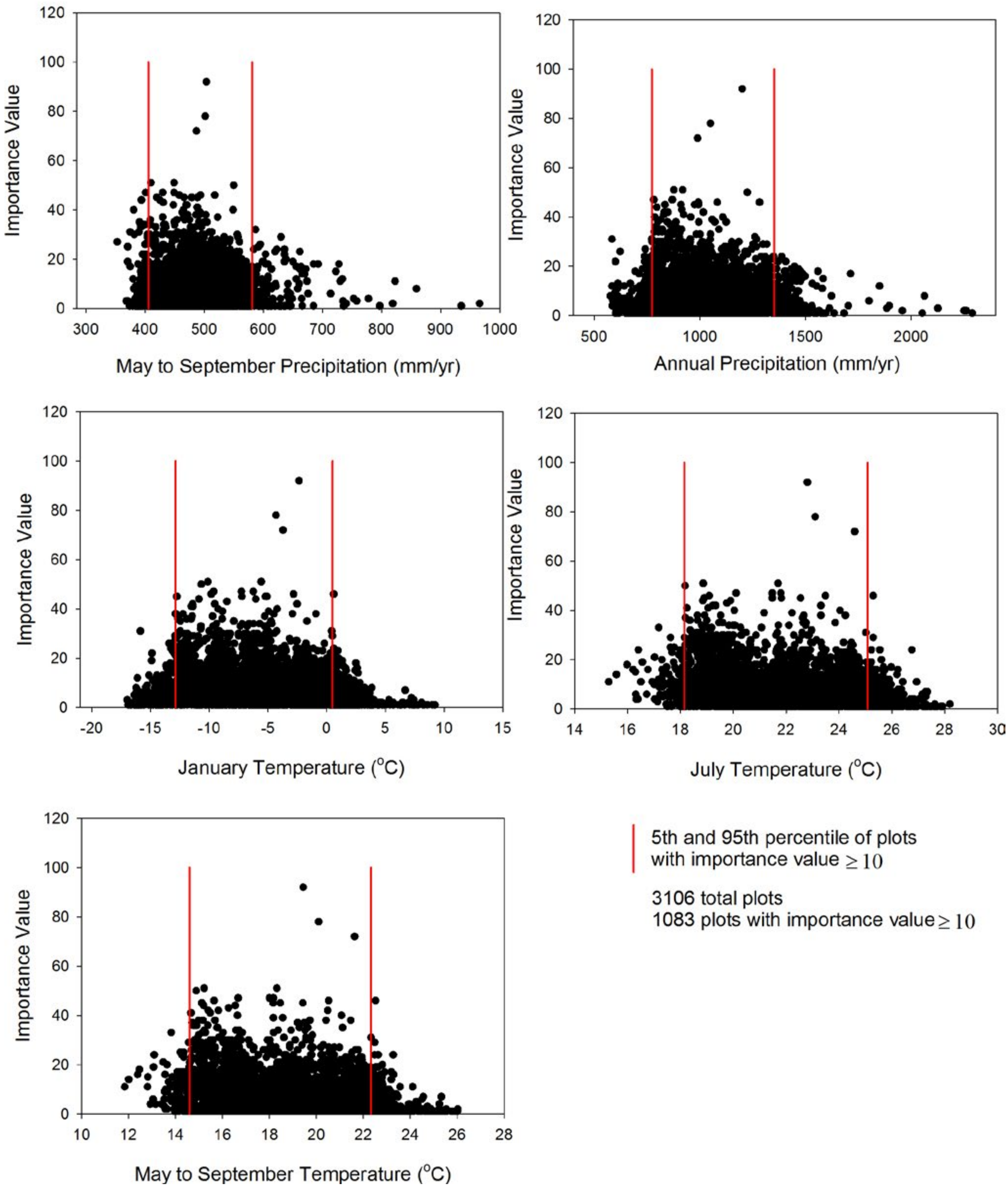




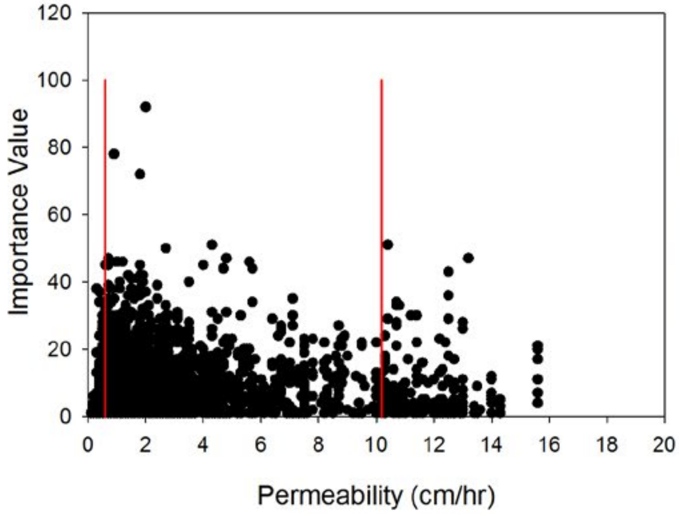
5th and 95th percentile of plots
with importance value ≥ 10

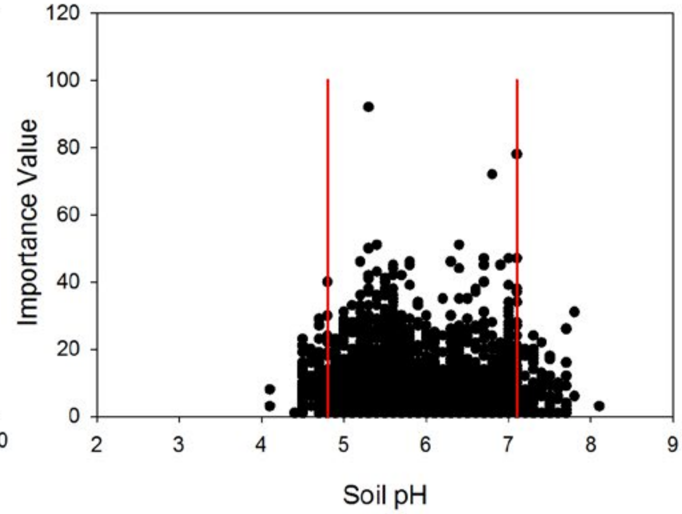
5313 total plots
1959 plots with importance value ≥ 10

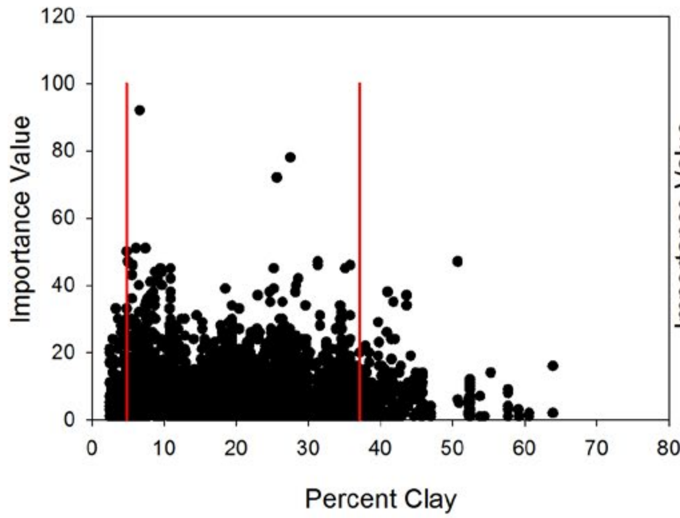
Acer saccharum - sugar maple - climate parameters

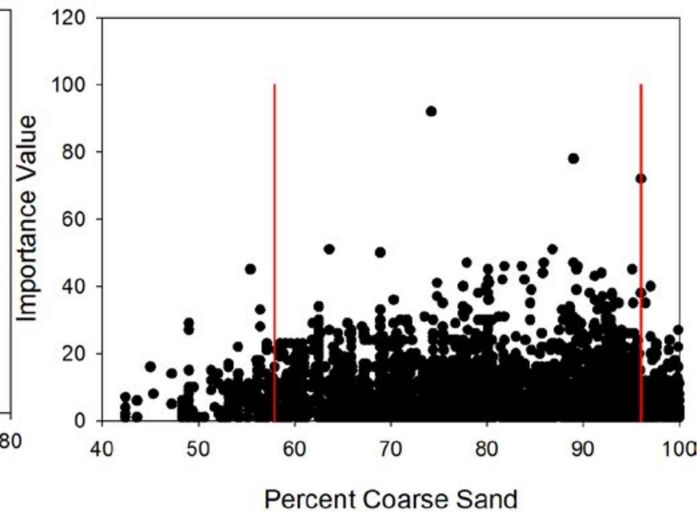


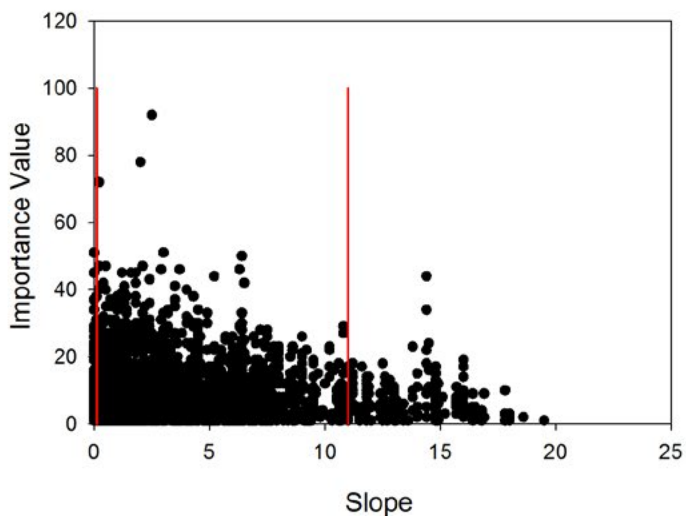
Acer saccharum - sugar maple - soil and topographic parameters







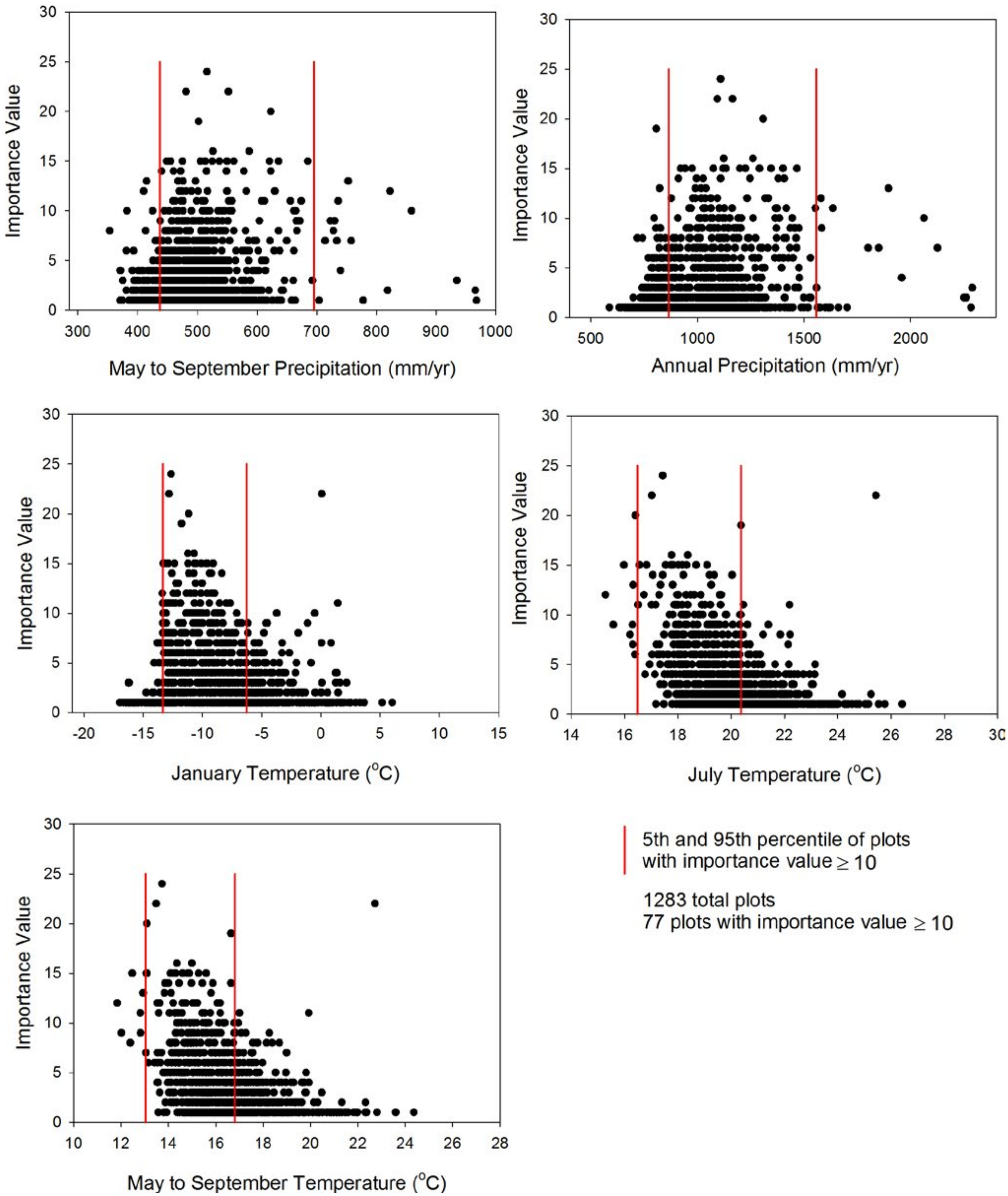




5th and 95th percentile of plots with importance value ≥ 10

3106 total plots
1083 plots with importance value ≥ 10

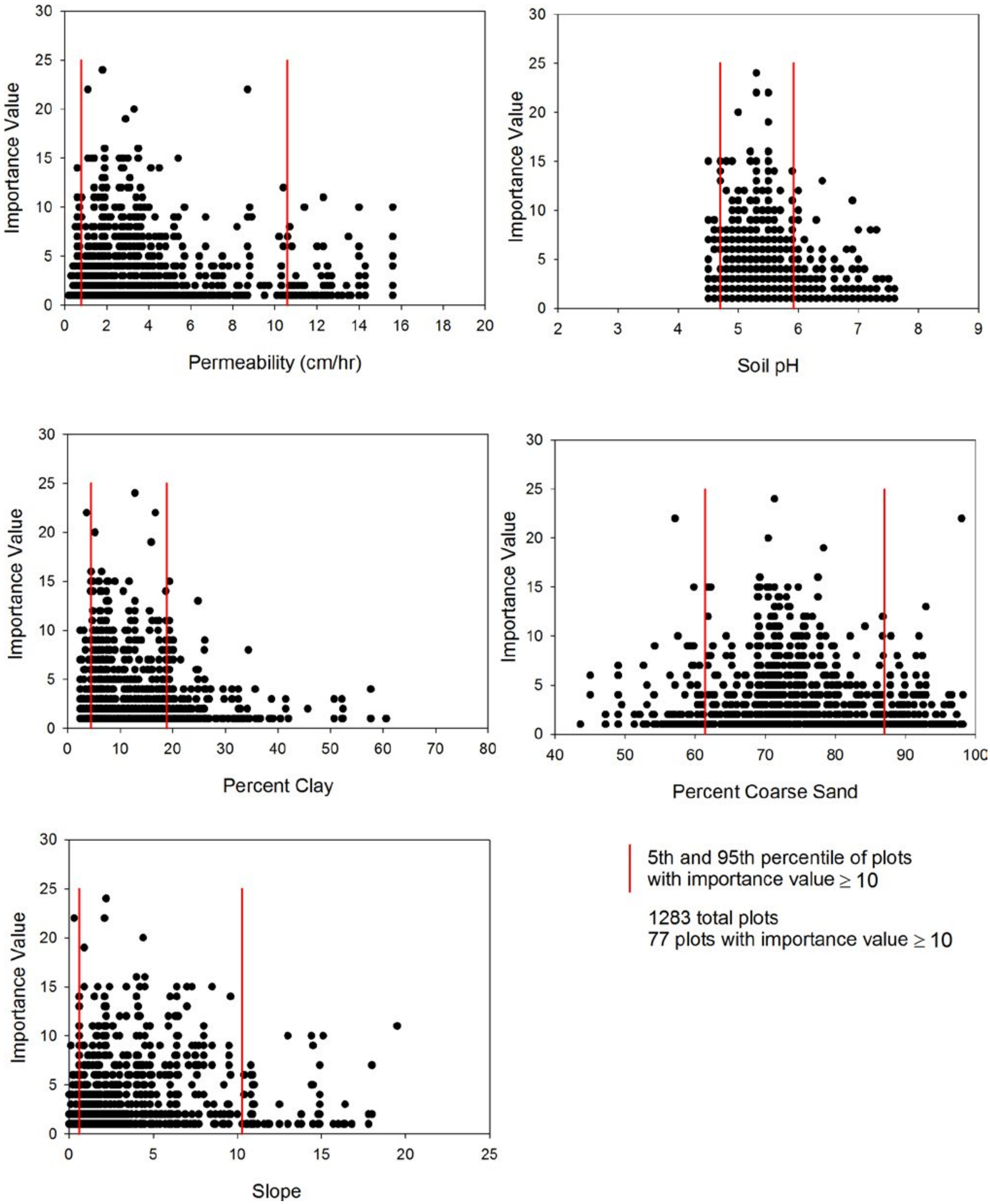
Betula alleghaniensis (yellow birch)
Climate Parameters



5th and 95th percentile of plots with importance value ≥ 10

1283 total plots
77 plots with importance value ≥ 10

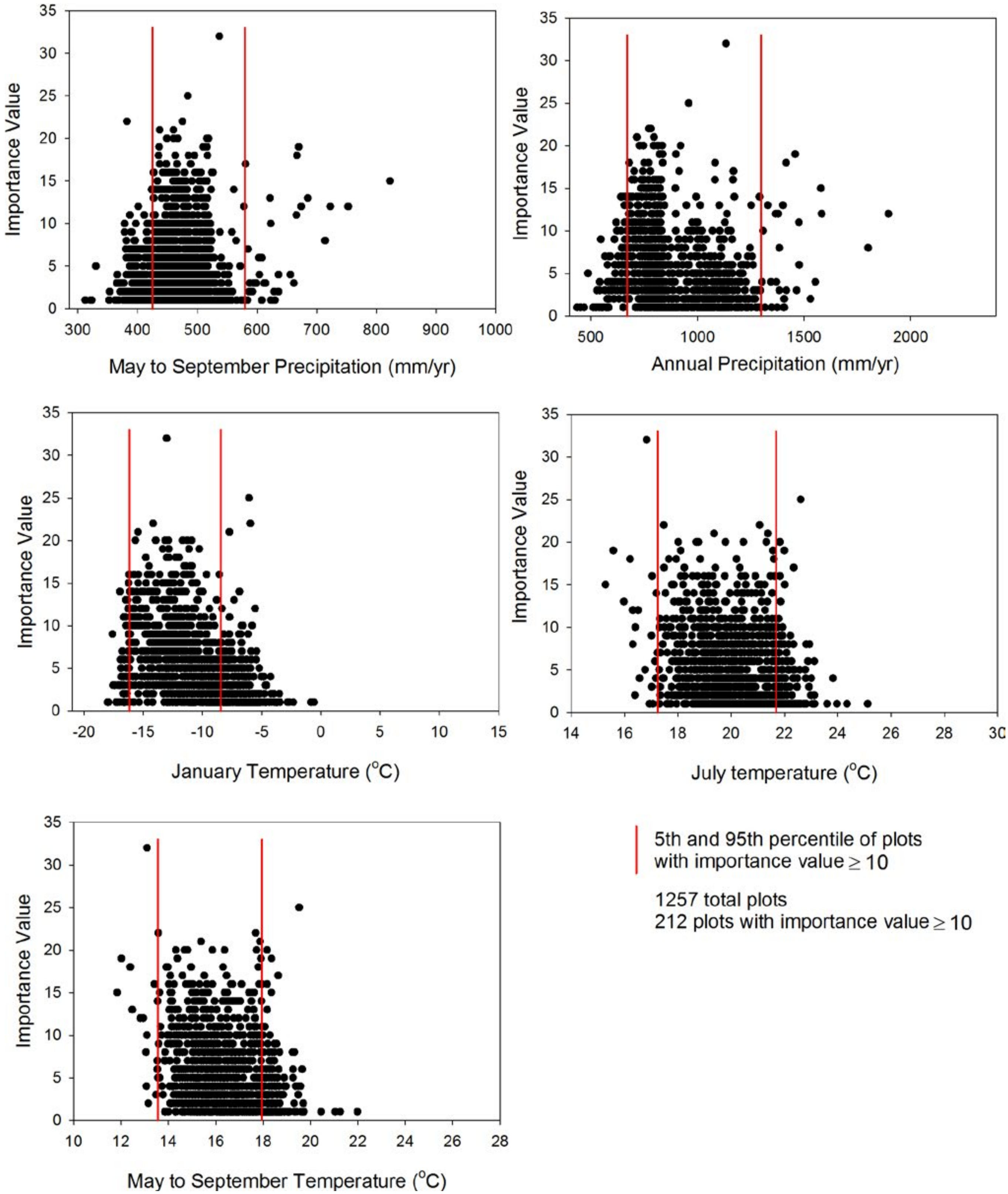
Betula alleghaniensis (yellow birch)
Soil and Topographic Parameters



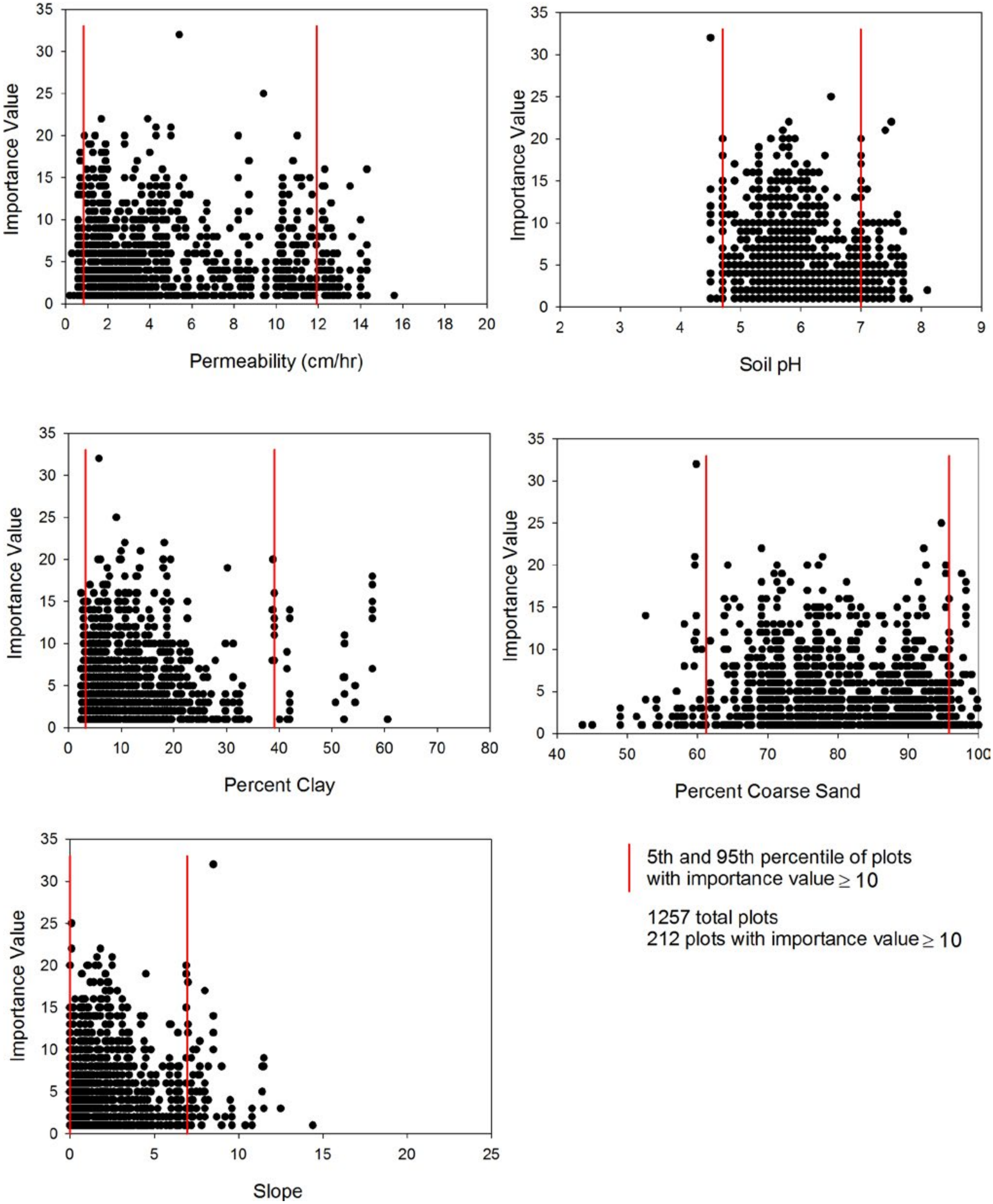
5th and 95th percentile of plots with importance value ≥ 10

1283 total plots
77 plots with importance value ≥ 10

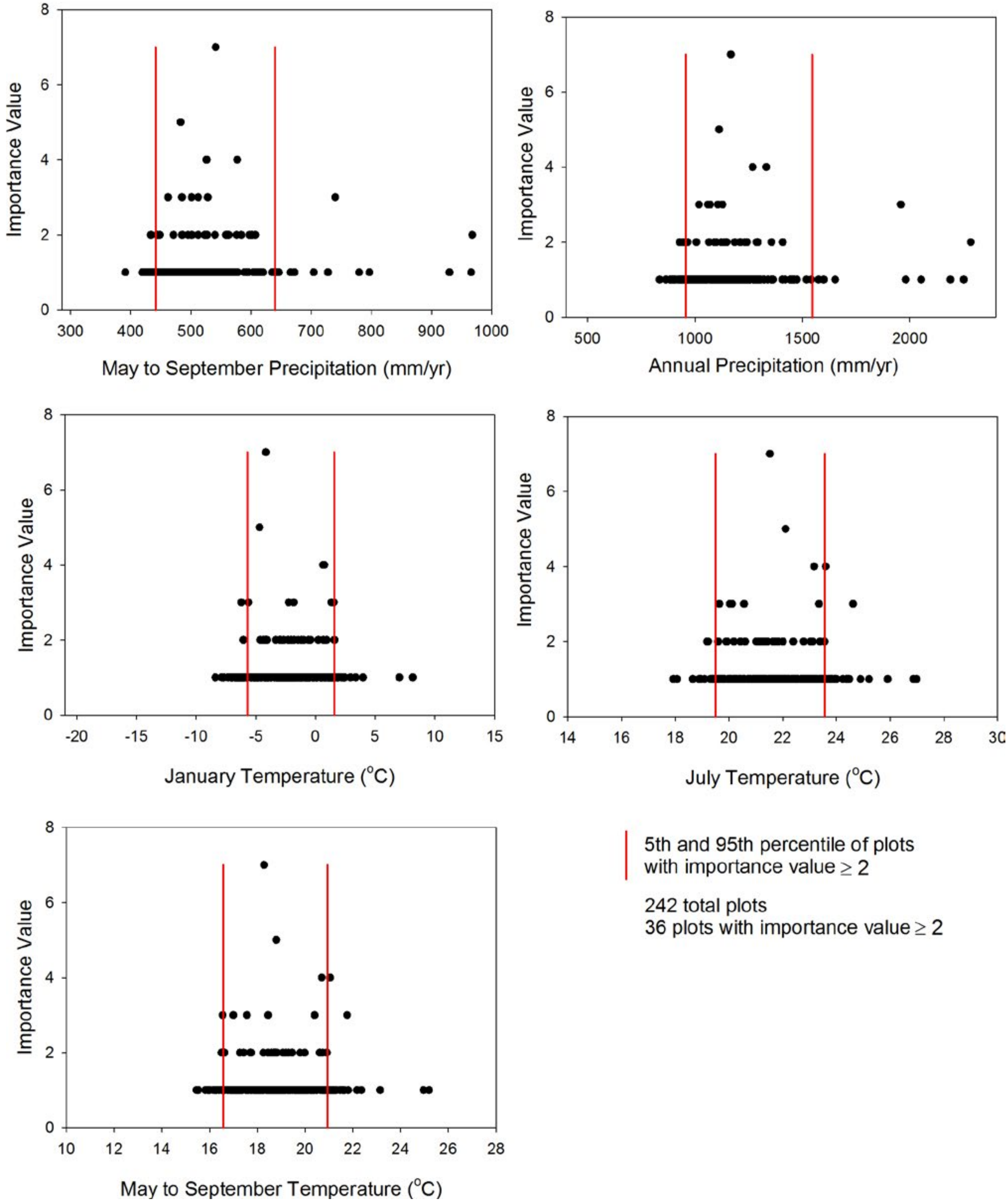
Betula papyrifera (paper birch)
Climate Parameters



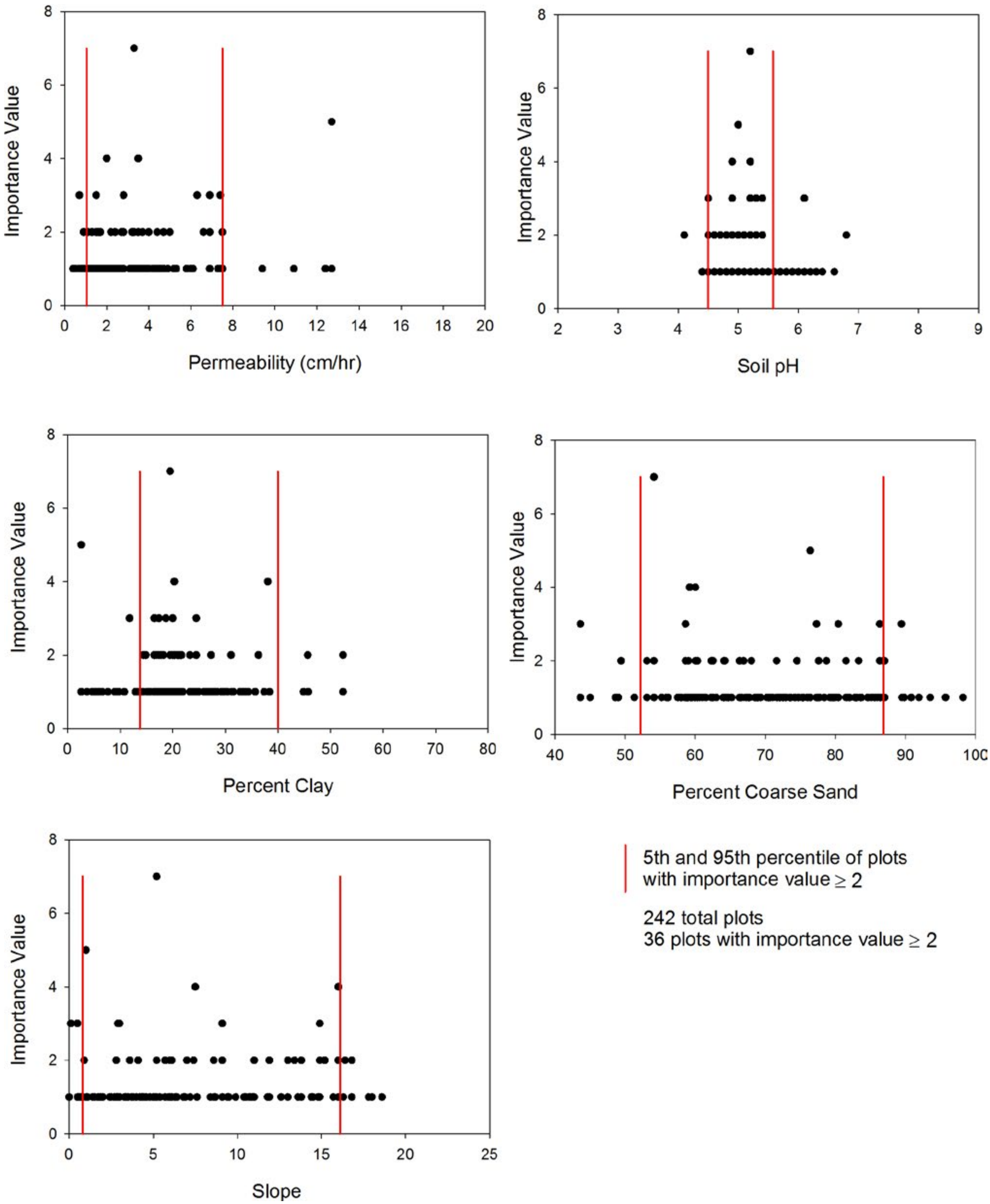
Betula papyrifera (paper birch)
Soil and Topographic Parameters



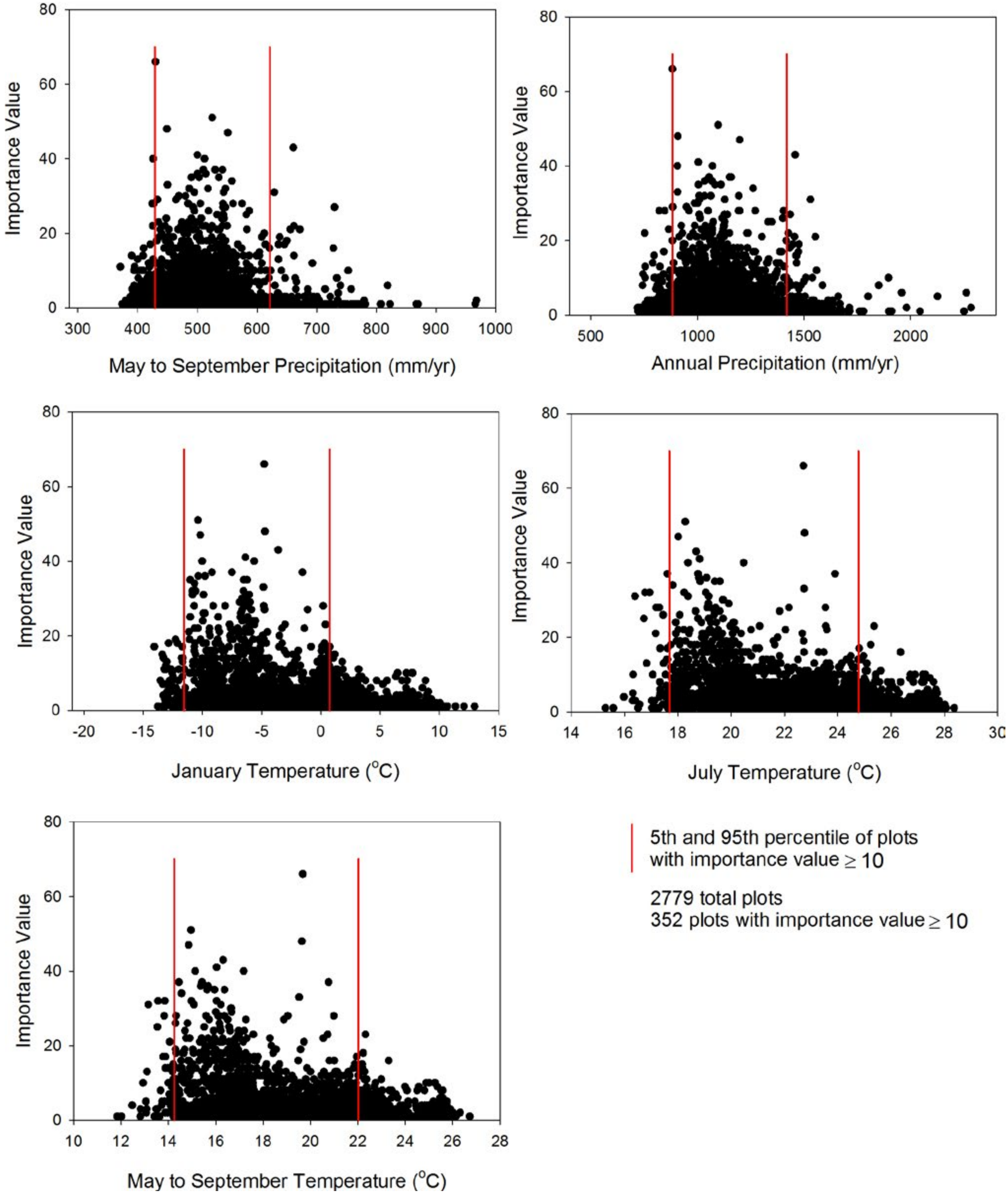
*Castanea dentata (*American chestnut)
Climate Parameters



Castanea dentata (American chestnut)
Soil and Topographic Parameters



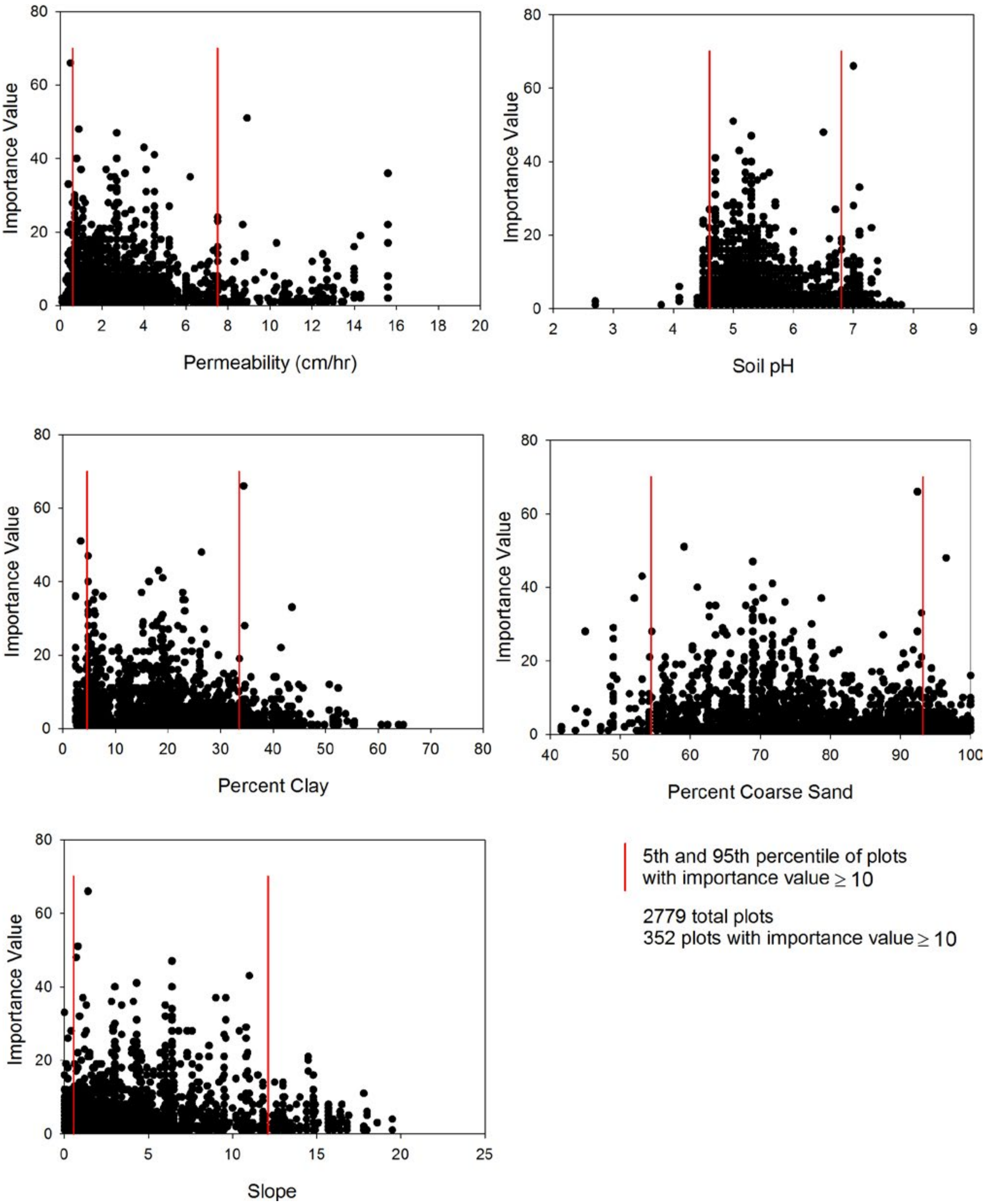
Fagus grandifolia (American beech)
Climate Parameters



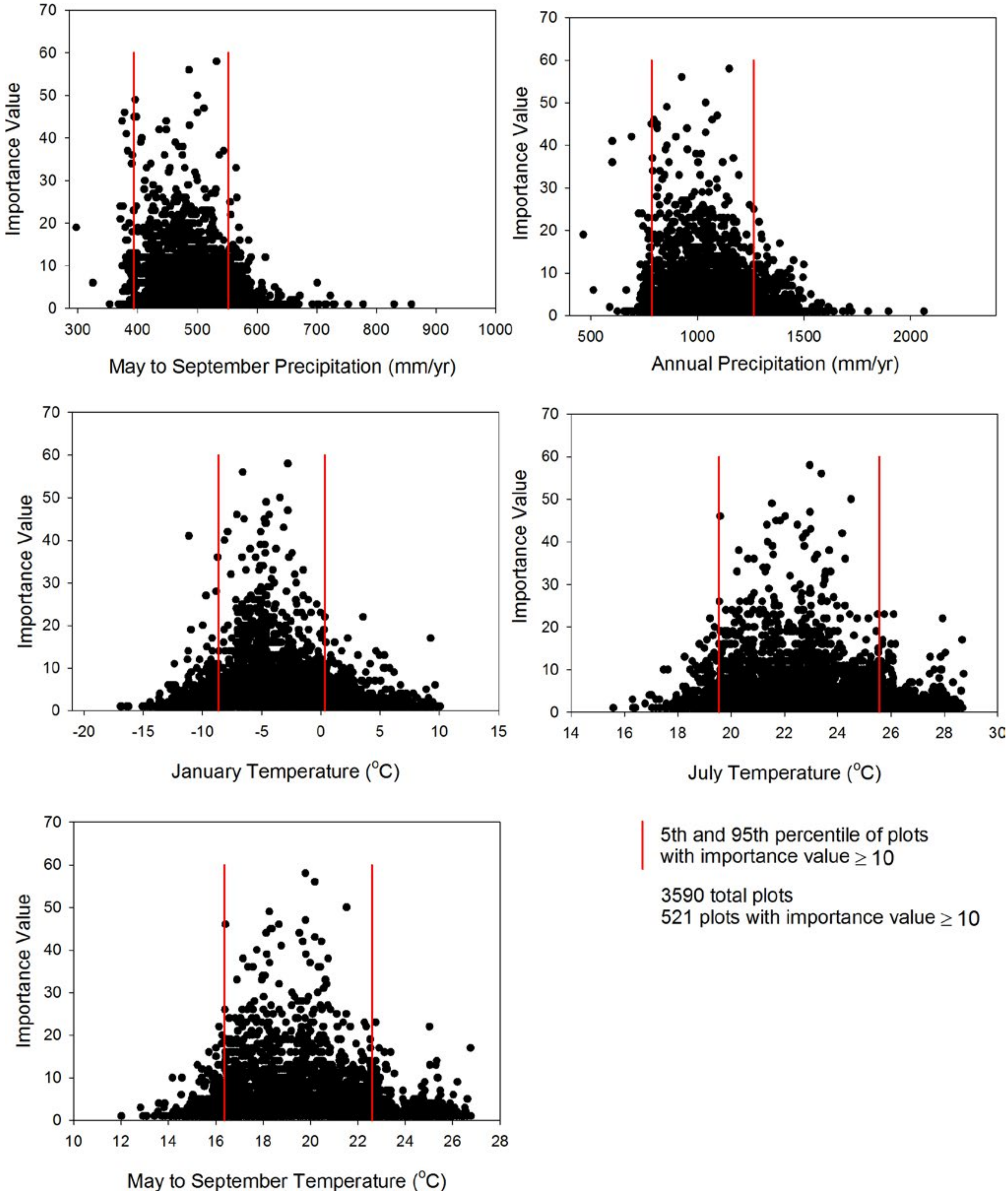
5th and 95th percentile of plots with importance value ≥ 10

2779 total plots
352 plots with importance value ≥ 10

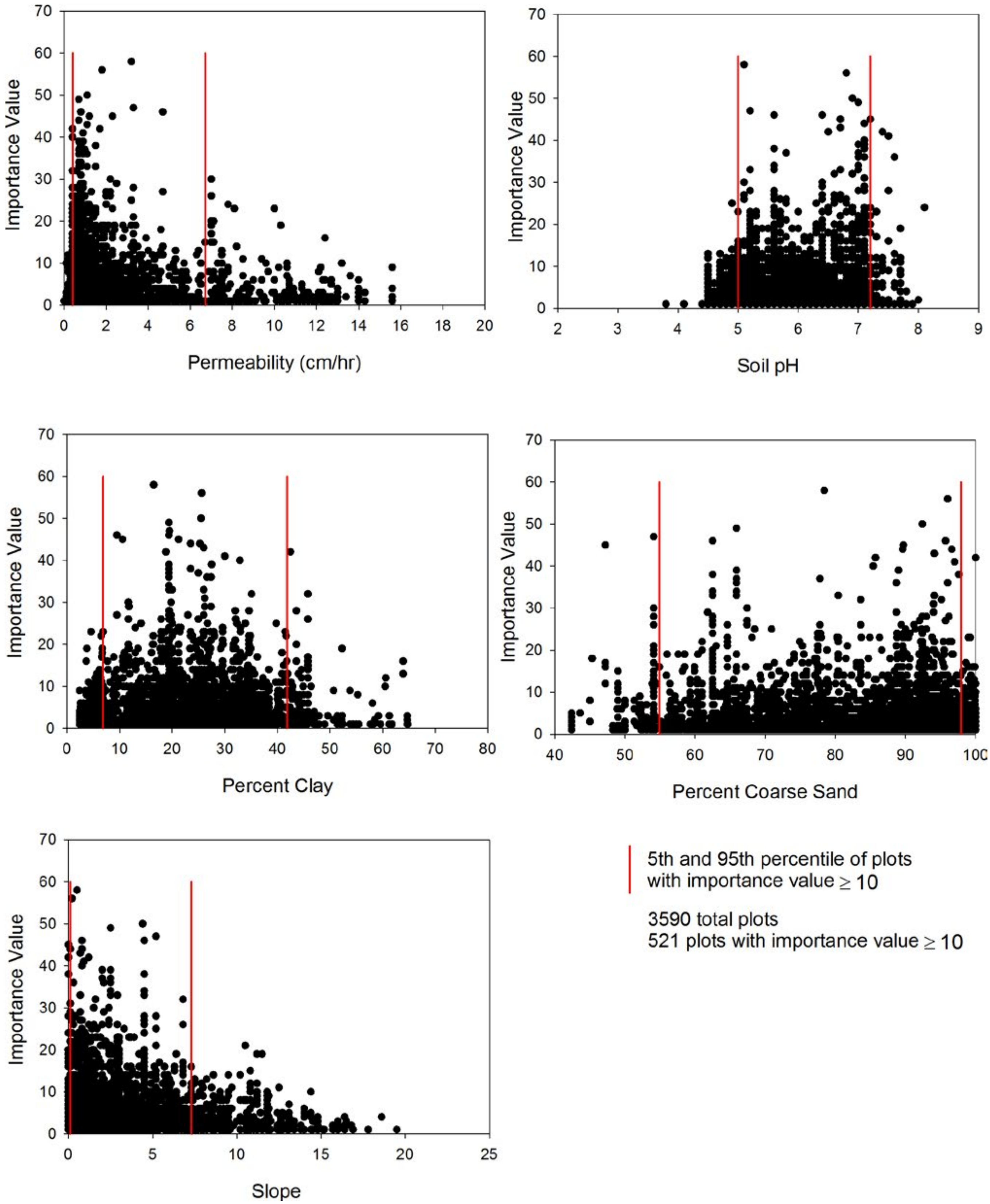
Fagus grandifolia (American beech)
Soil and Topographic Parameters



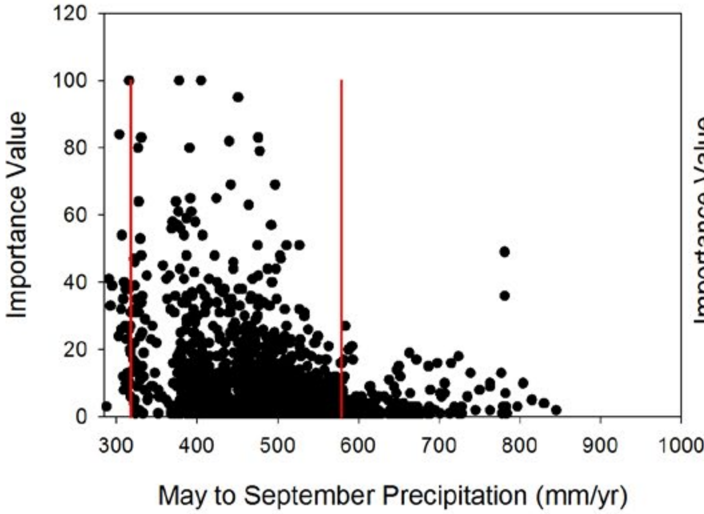
Fraxinus americana (white ash)
Climate Parameters

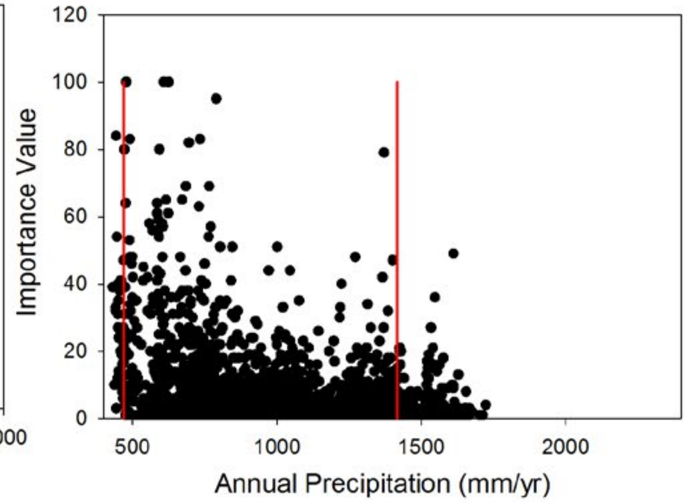


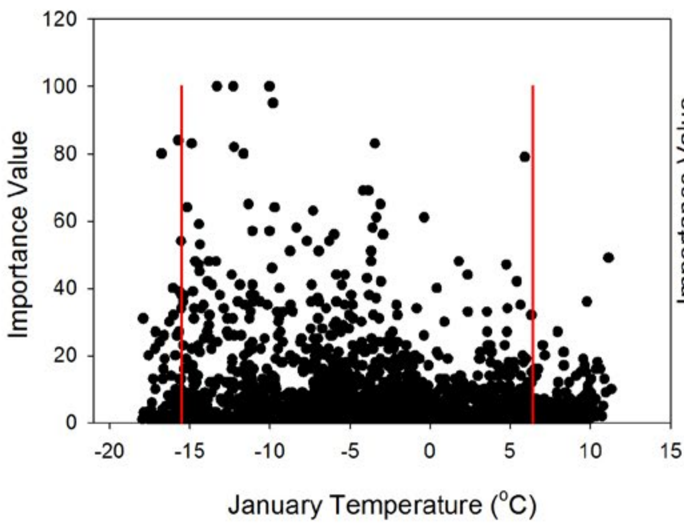
Fraxinus americana (white ash)
Soil and Topographic Parameters

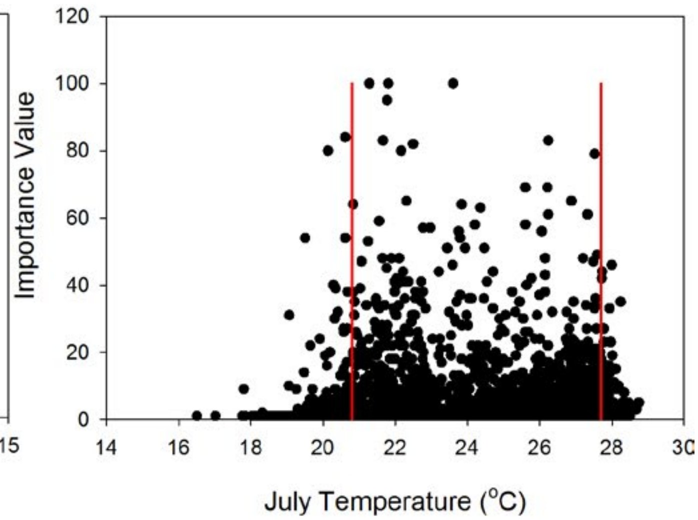


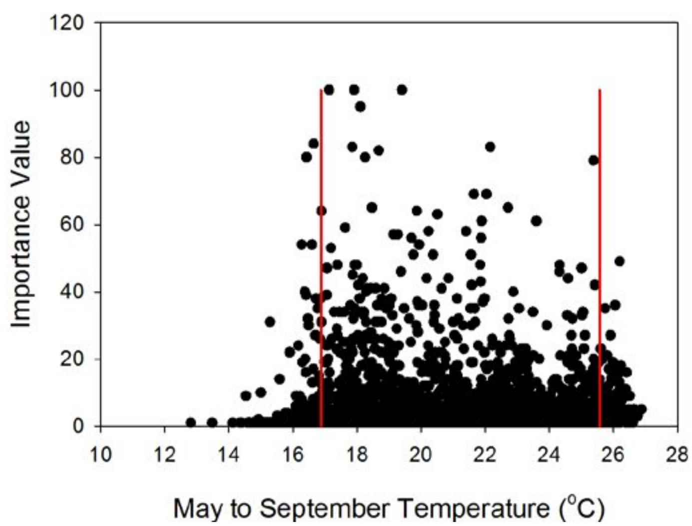
Fraxinus pennsylvanica (green ash)
Climate Parameters







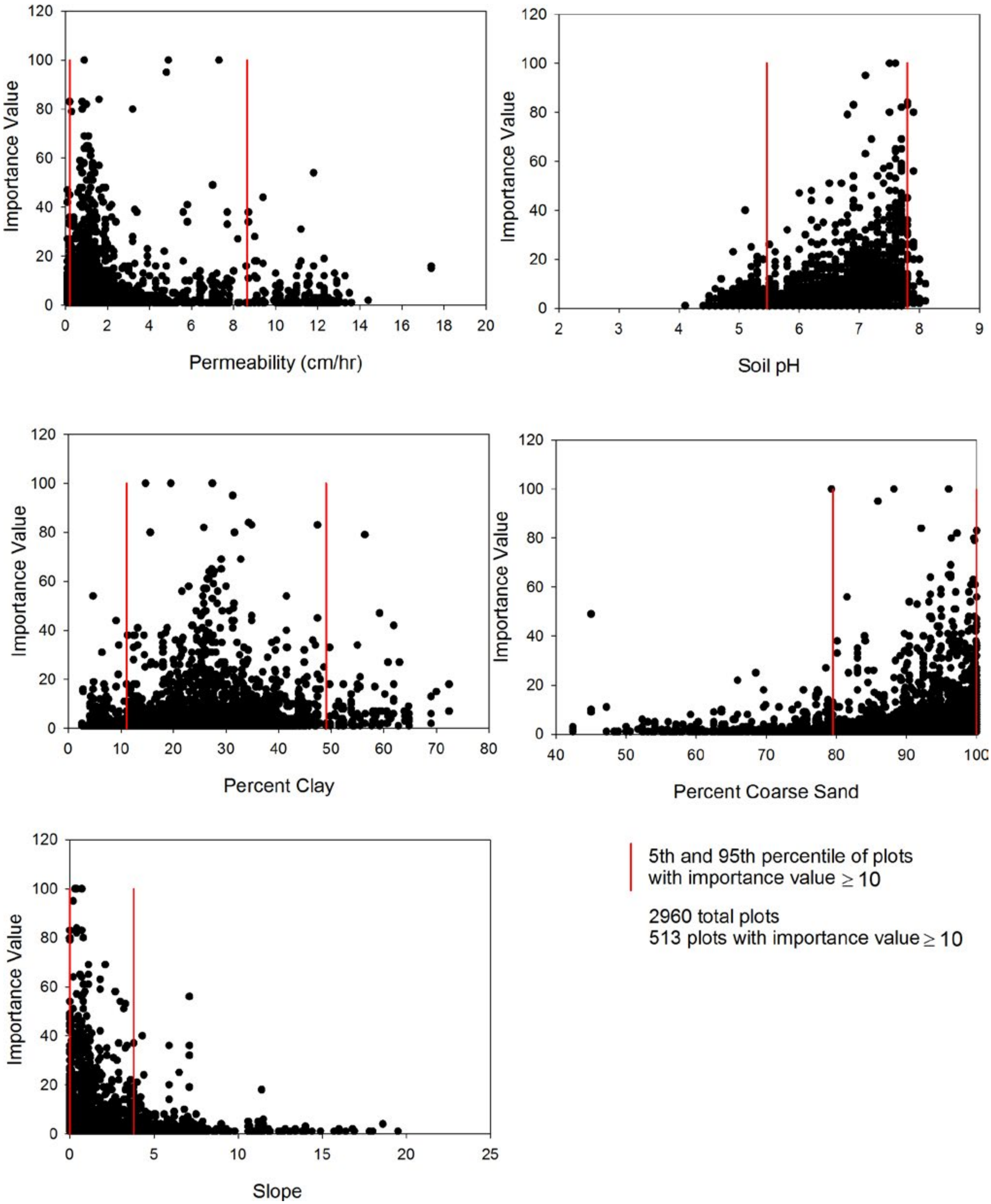




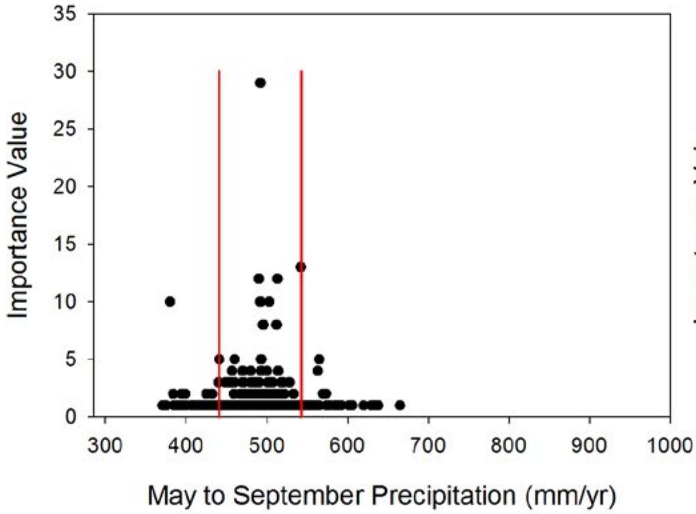
5th and 95th percentile of plots with importance value ≥ 10

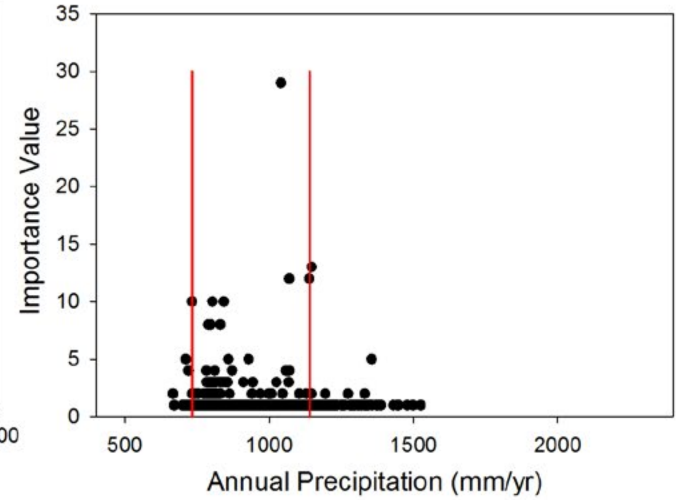
2960 total plots
513 plots with importance value ≥ 10

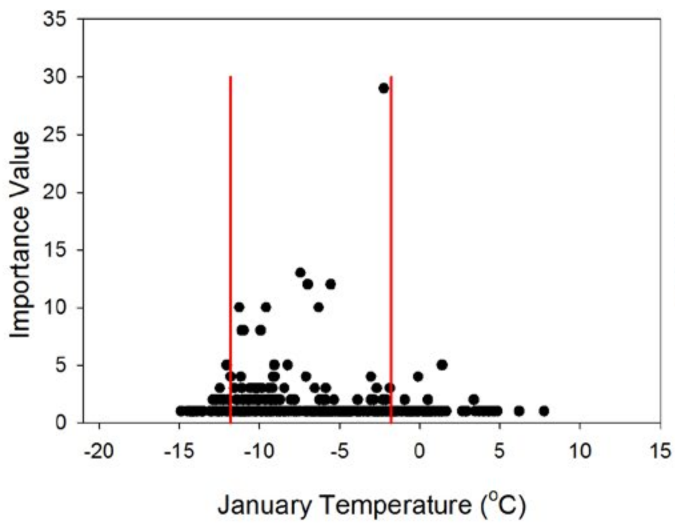
Fraxinus pennsylvanica (green ash)
Soil and Topographic Parameters

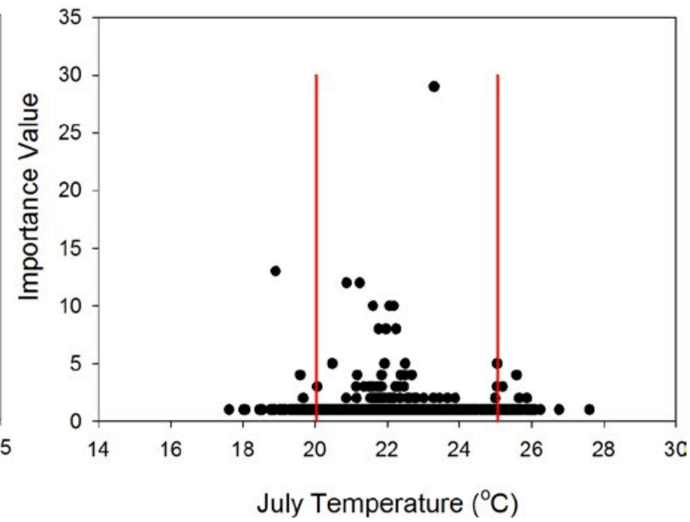


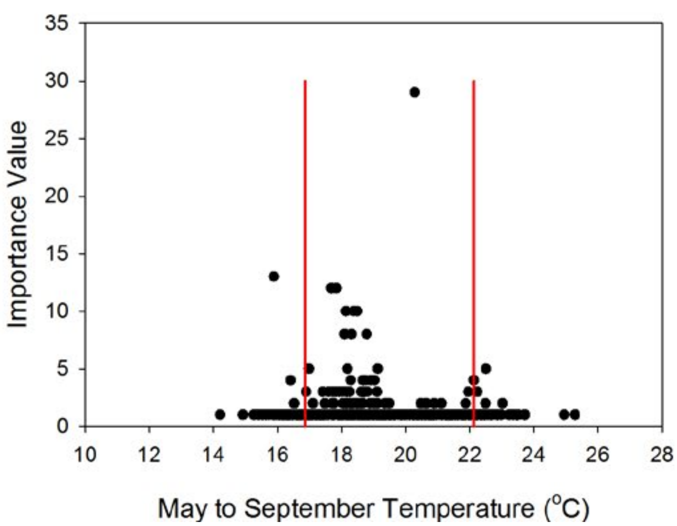
Juglans cinerea (butternut)
Climate Parameters







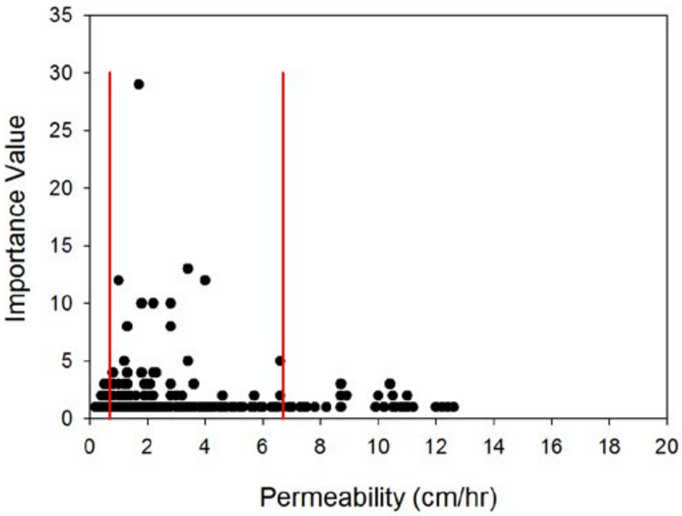


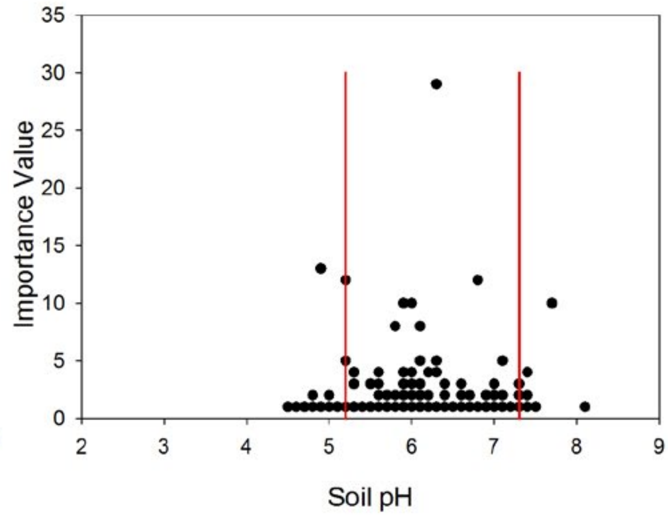


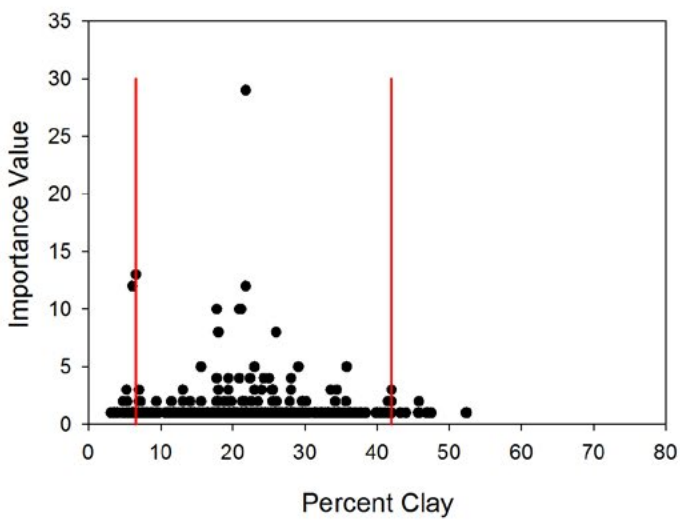
5th and 95th percentile of plots with importance value ≥ 3

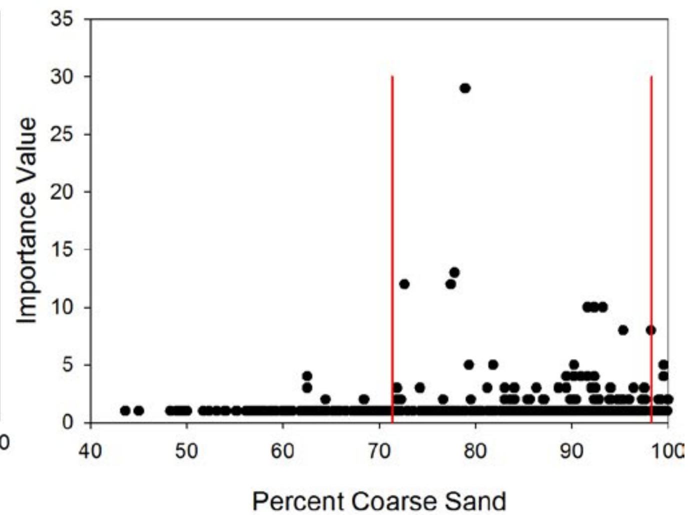
457 total plots
40 plots with importance value ≥ 3

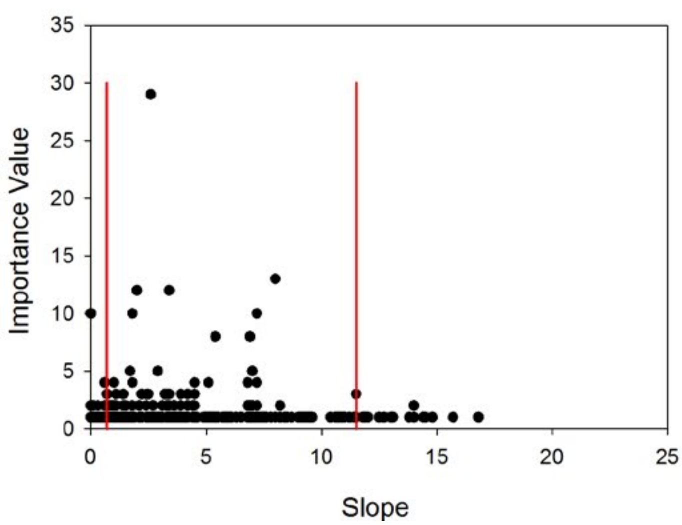
Juglans cinerea (butternut)
Soil and Topographic Parameters







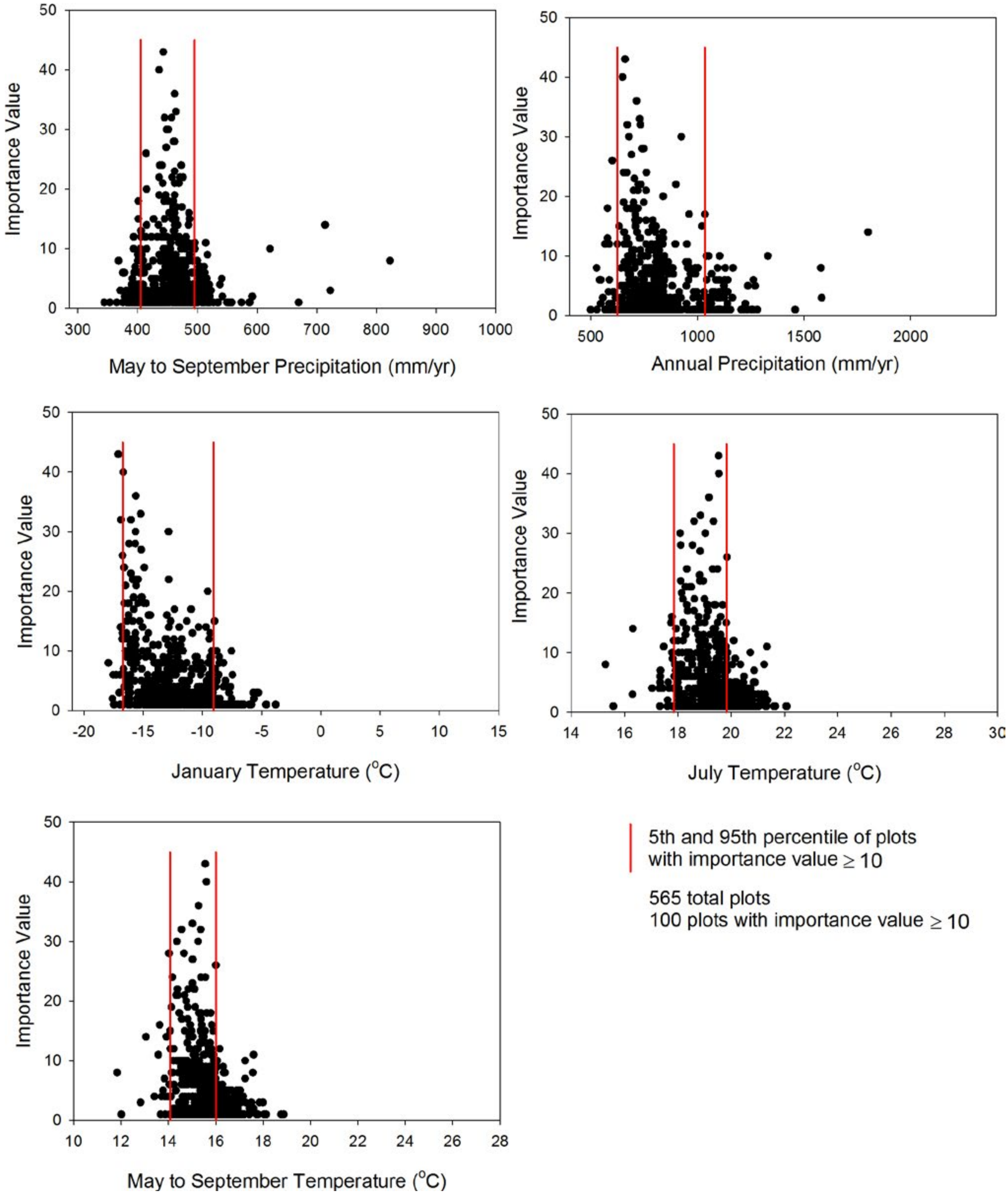




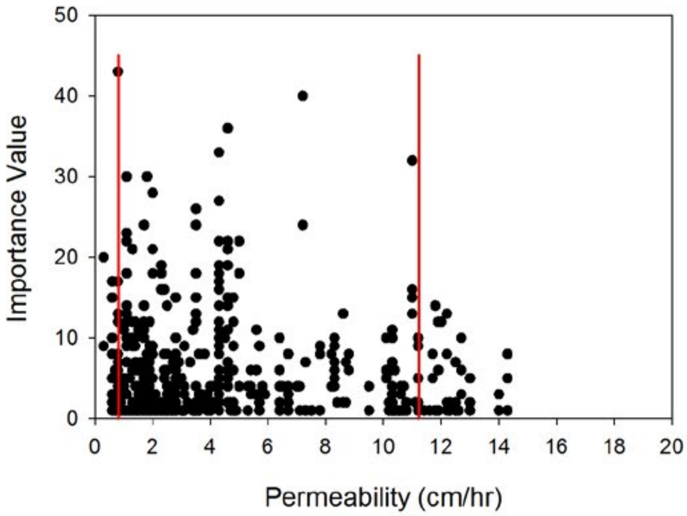
5th and 95th percentile of plots
with importance value ≥ 3

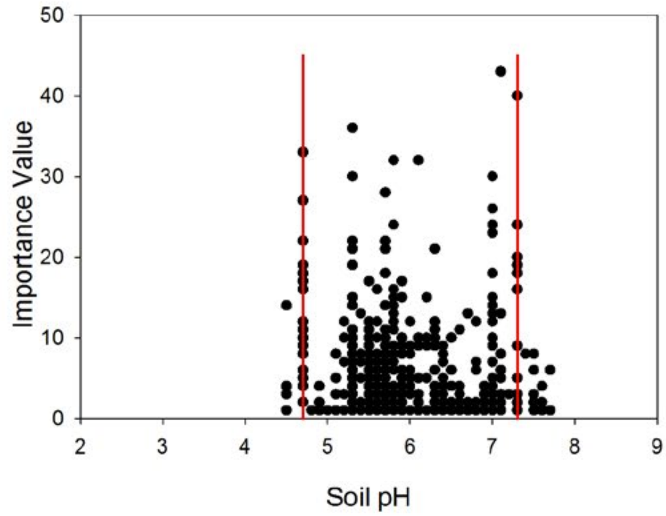
457 total plots
40 plots with importance value ≥ 3

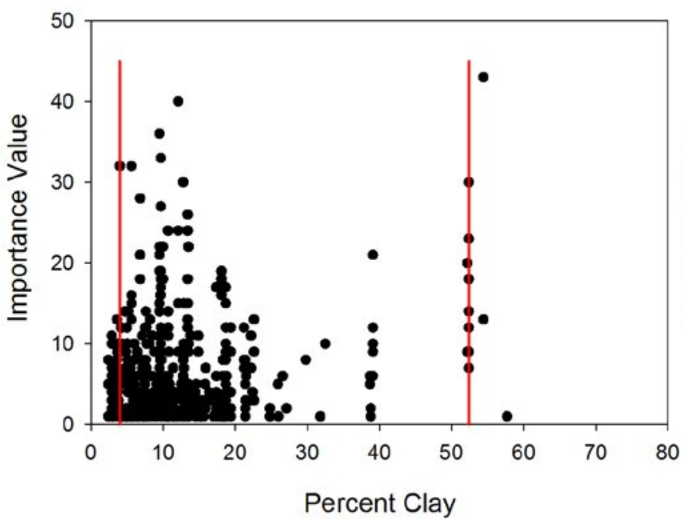
Picea mariana (black spruce)
Climate Parameters

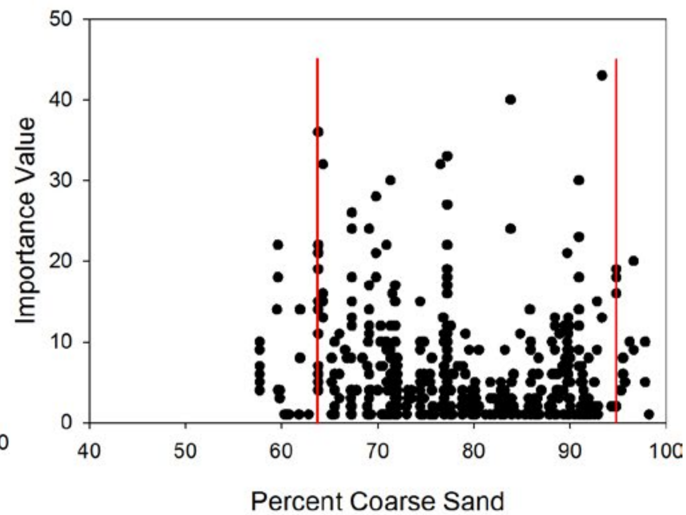


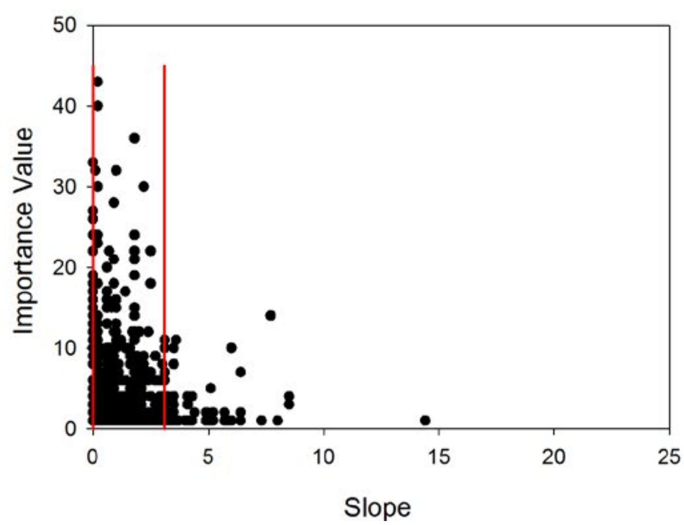
Picea mariana (black spruce)
Soil and Topographic Parameters







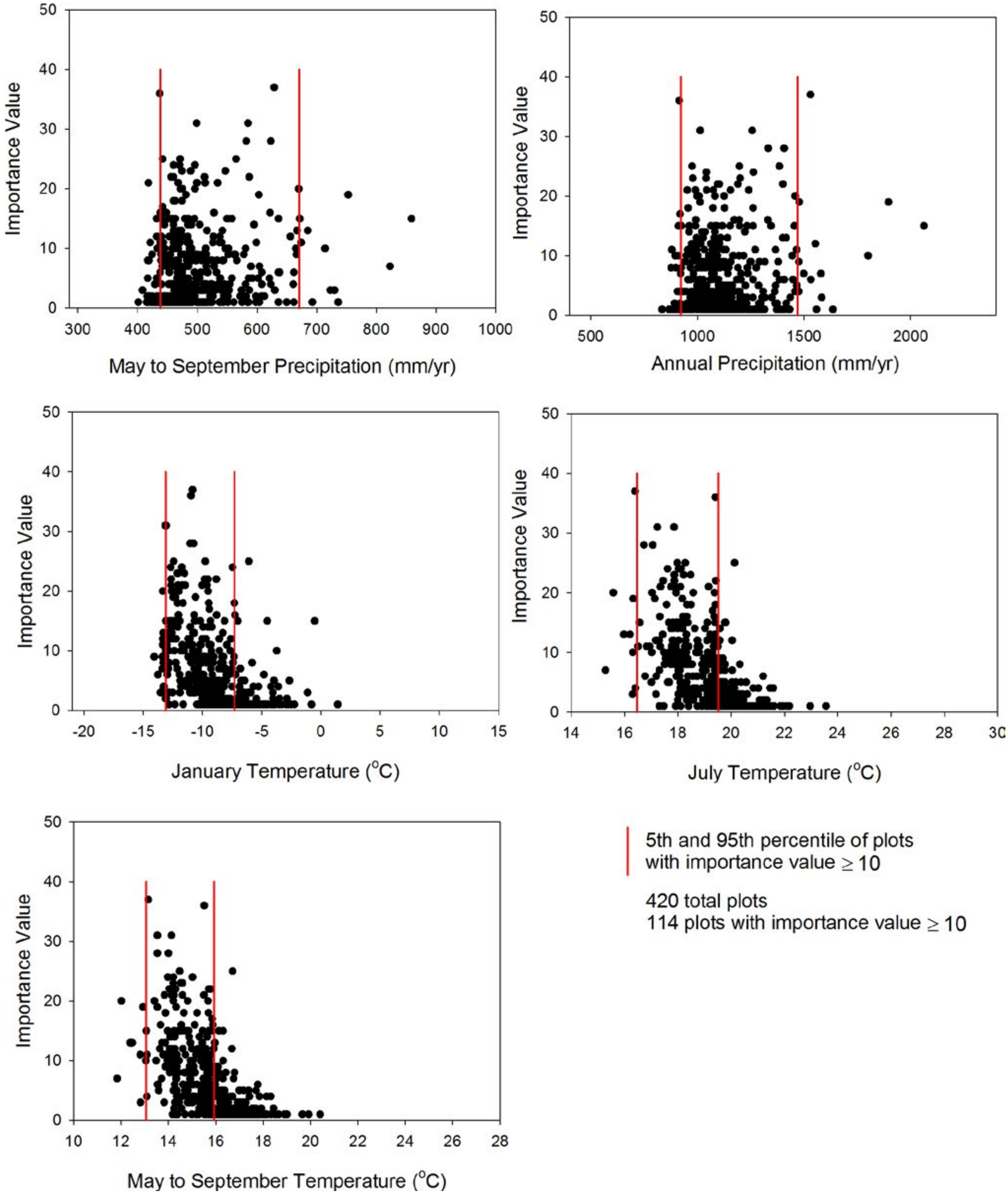




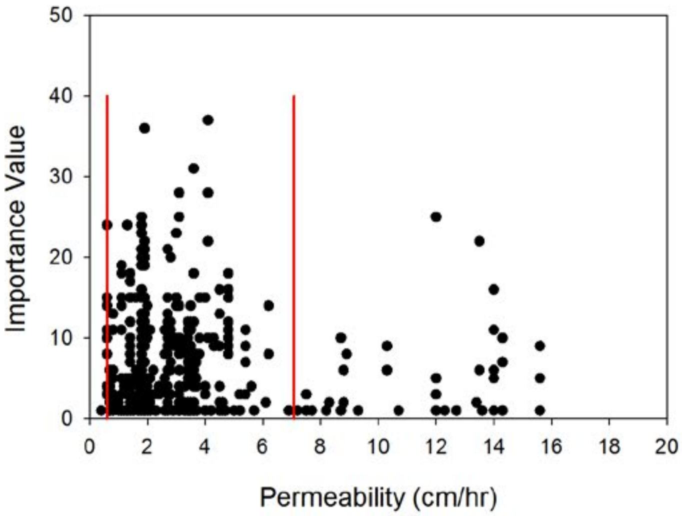
5th and 95th percentile of plots with importance value ≥ 10

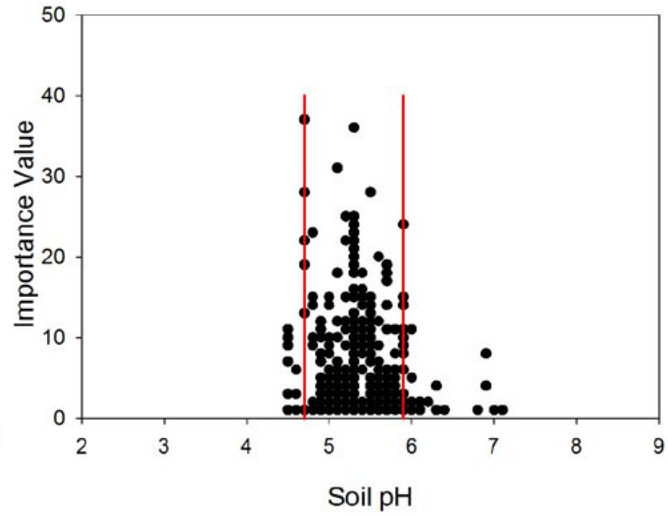
565 total plots
100 plots with importance value ≥ 10

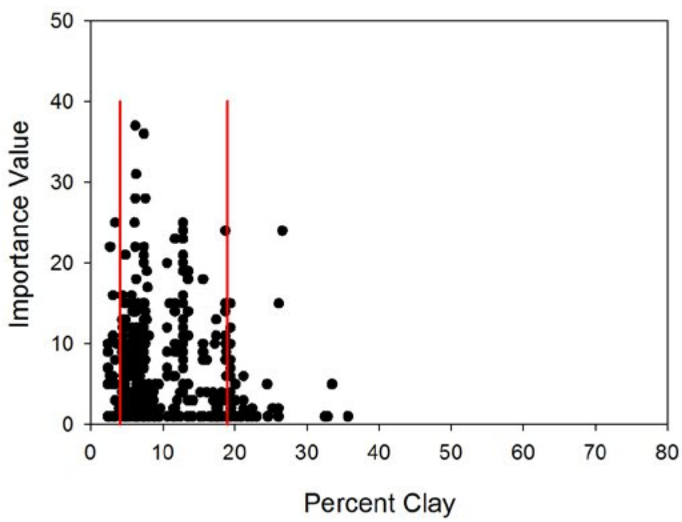
Picea rubens (red spruce)
Climate Parameters

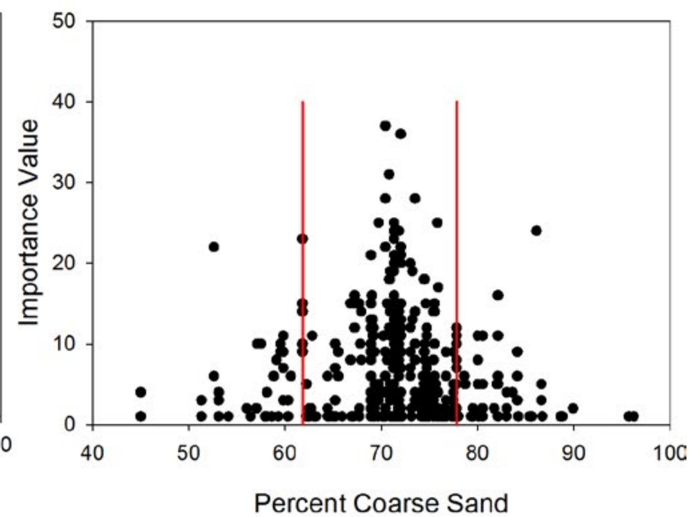


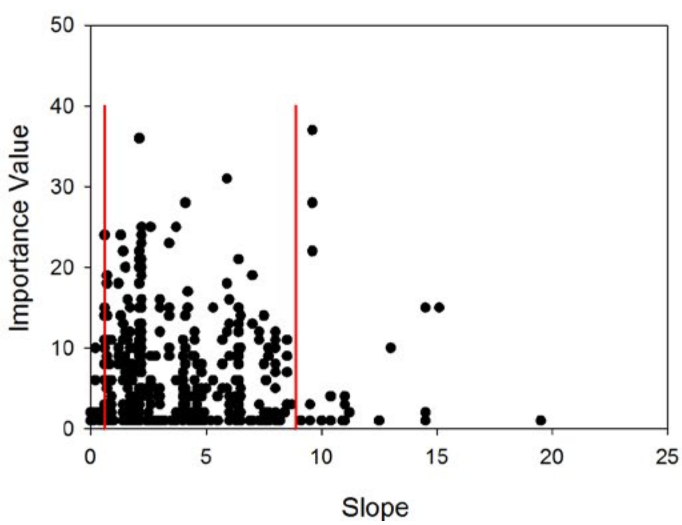
Picea rubens (red spruce)
Soil and Topographic Parameters







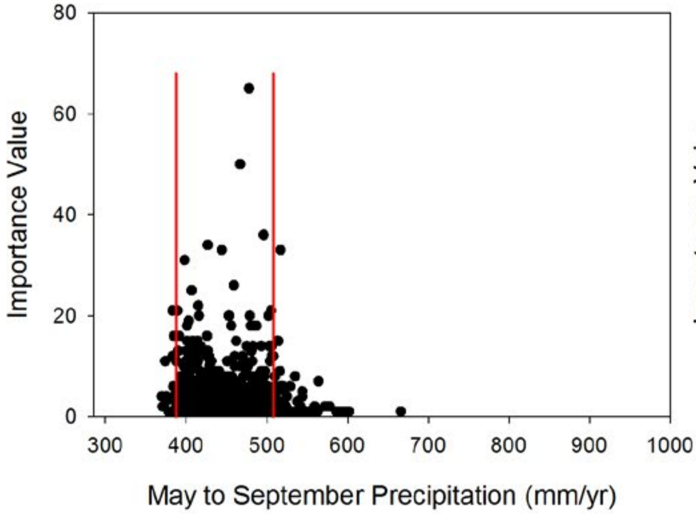


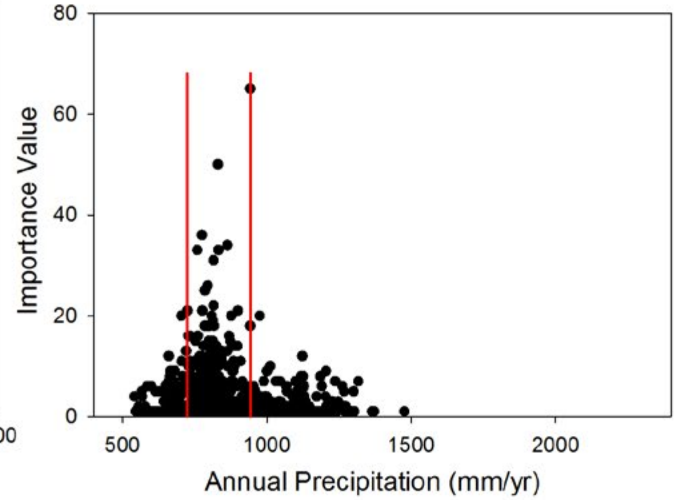


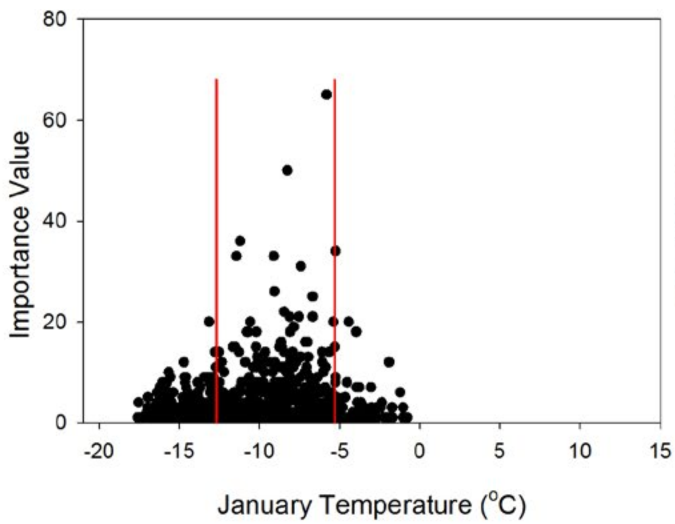
5th and 95th percentile of plots with importance value ≥ 10

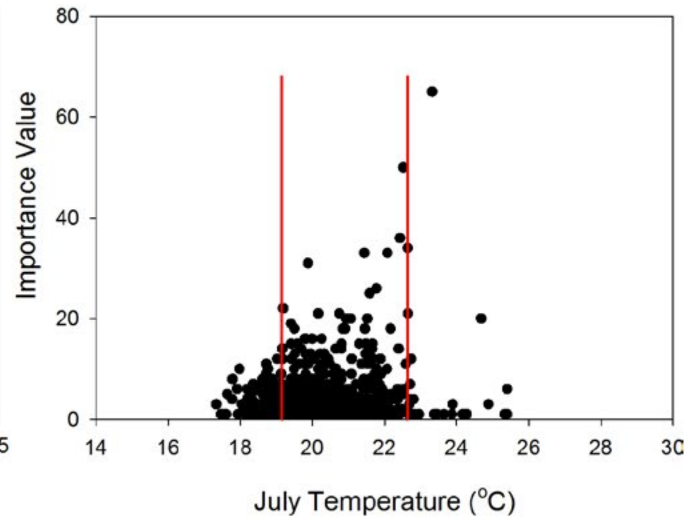
420 total plots
114 plots with importance value ≥ 10

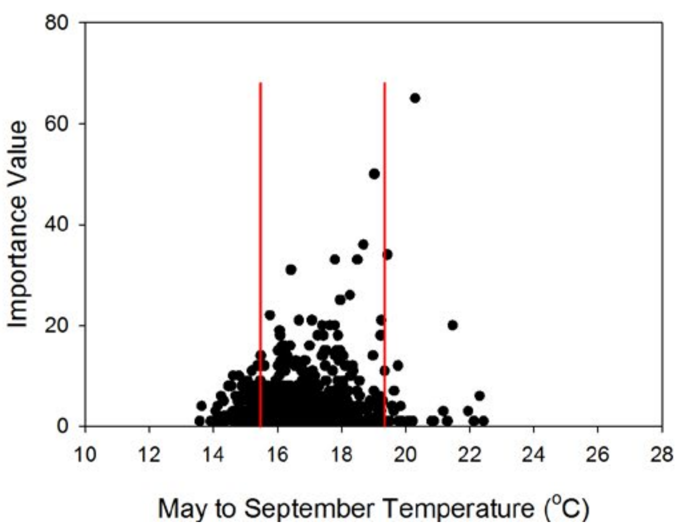
Pinus resinosa (red pine)
Climate Parameters







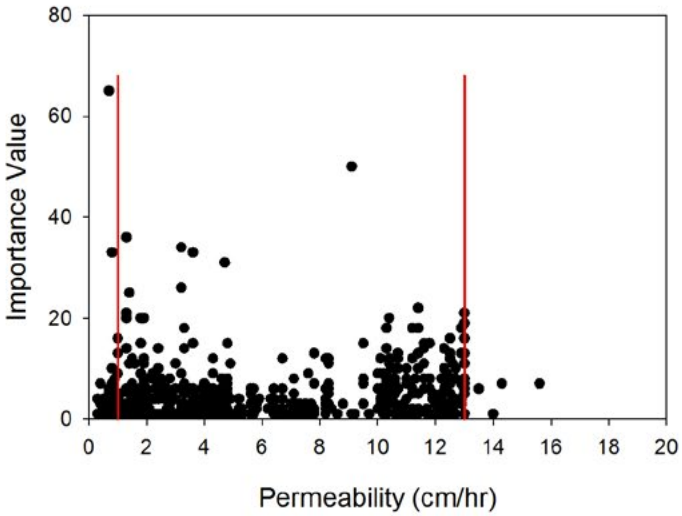


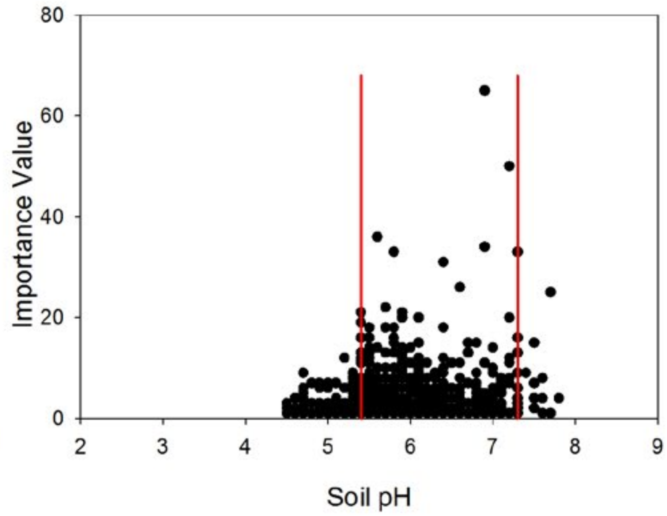


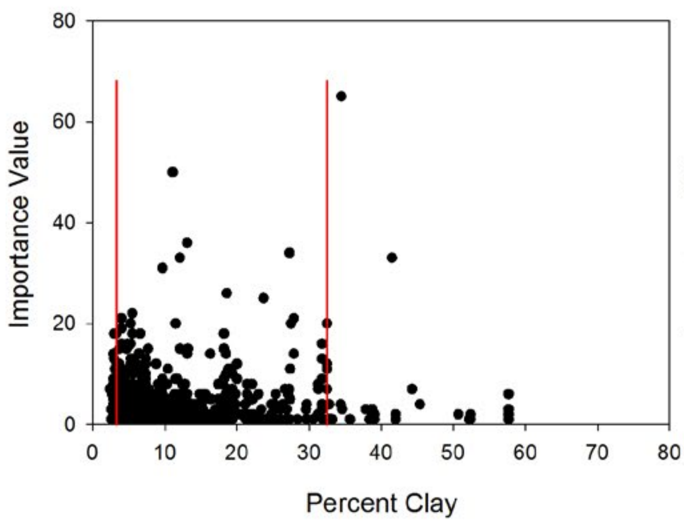
5th and 95th percentile of plots with importance value ≥ 10

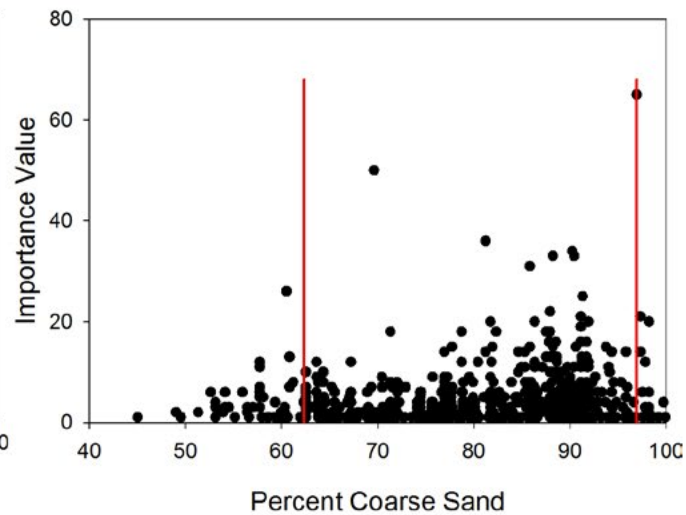
763 total plots
79 plots with importance value ≥ 10

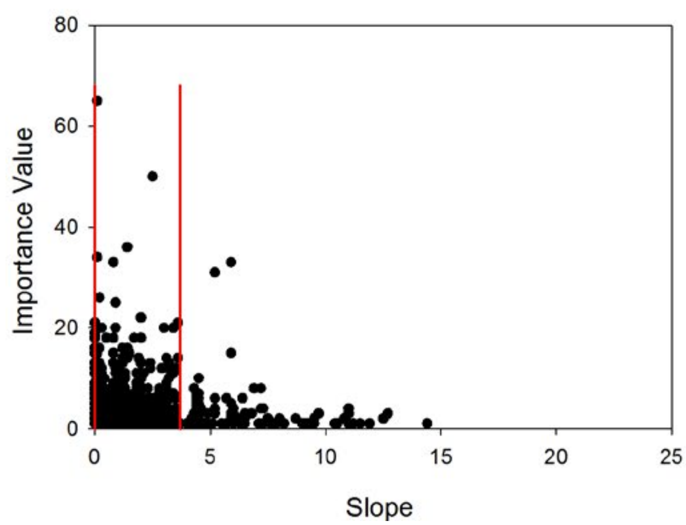
Pinus resinosa (red pine)
Soil and Topographic Parameters







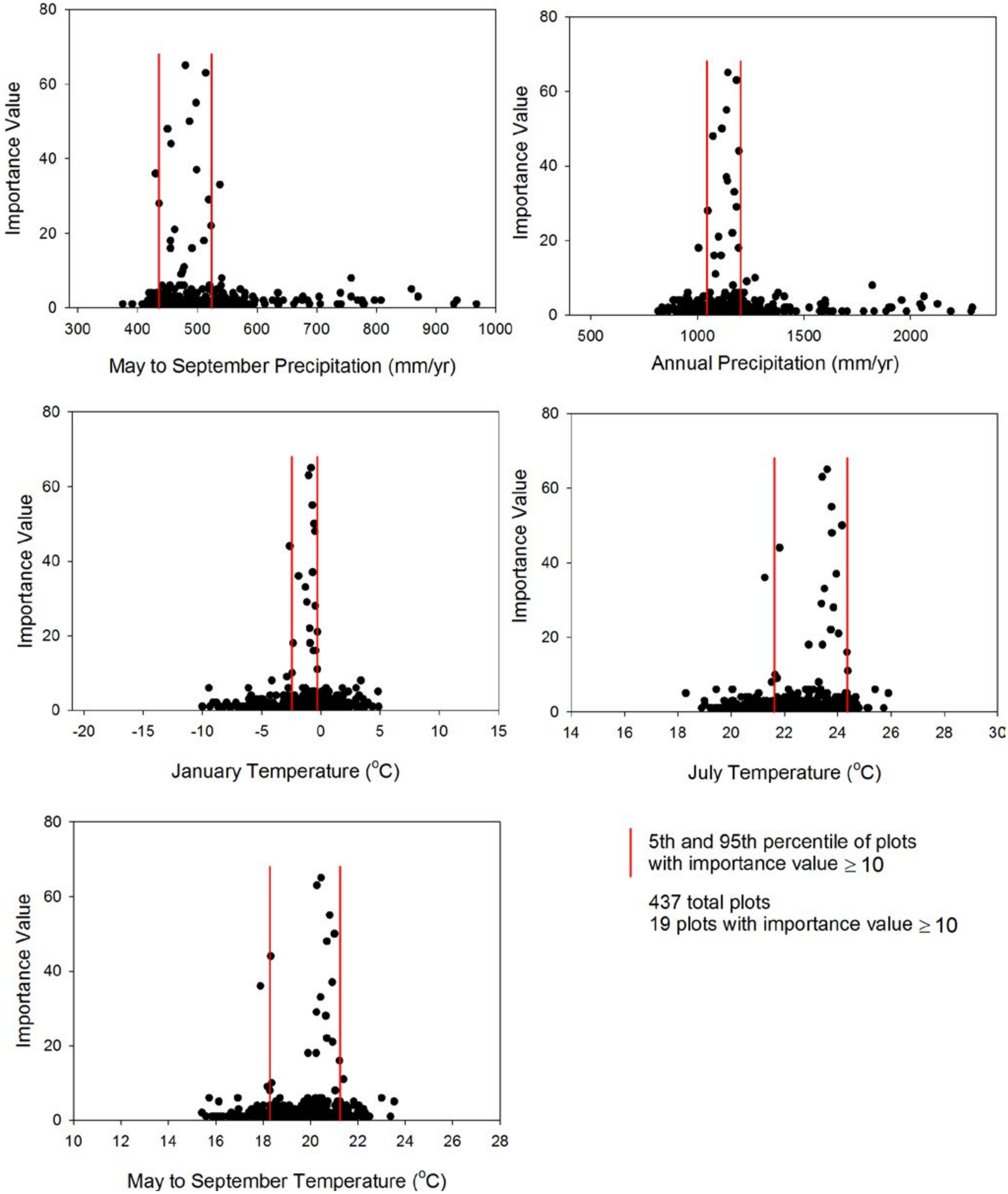




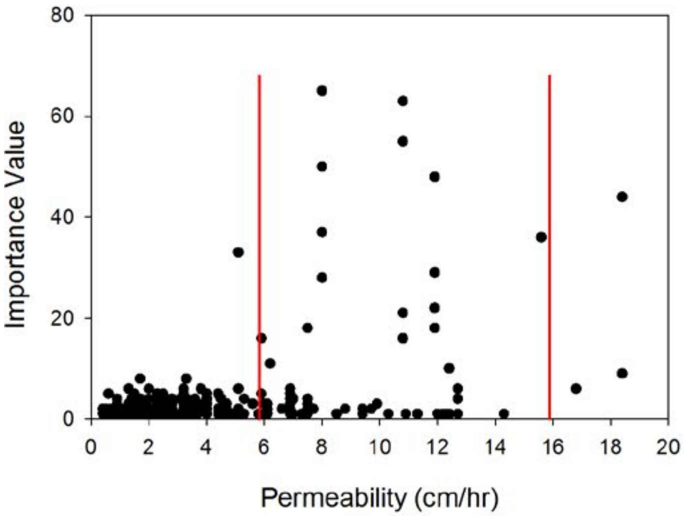
5th and 95th percentile of plots with importance value ≥ 10

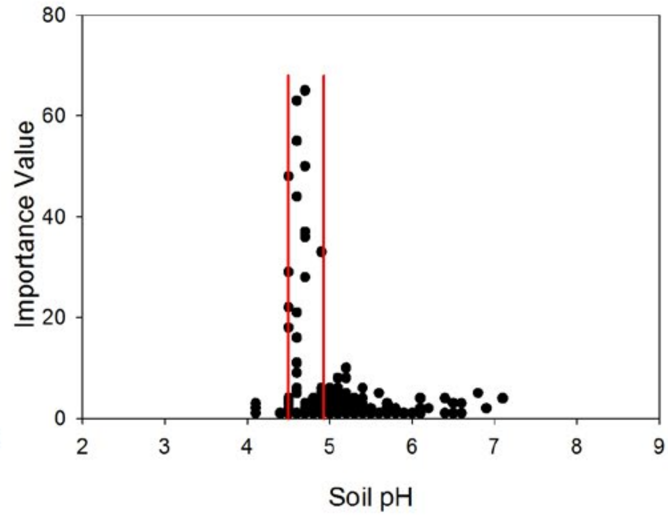
763 total plots
79 plots with importance value ≥ 10

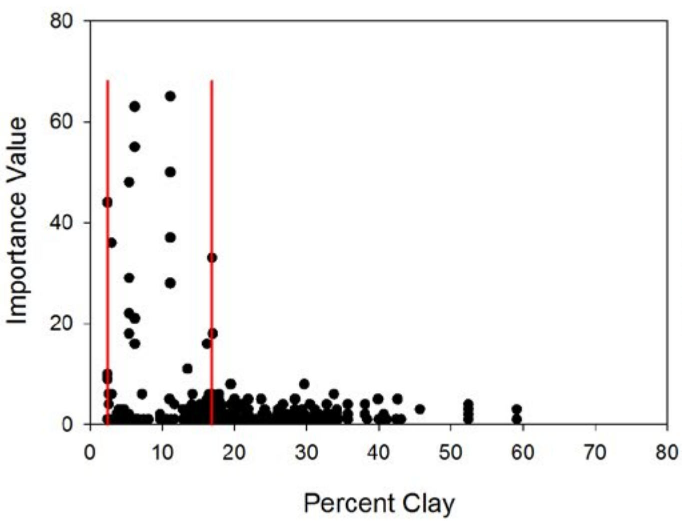
Pinus rigida (pitch pine)
Climate Parameters

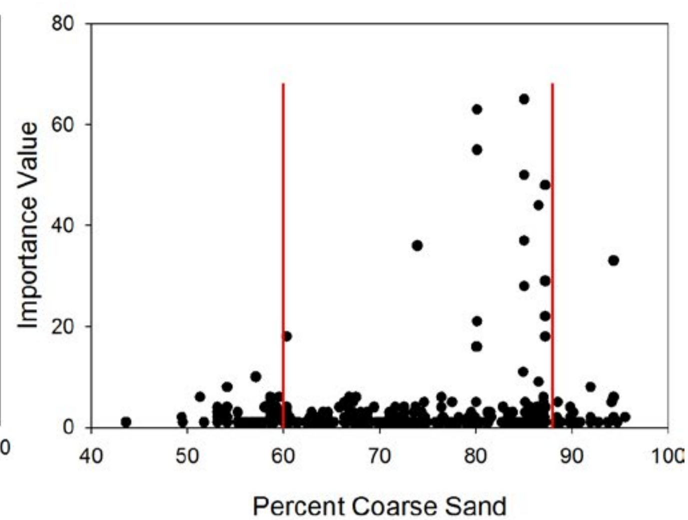


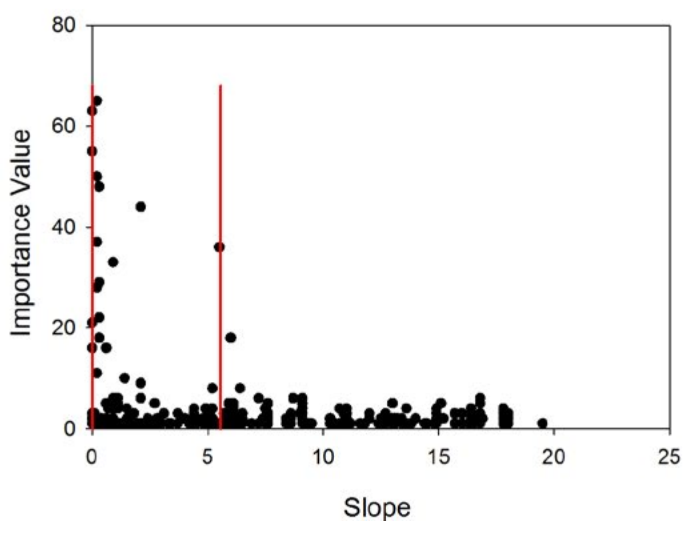
Pinus rigida (pitch pine)
Soil and Topographic Parameters







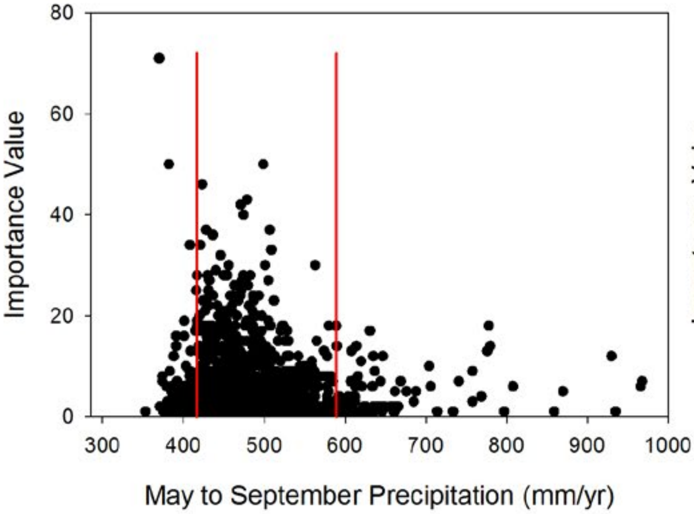


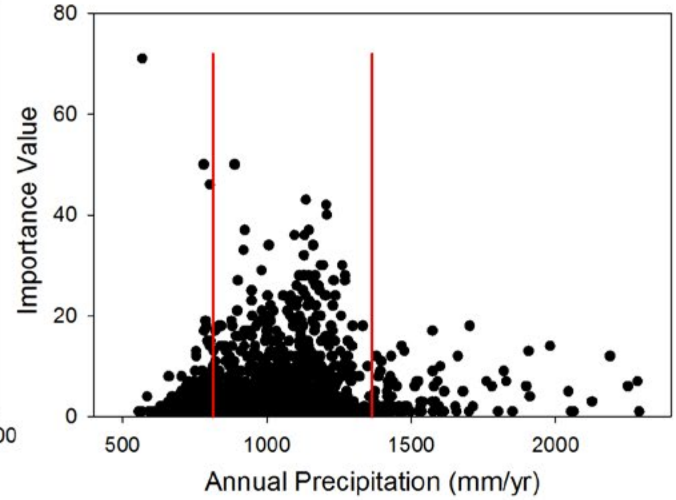


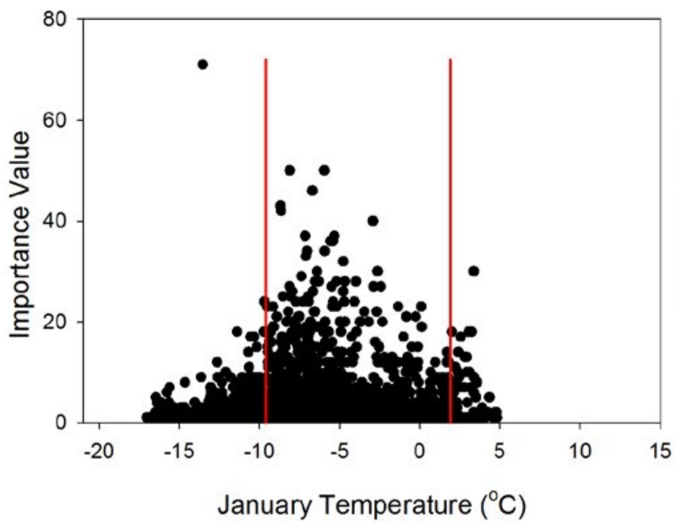
5th and 95th percentile of plots with importance value ≥ 10

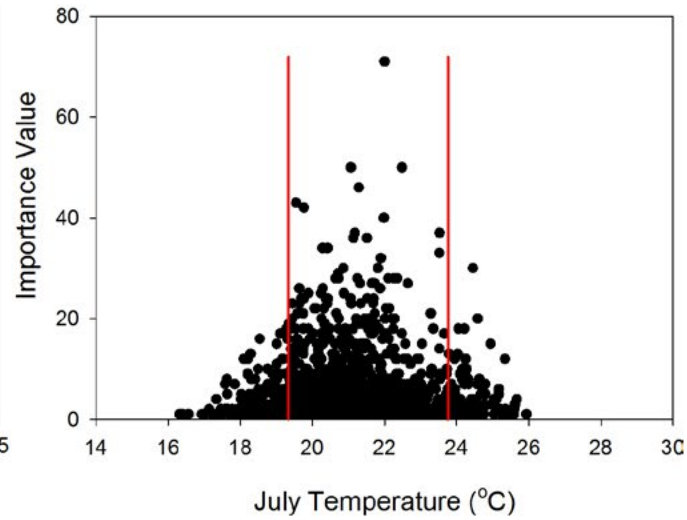
437 total plots
19 plots with importance value ≥ 10

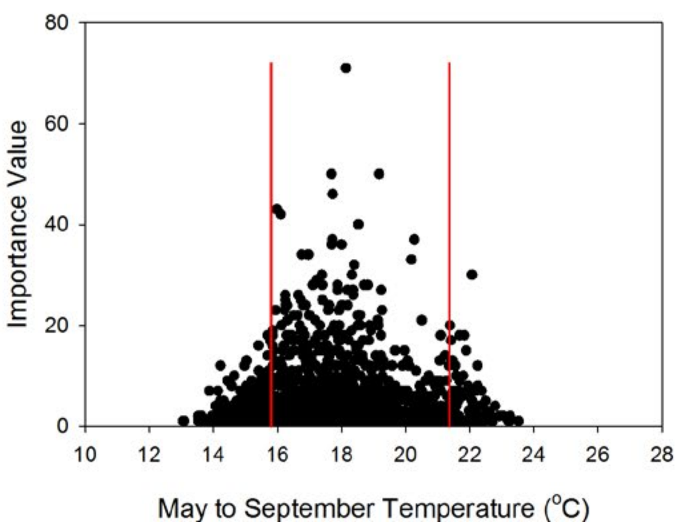
Pinus strobus (white pine)
Climate Parameters







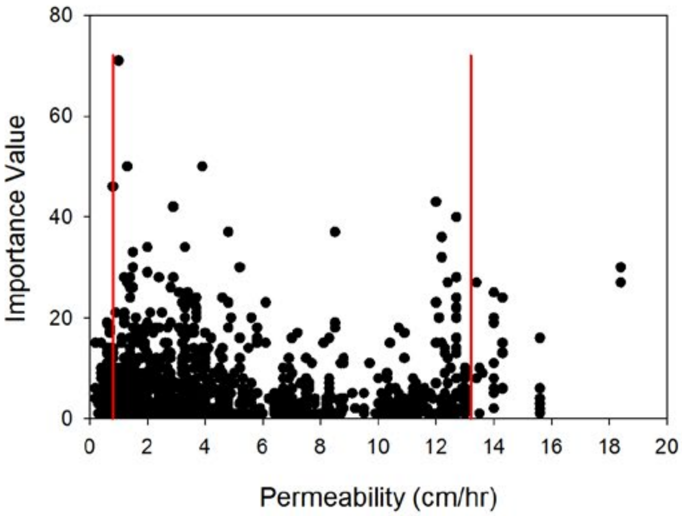


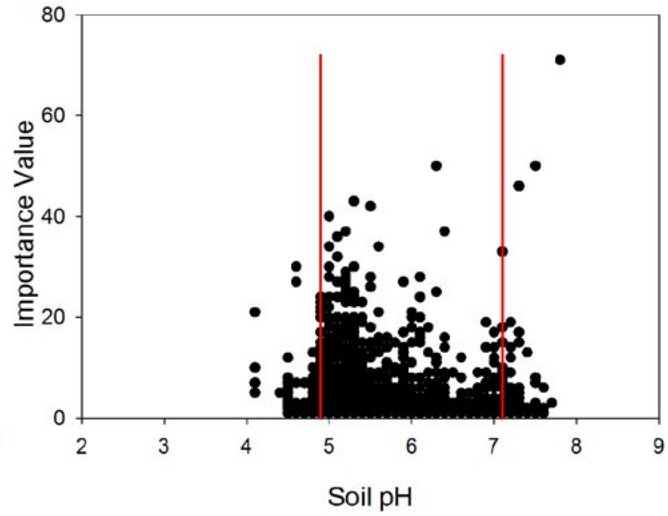


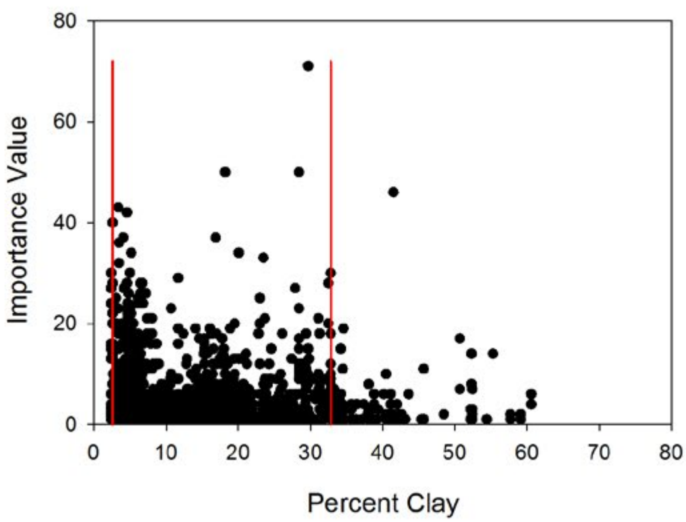
5th and 95th percentile of plots with importance value ≥ 10

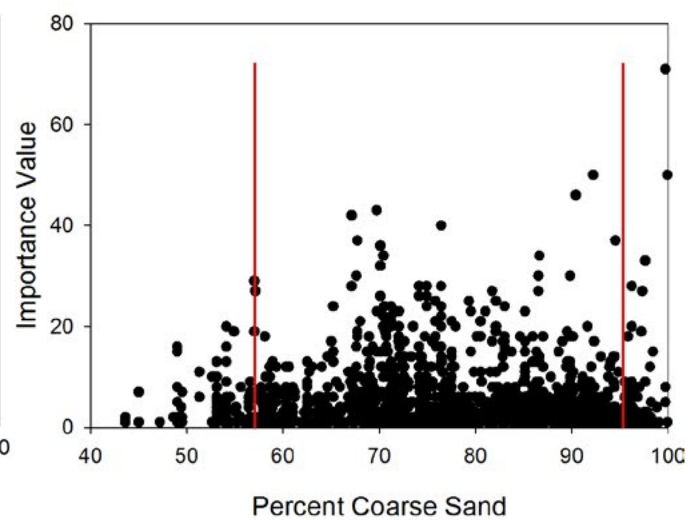
1722 total plots
231 plots with importance value ≥ 10

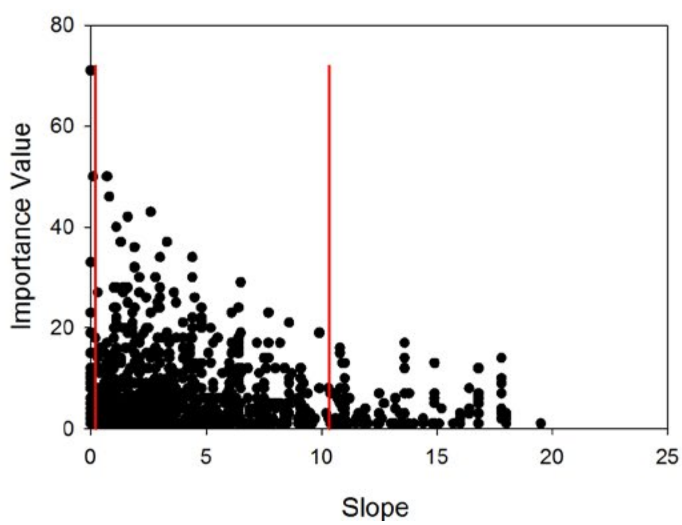
Pinus strobus (white pine)
Soil and Topographic Parameters







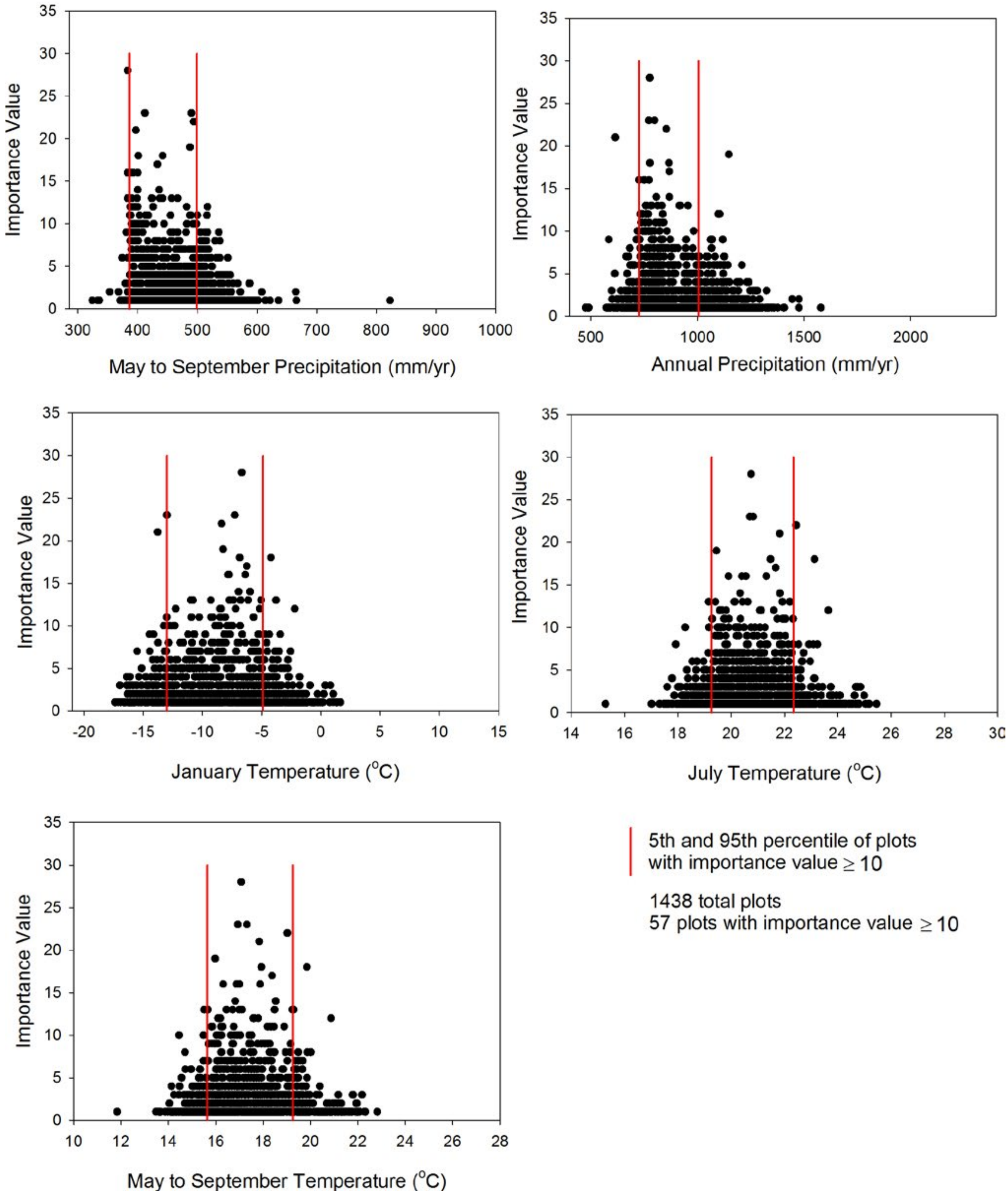




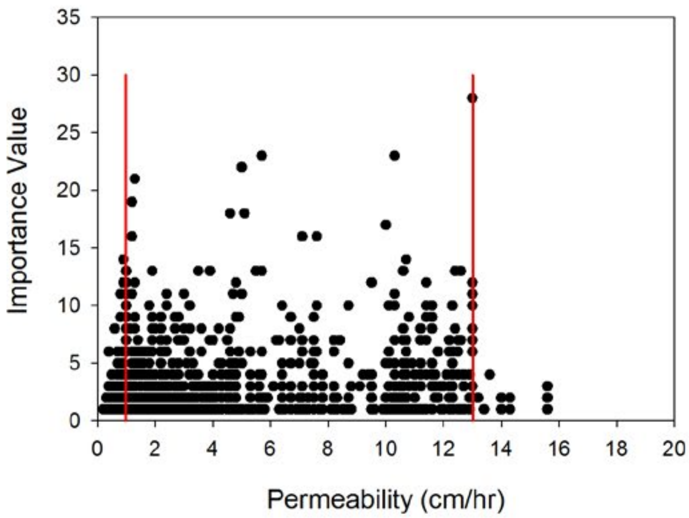
5th and 95th percentile of plots
with importance value ≥ 10

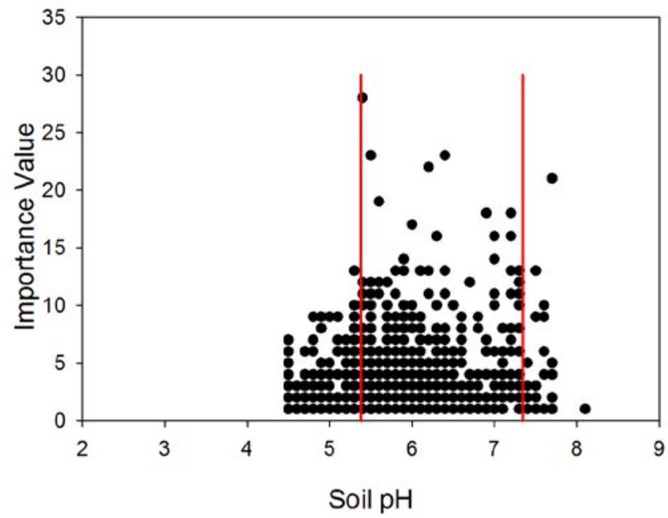
1722 total plots
231 plots with importance value ≥ 10

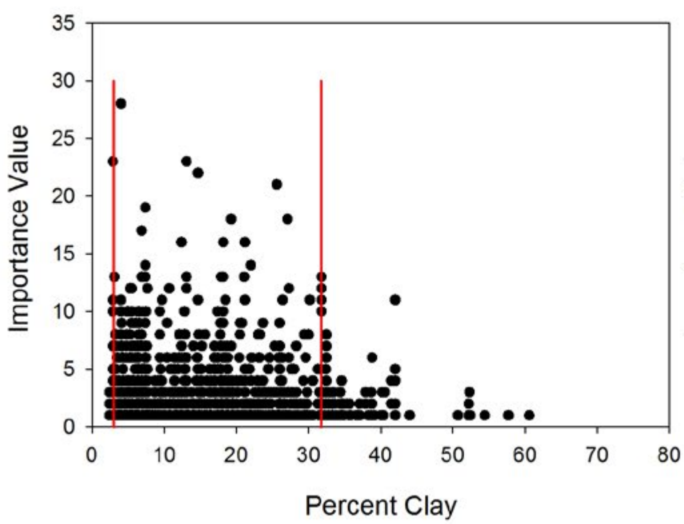
Populus grandidentata (bigtooth aspen)
Climate Parameters

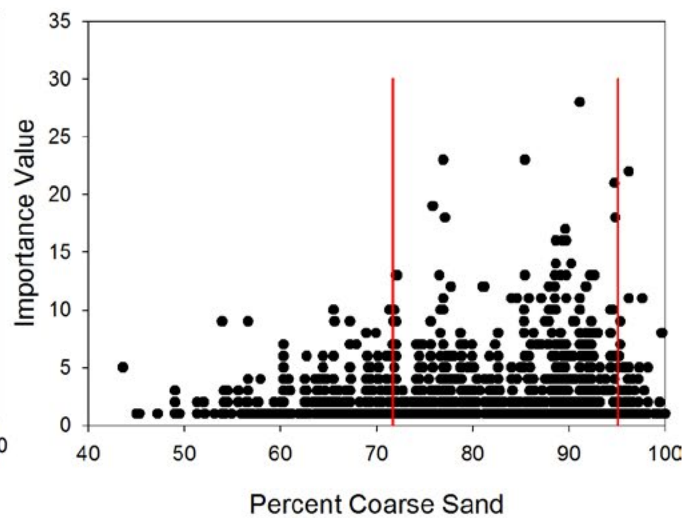


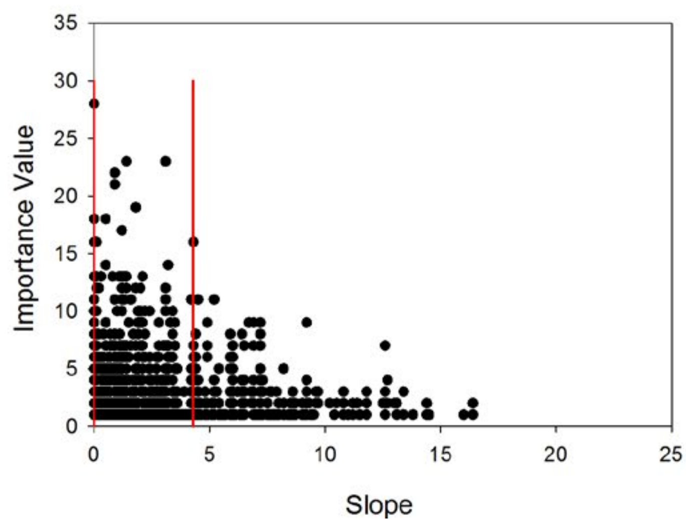
Populus grandidentata (bigtooth aspen)
Soil and Topographic Parameters







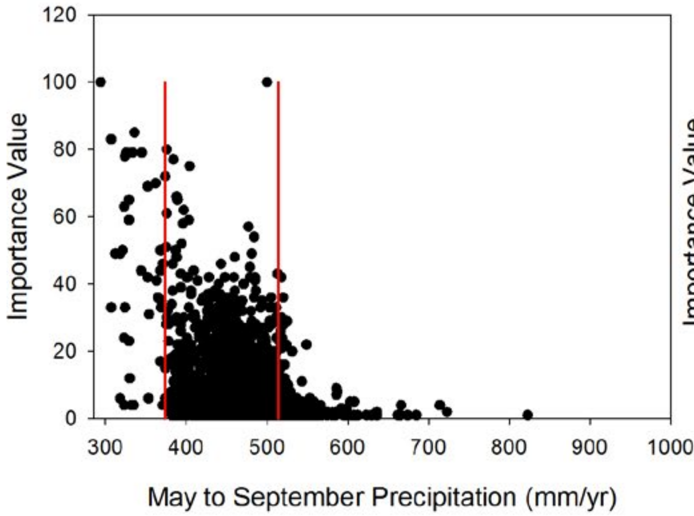


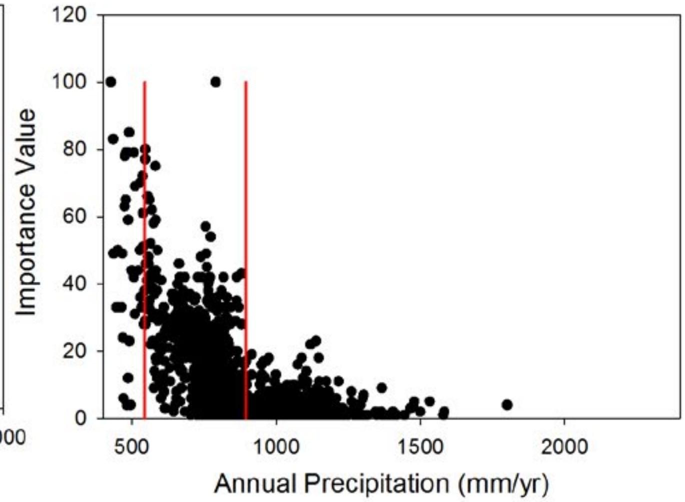


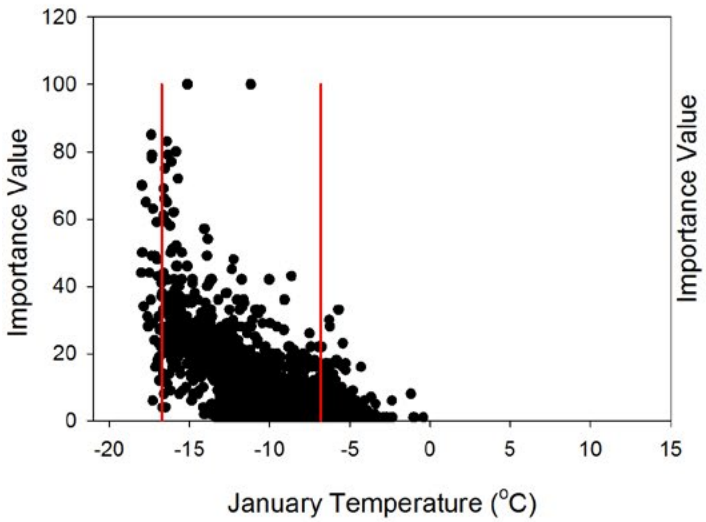
5th and 95th percentile of plots with importance value ≥ 10

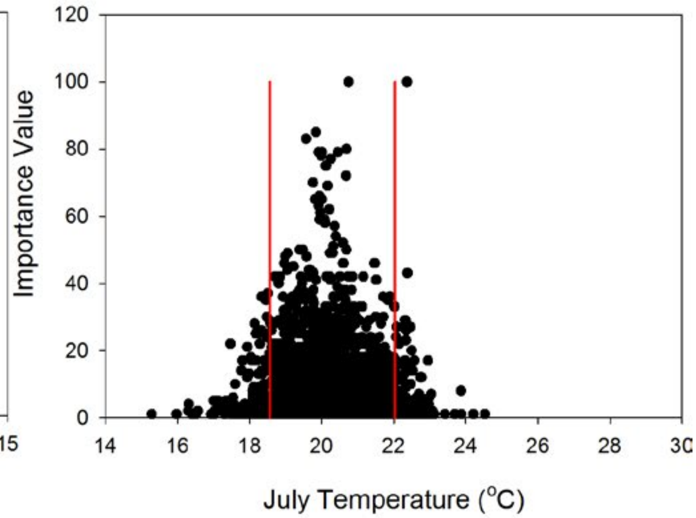
1438 total plots
57 plots with importance value ≥ 10

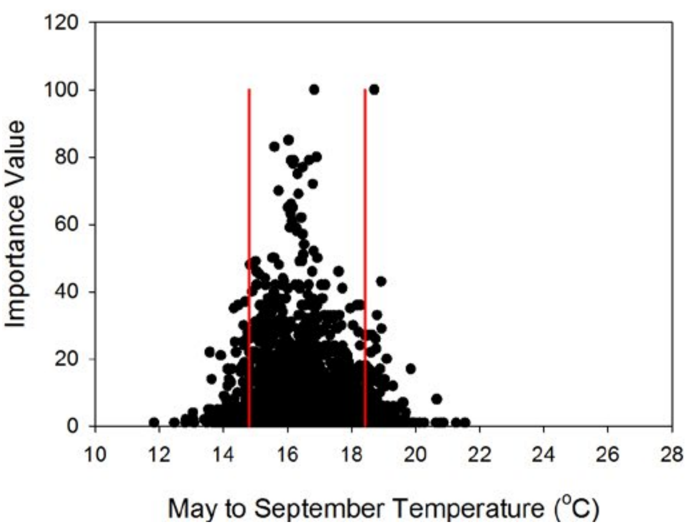
Populus tremuloides (quaking aspen)
Climate Parameters







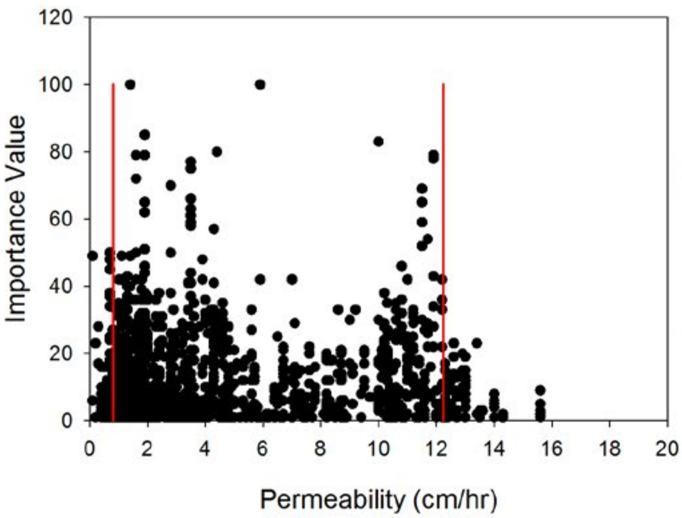


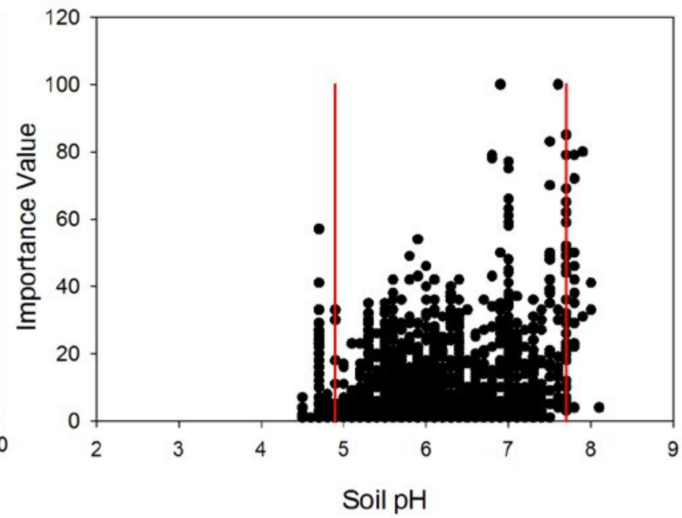


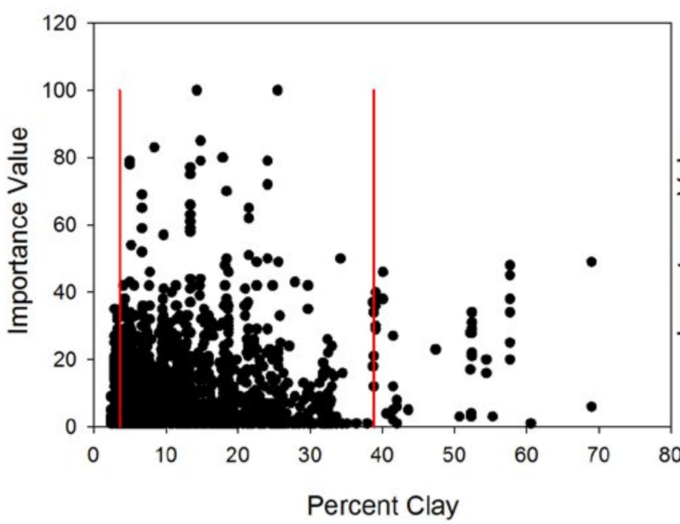
5th and 95th percentile of plots with importance value ≥ 10

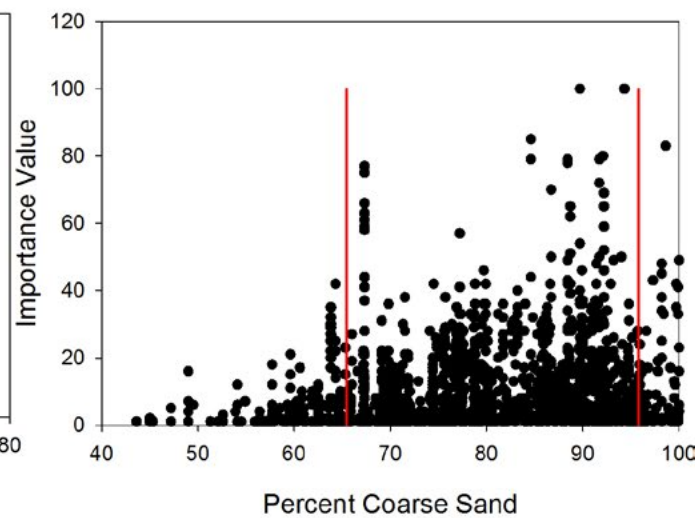
1621 total plots
615 plots with importance value ≥ 10

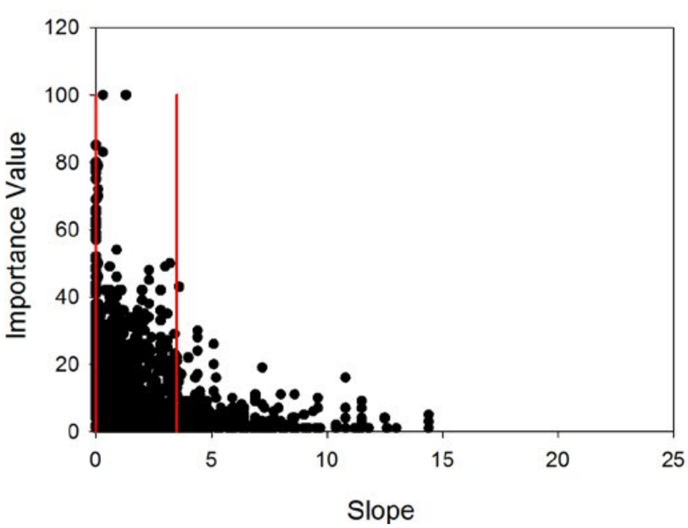
Populus tremuloides (quaking aspen)
Soil and Topographic Parameters







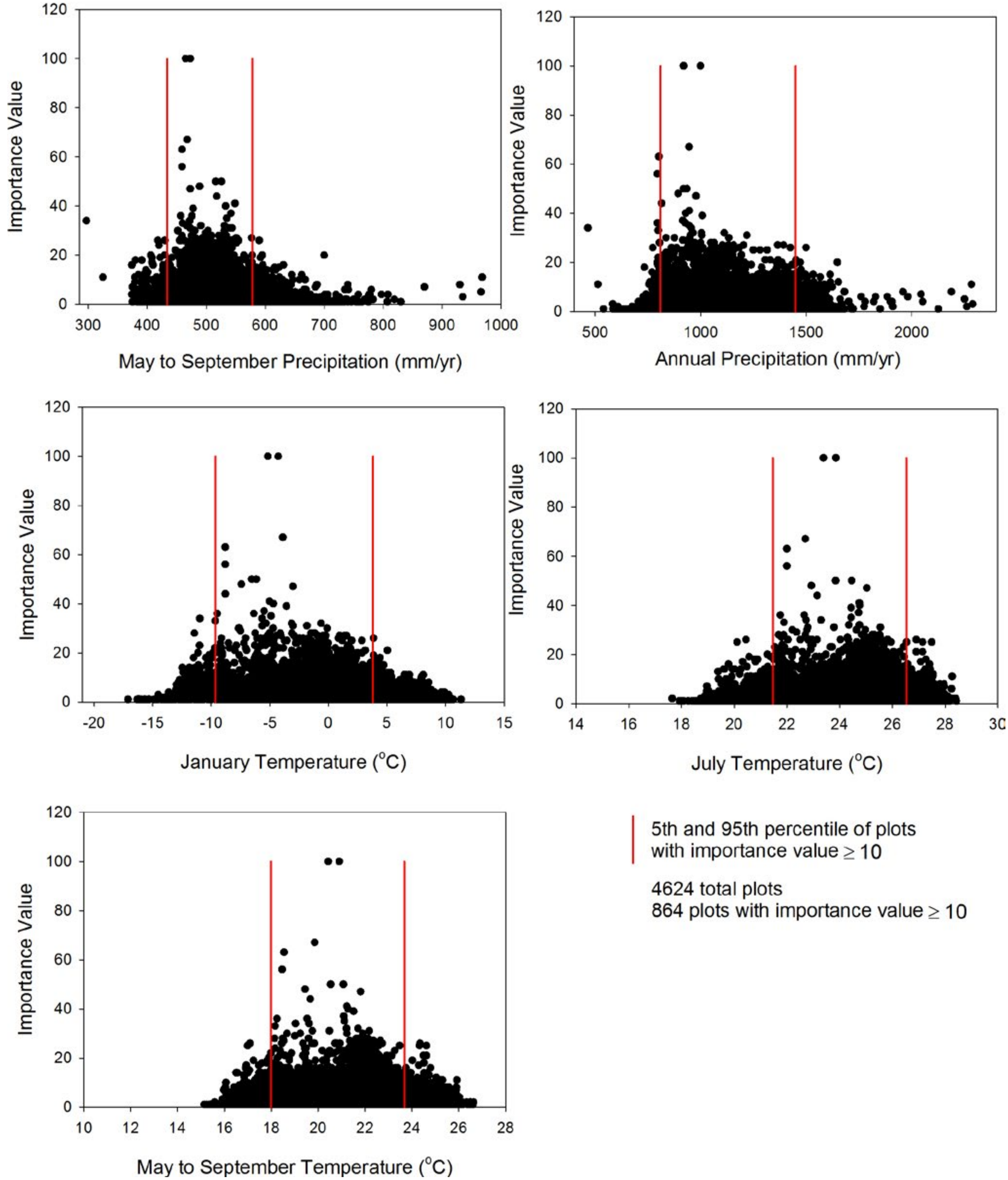




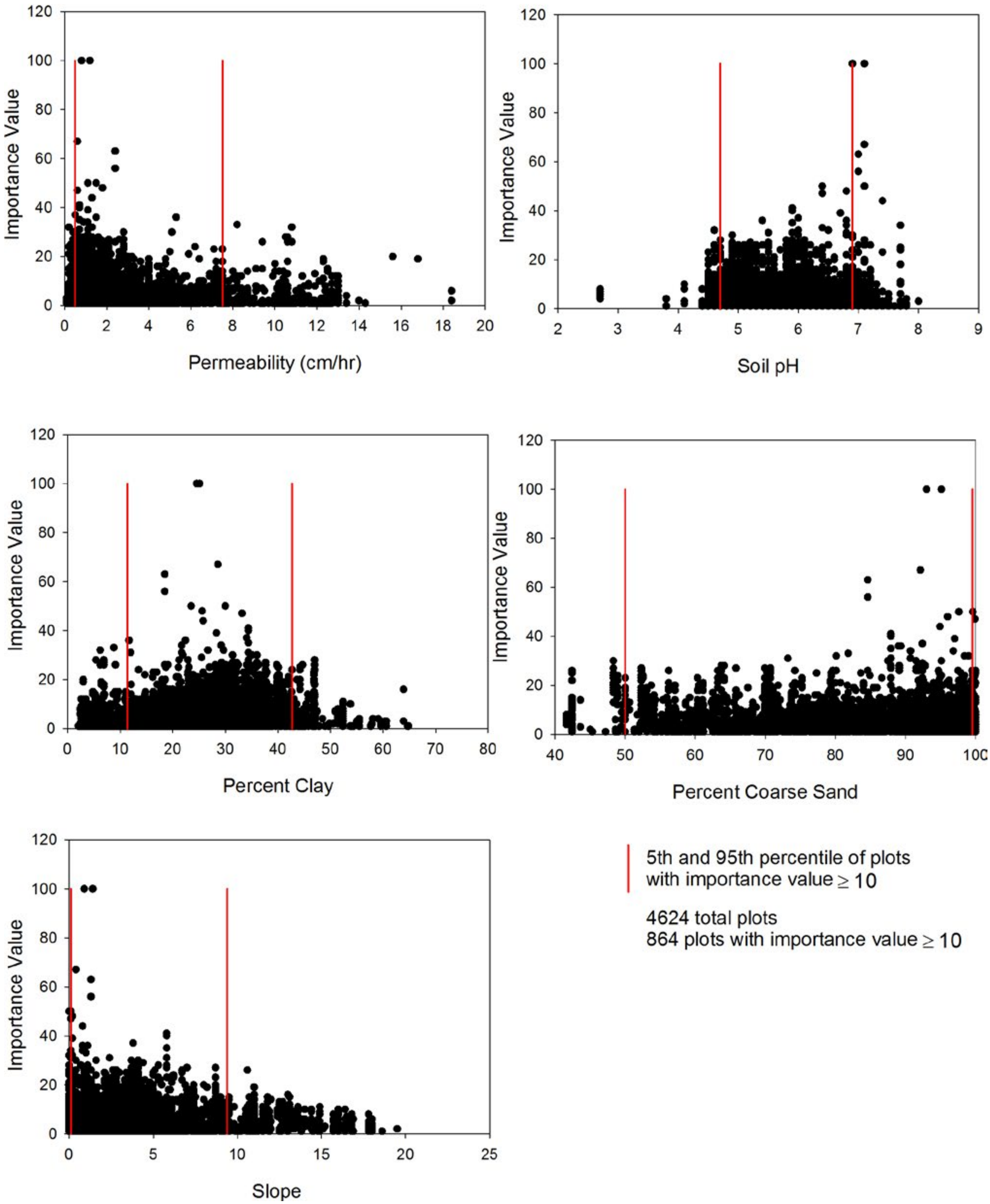
5th and 95th percentile of plots with importance value ≥ 10

1621 total plots
615 plots with importance value ≥ 10

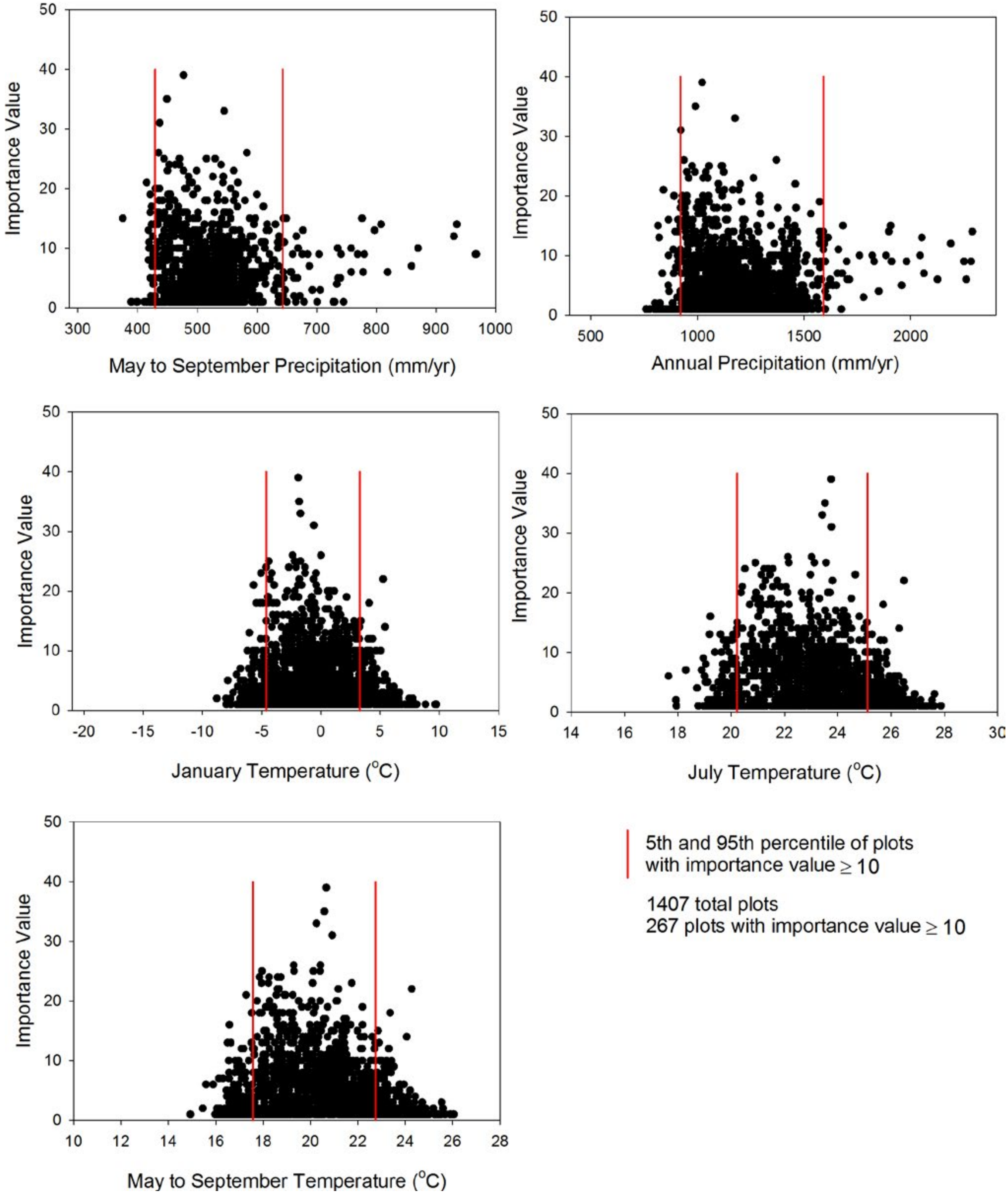
Quercus alba (white oak)
Climate Parameters



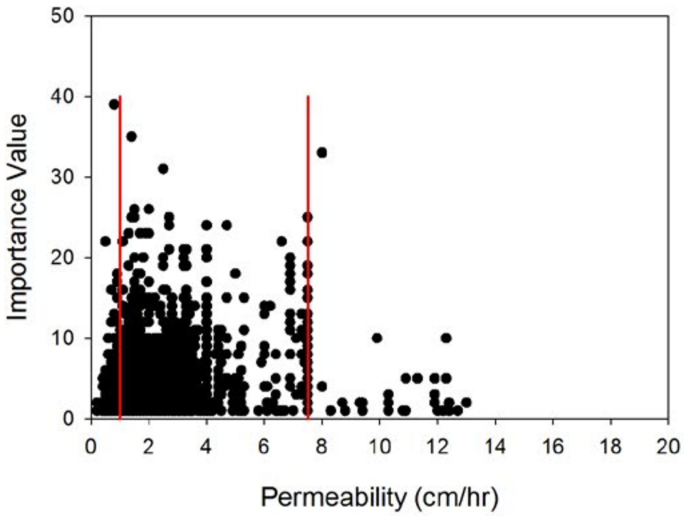
Quercus alba (white oak)
Soil and Topographic Parameters

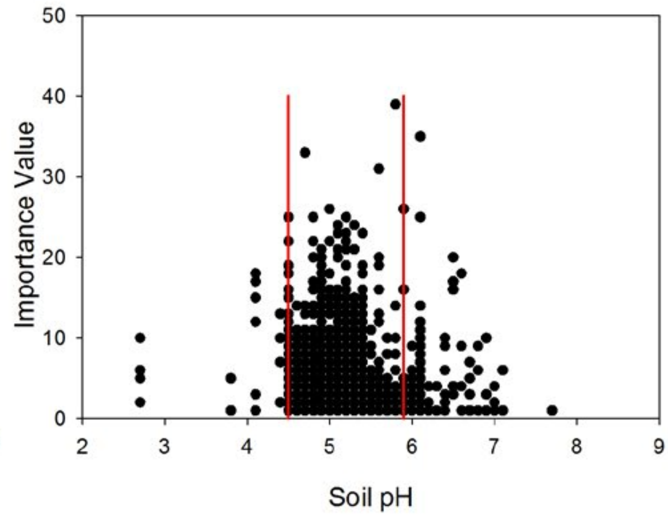


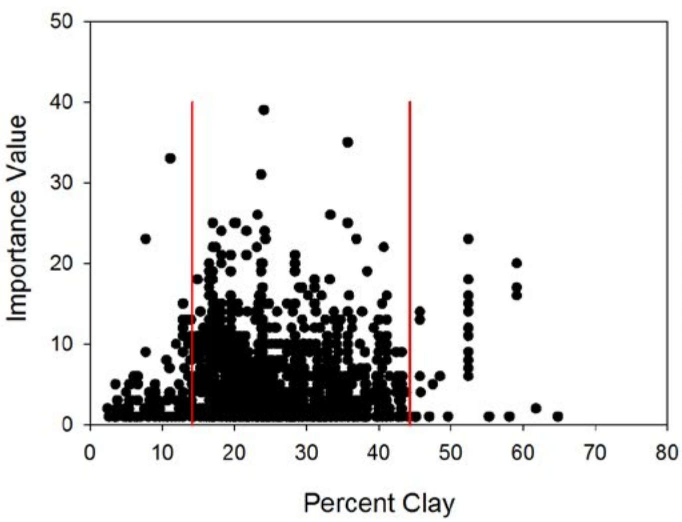
Quercus prinus (chestnut oak)
Climate Parameters

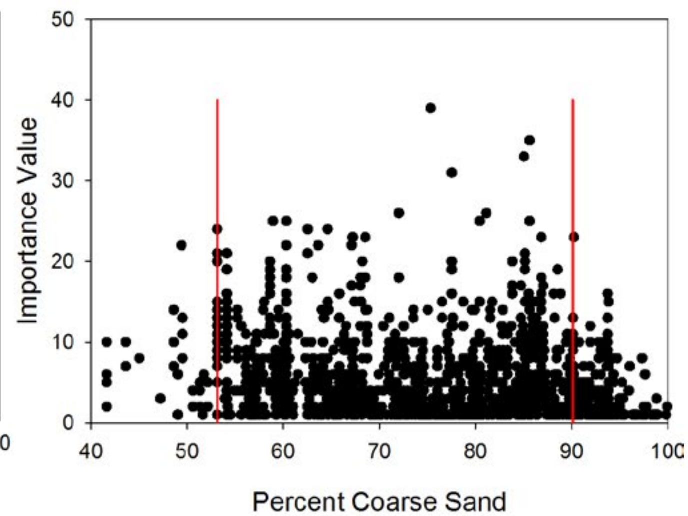


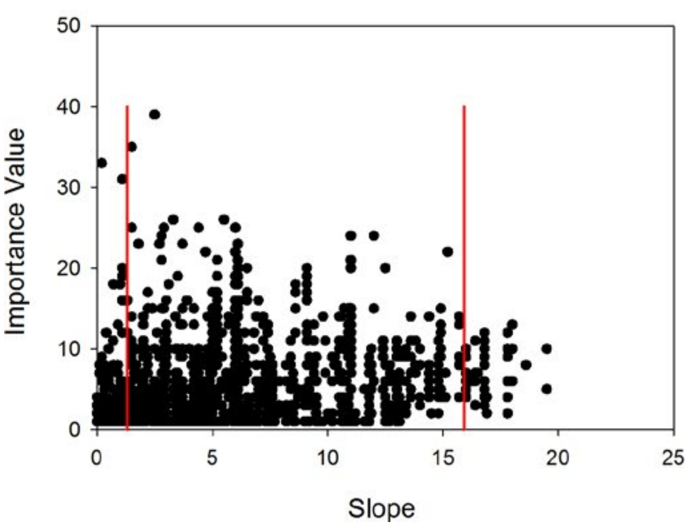
Quercus prinus (chestnut oak)
Soil and Topographic parameters







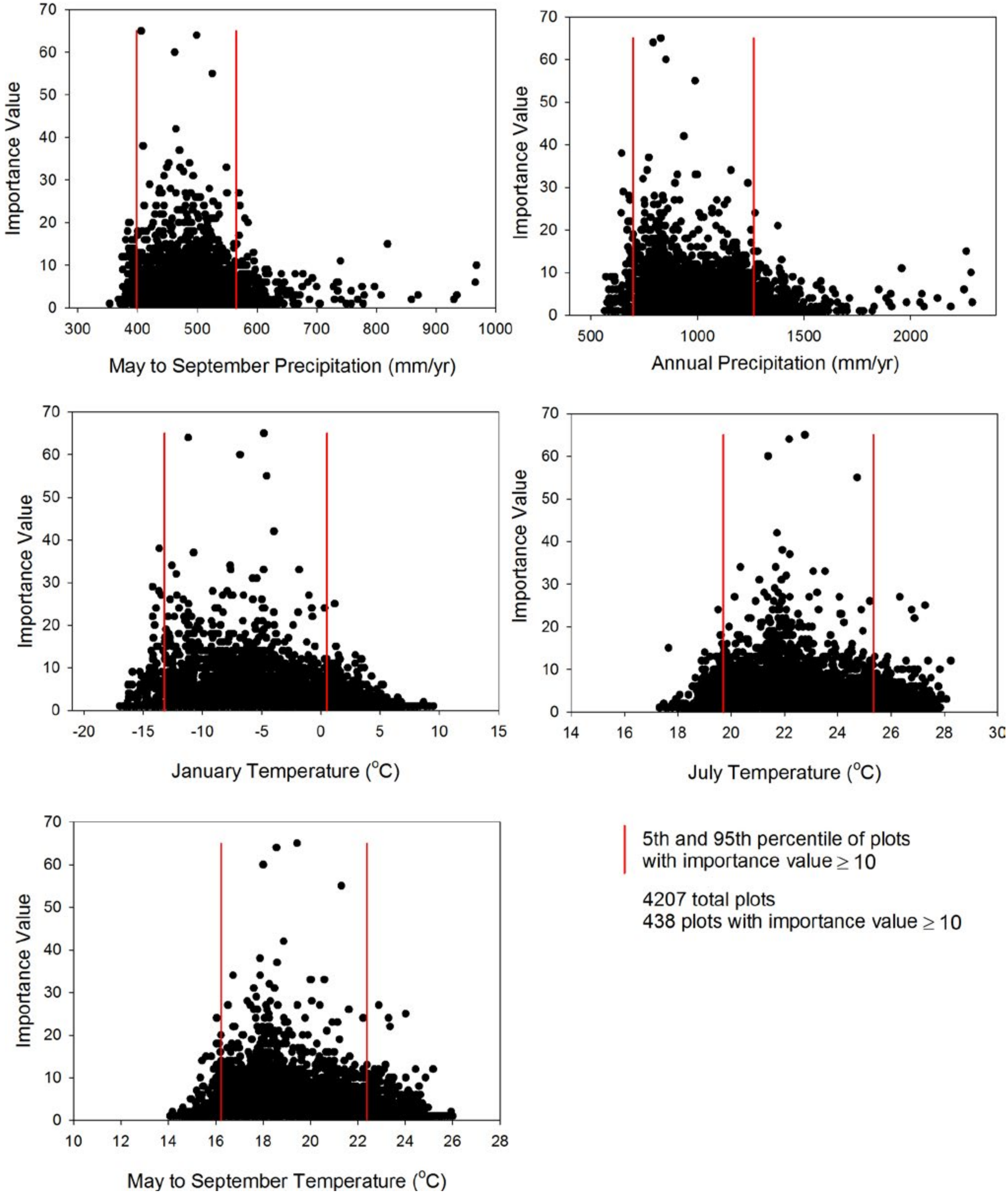




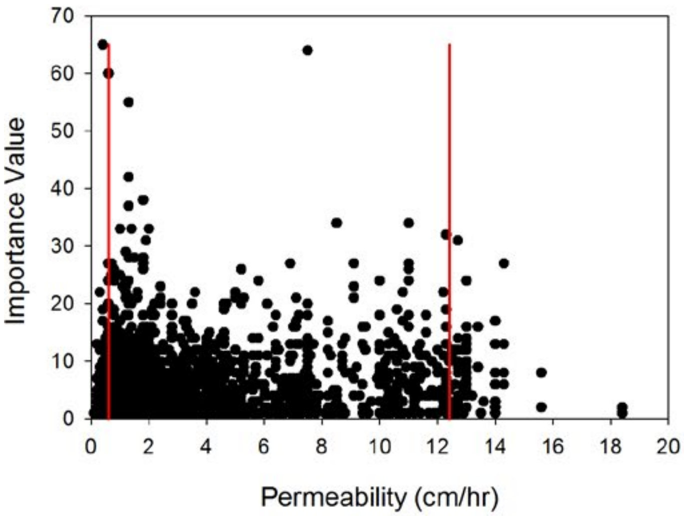
| 5th and 95th percentile of plots with importance value ≥ 10

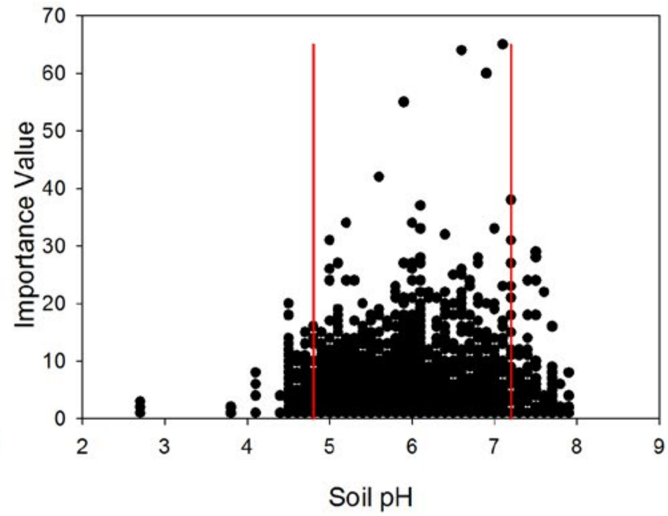
1407 total plots
267 plots with importance value ≥ 10

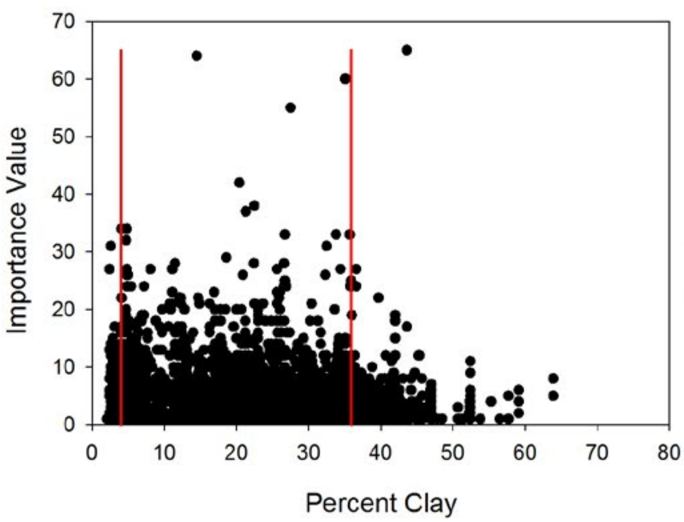
Quercus rubra (northern red oak)
Climate Parameters

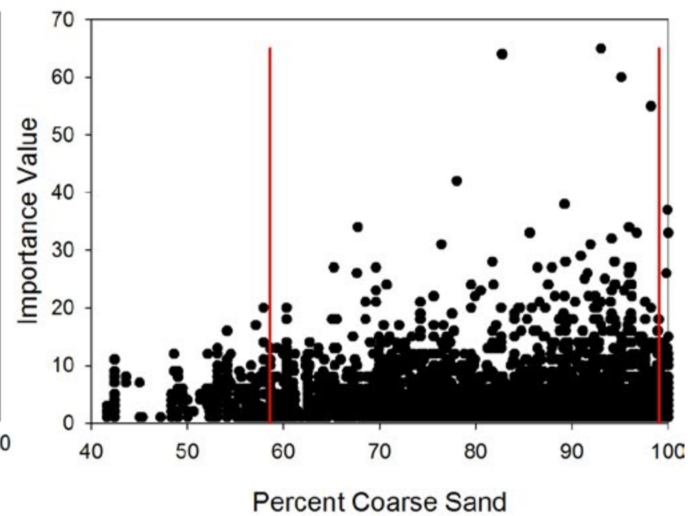


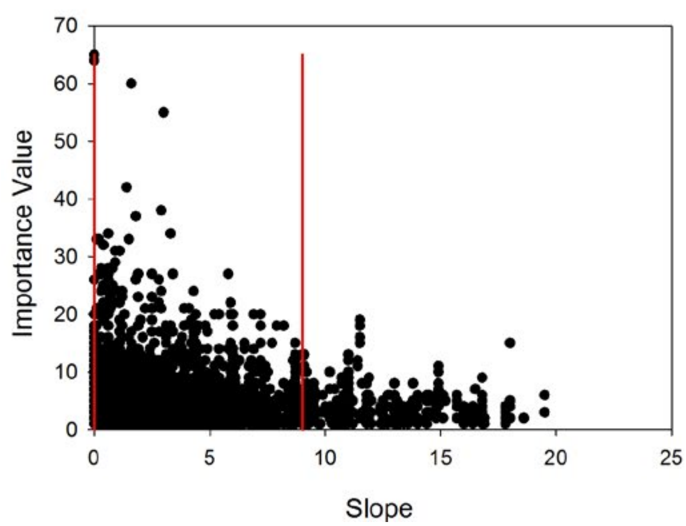
Quercus rubra (northern red oak)
Soil and Topographic Parameters







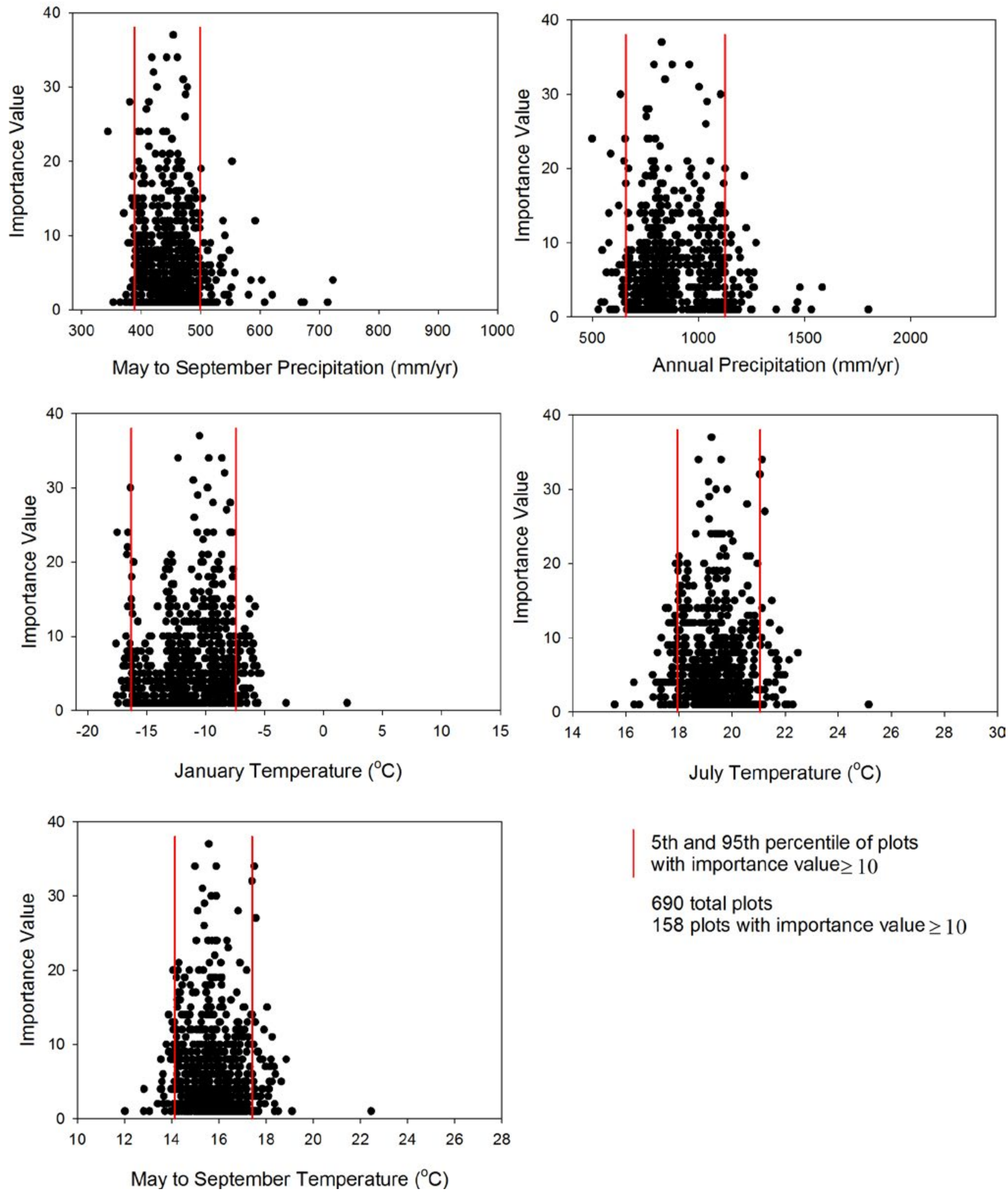




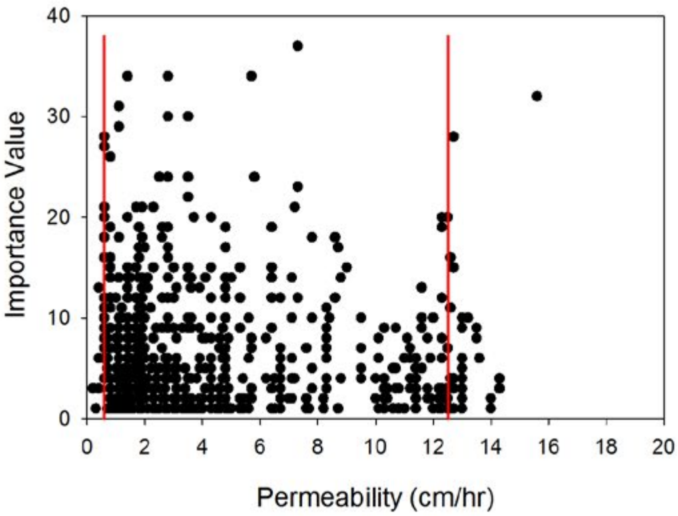
5th and 95th percentile of plots with importance value ≥ 10

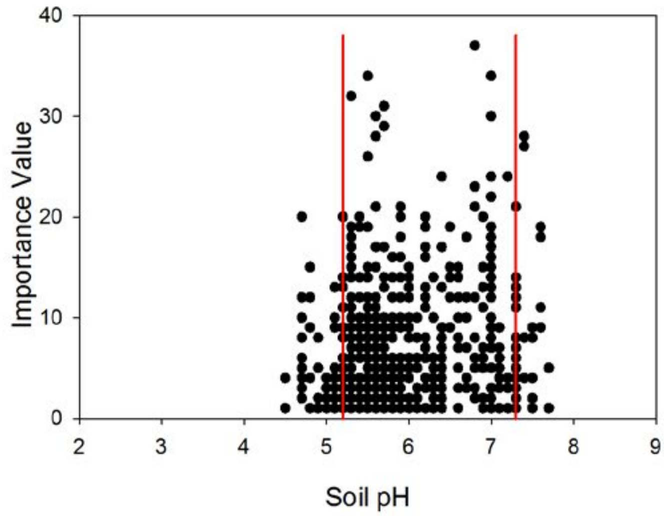
4207 total plots
438 plots with importance value ≥ 10

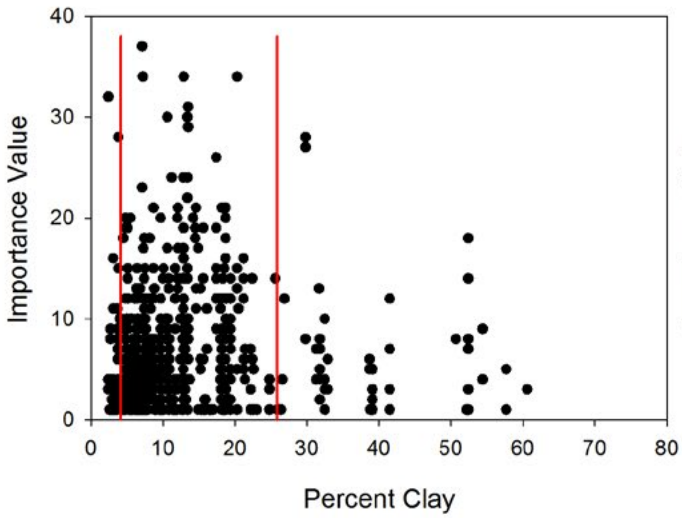
Thuja occidentalis - northern white cedar - climate parameters

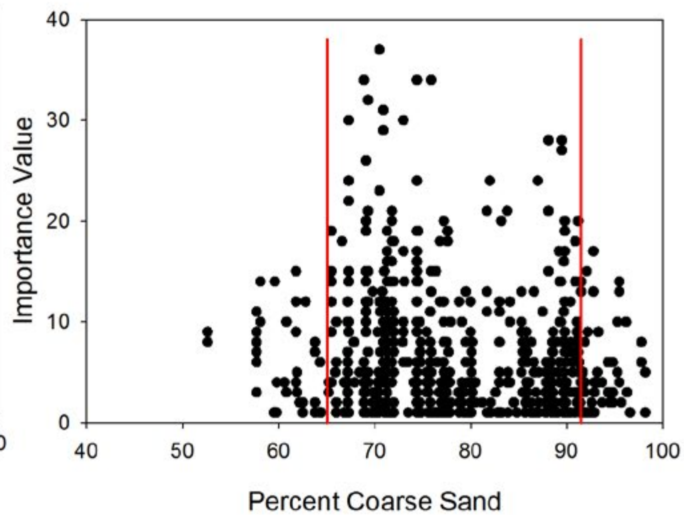


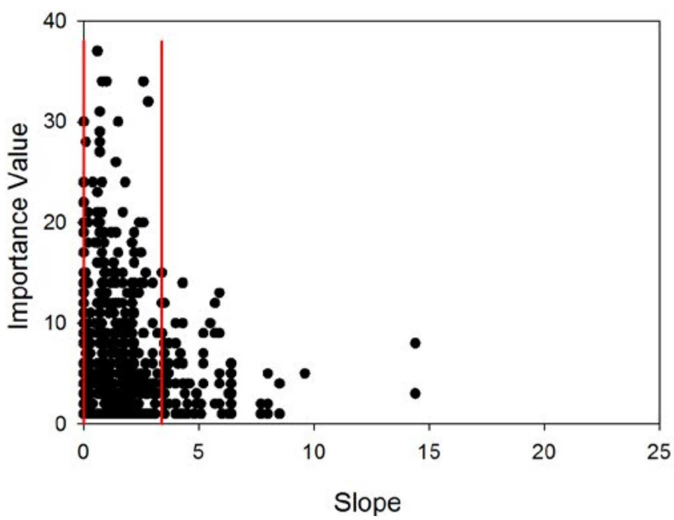
Thuja occidentalis - northern white cedar - soil and topographic parameters







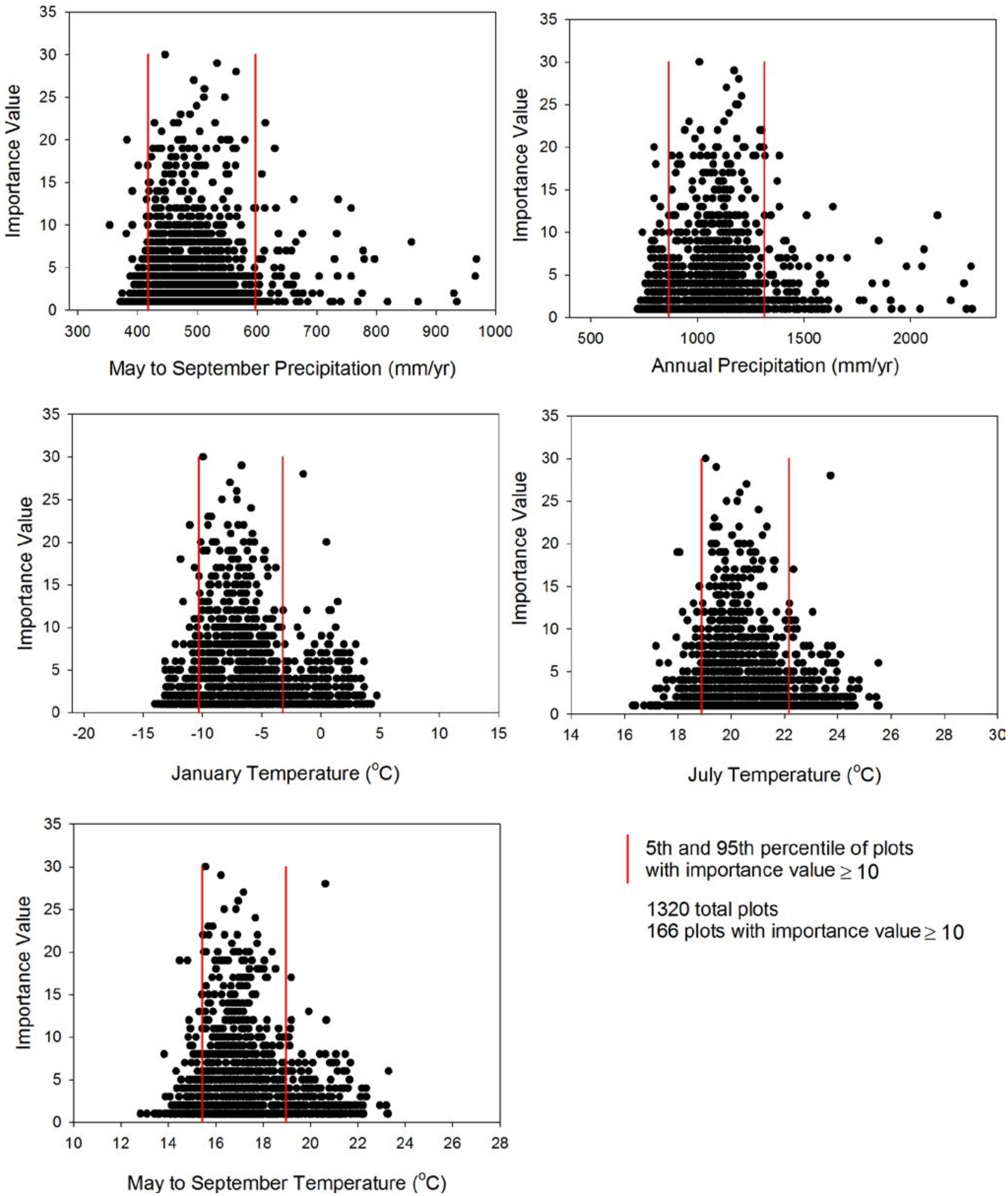




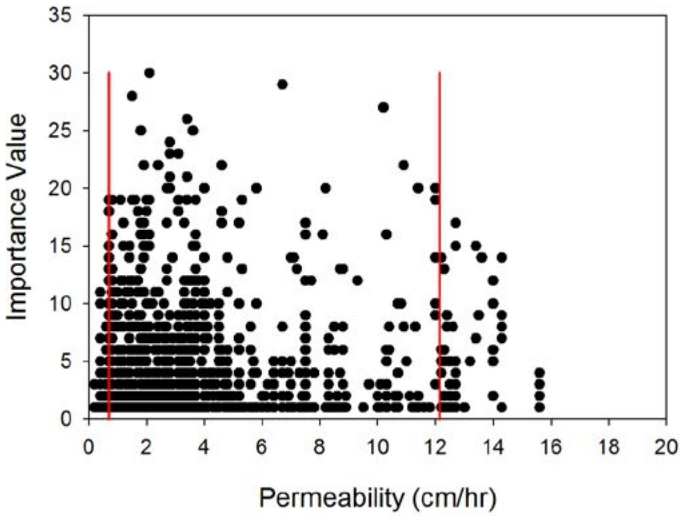
5th and 95th percentile of plots with importance value ≥ 10

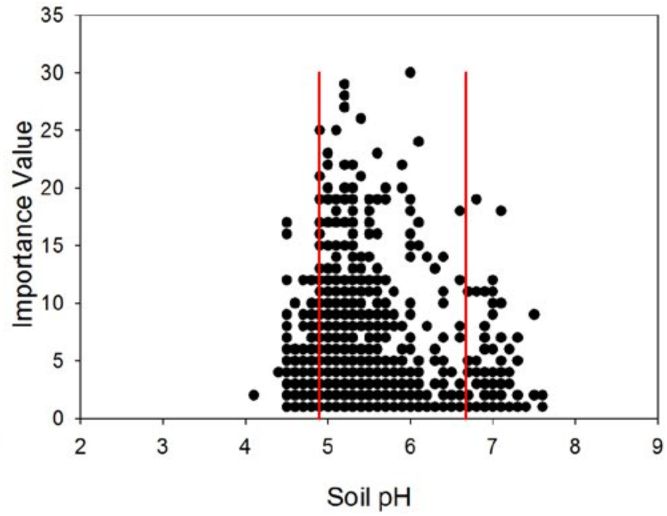
690 total plots
158 plots with importance value ≥ 10

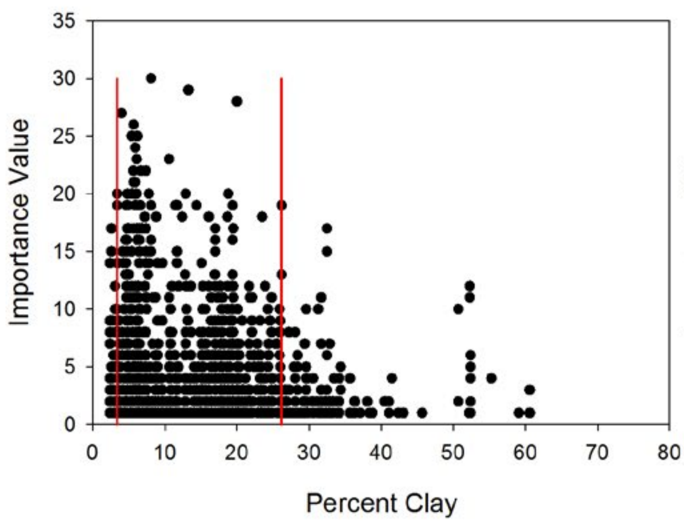
Tsuga canadensis (eastern hemlock)
Climate Parameters

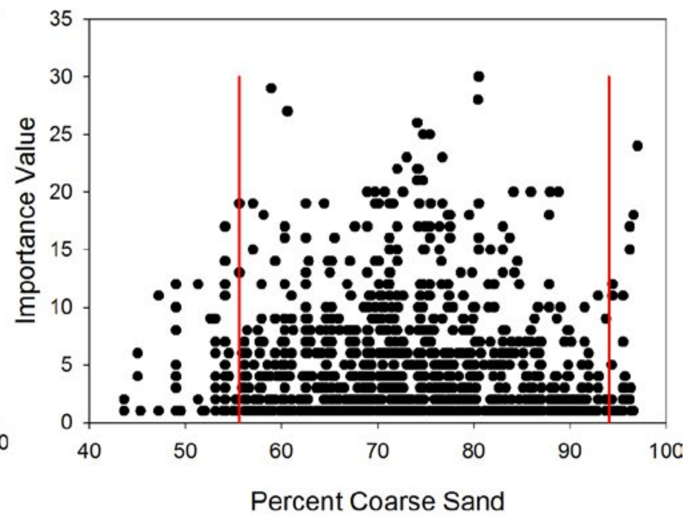


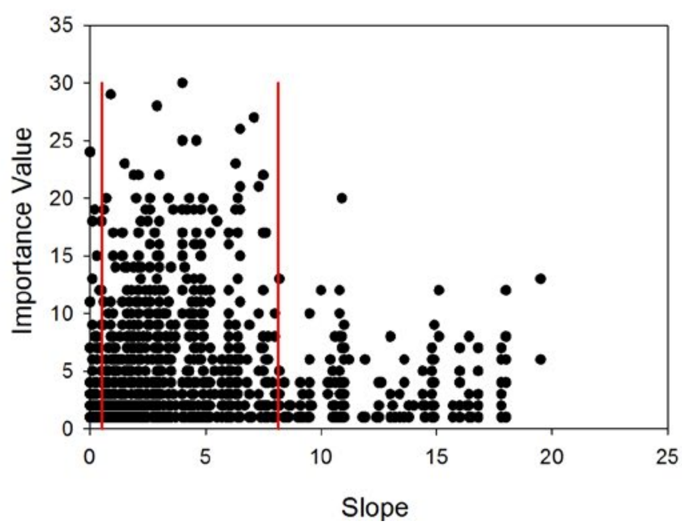
Tsuga canadensis (eastern hemlock)
Soil and Topographic Parameters







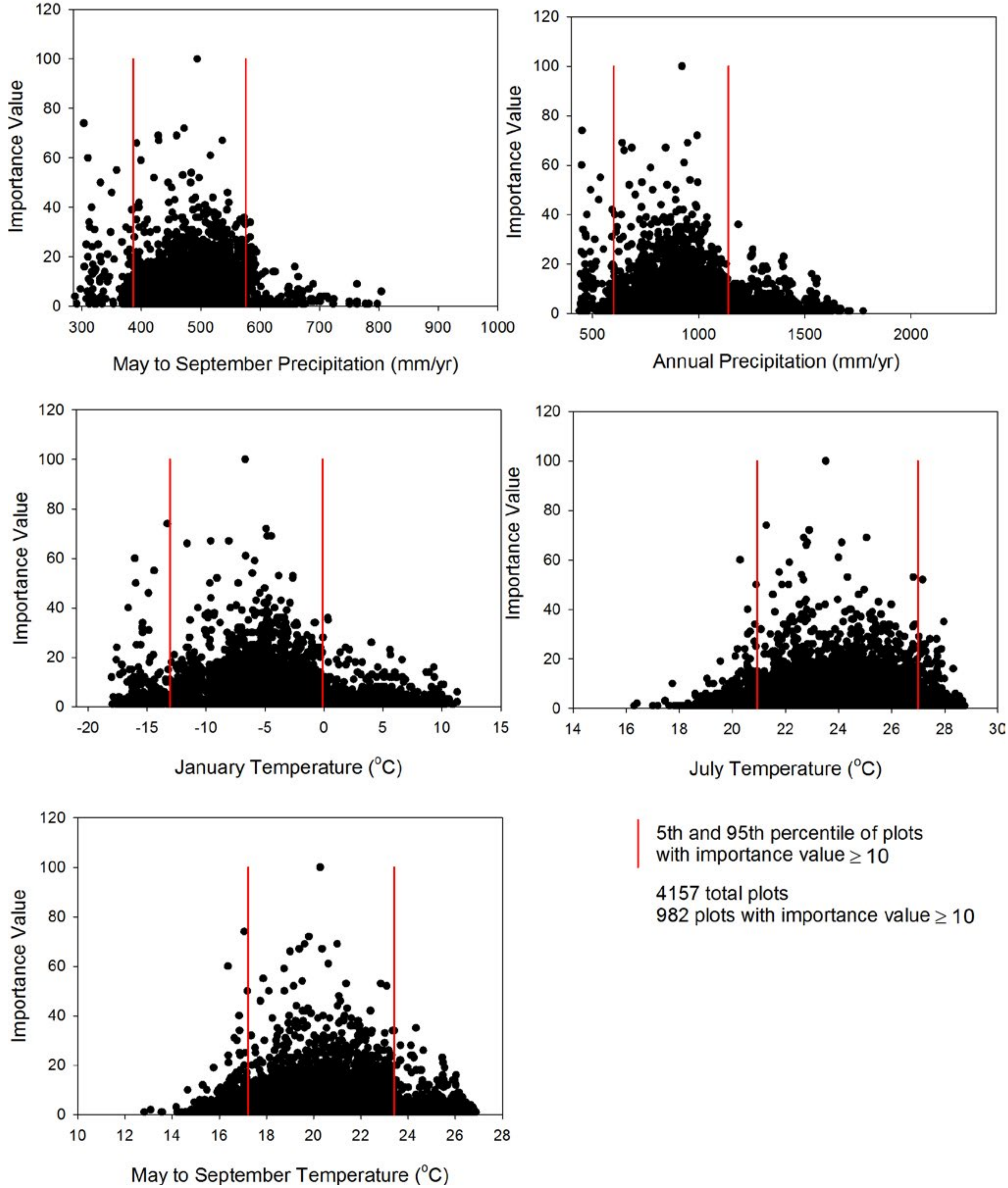




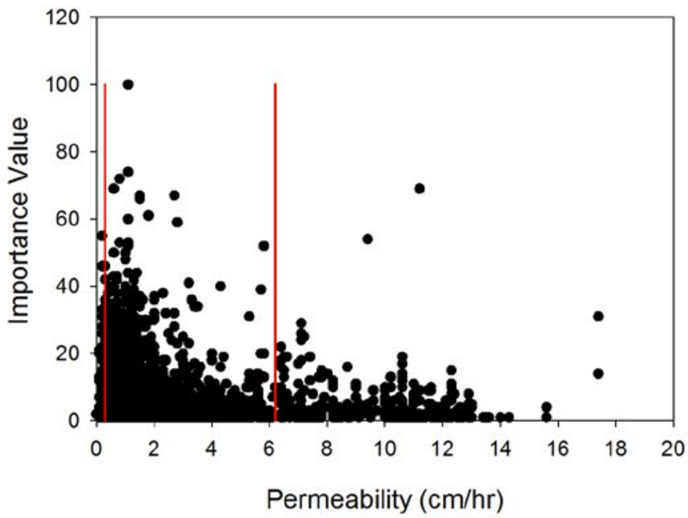
5th and 95th percentile of plots with importance value ≥ 10

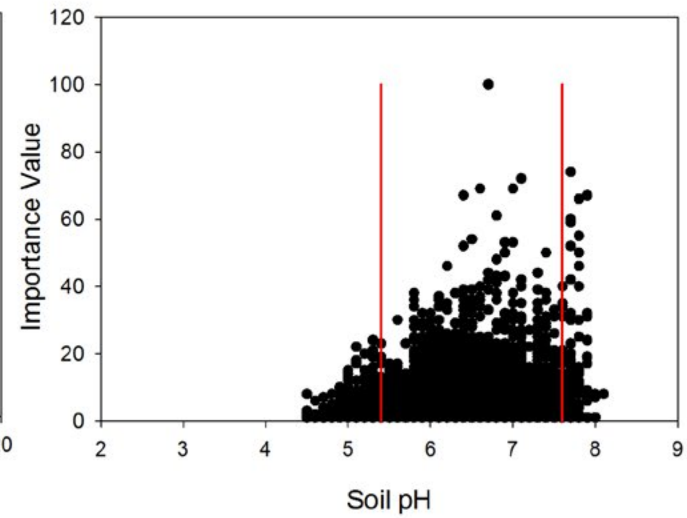
1320 total plots
166 plots with importance value ≥ 10

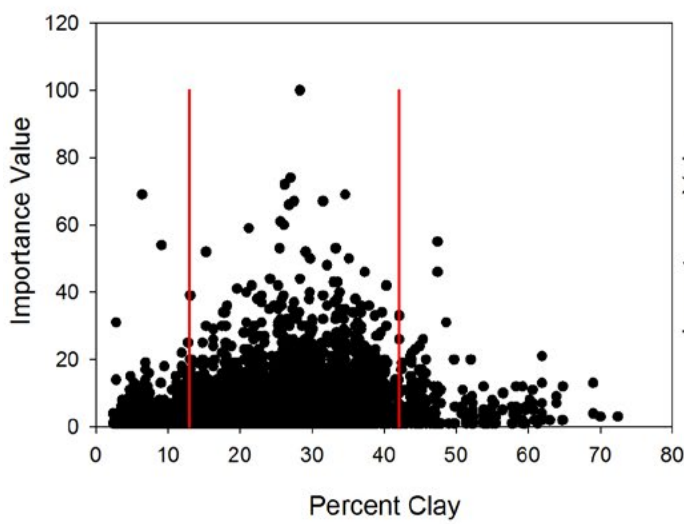
Ulmus americana (American elm)
Climate Parameters

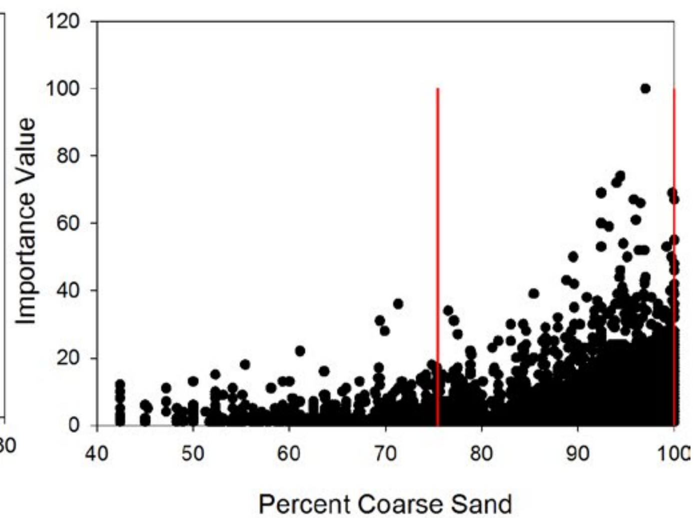


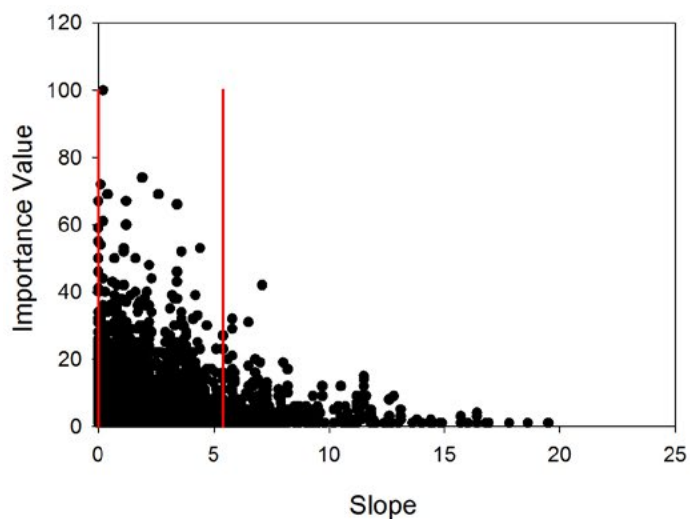
Ulmus americana (American elm)
Soil and Topographic Parameters











5th and 95th percentile of plots with importance value ≥ 10

4157 total plots
982 plots with importance value ≥ 10

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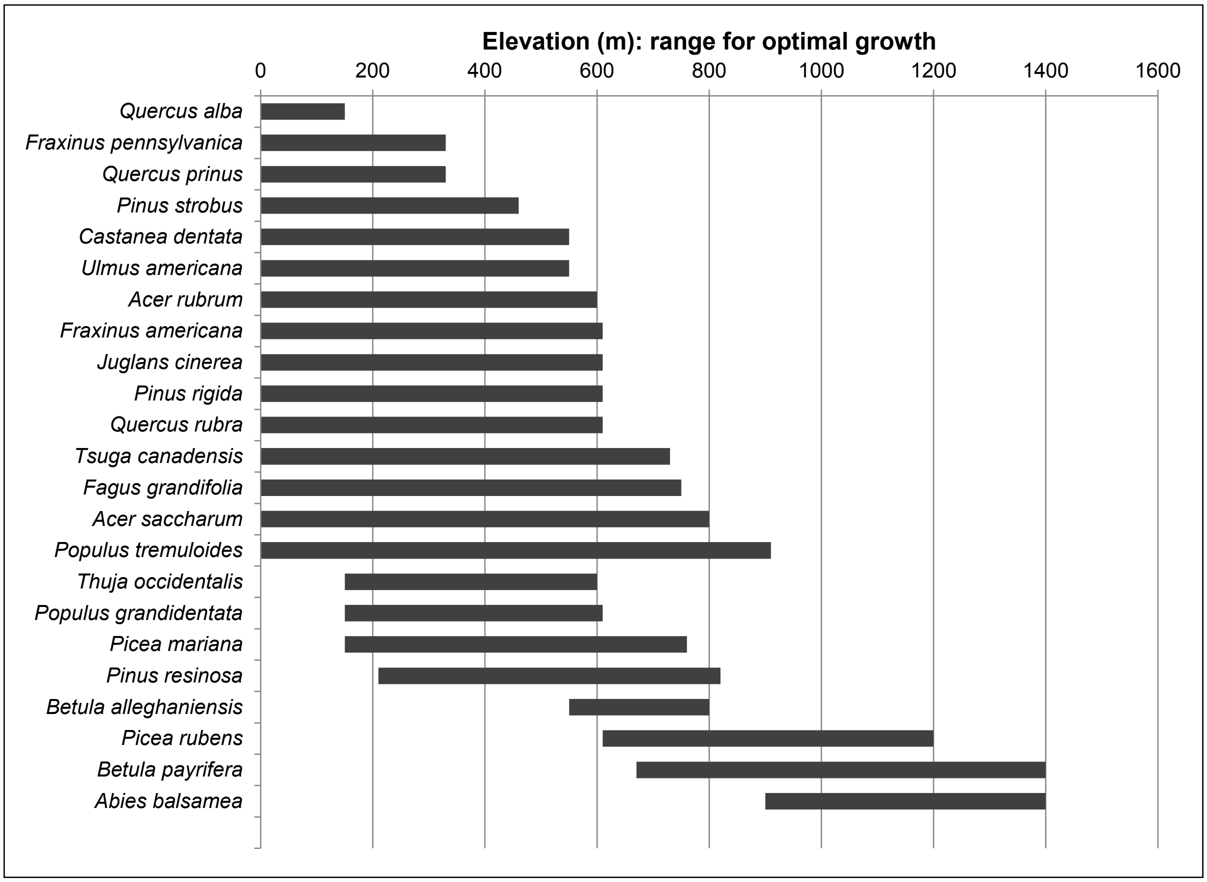
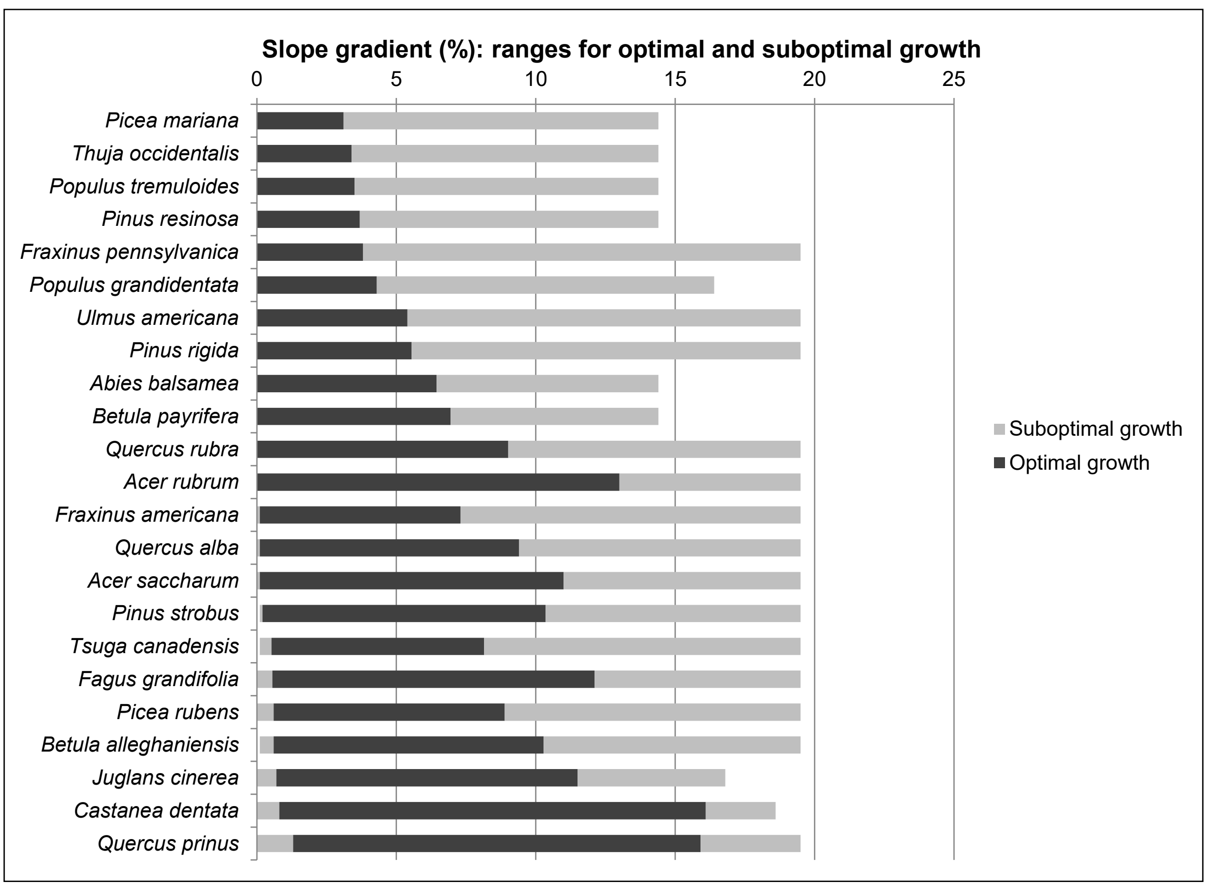
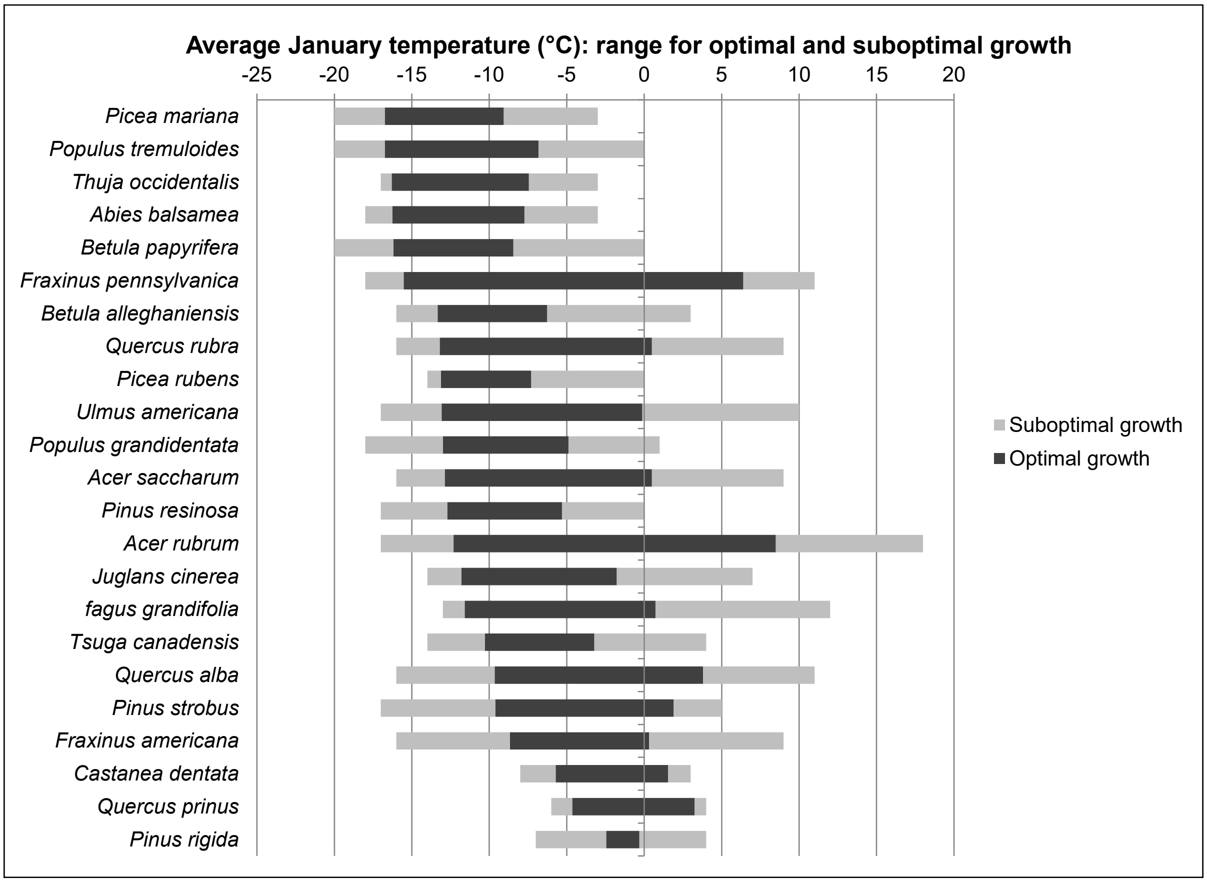
APPENDIX 2

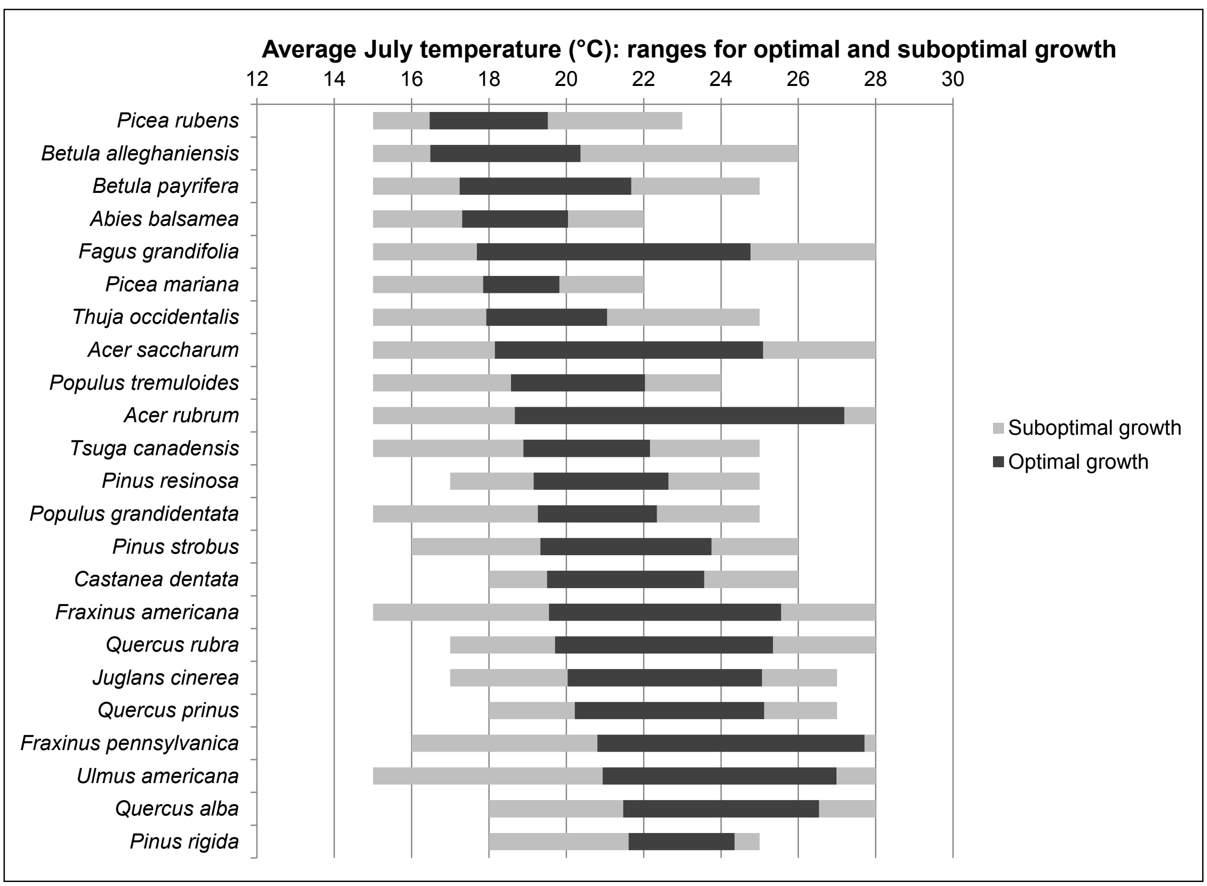
Ranges for Optimal and Suboptimal Growth for Site, Climate, and Soil Variables

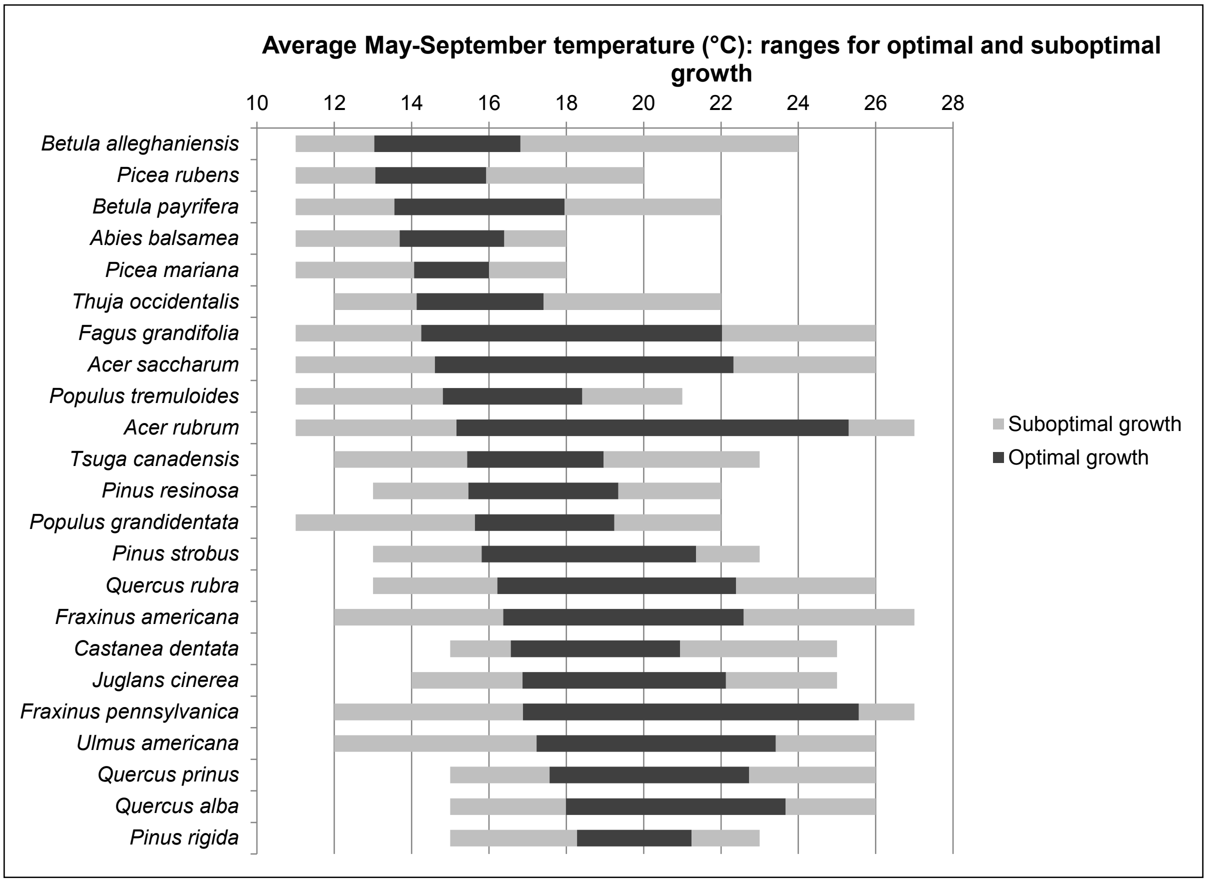
Climate and soil data in these figures were provided by the Landscape Change Research Group (U.S. Forest Service, n.d.). Current climate parameter data are from Hayhoe et al. (2007) and are based on United States Historical Climatology network data from 1961-1990. Soil and topographic parameter data are from STATSGO data (Soil Conservation Service 1991). For further information, see the Climate Change Atlas website: https://www.fs.fed.us/nrs/atlas/. Optimal elevation ranges were derived from information in "Silvics of North America" (Burns and Honkala 1990), Leak and Graber (1974), Beckage et al. (2008), and other sources. Depth to bedrock (minimum rooting depth) values come from the PLANTS database (NRCS 2014). Because optimal and suboptimal ranges are not known for minimum rooting depth, arrows indicate the beginning of the range.

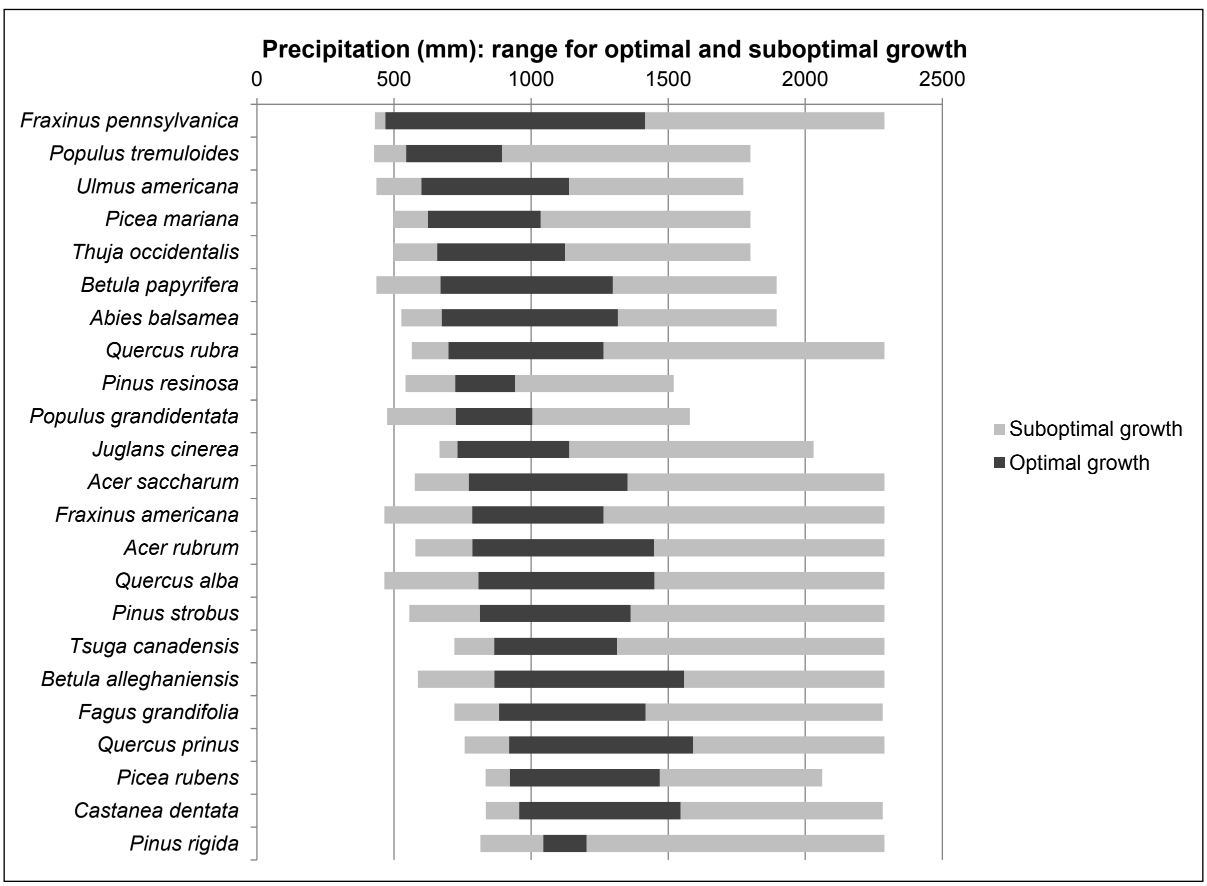

Elevation (m): range for optimal growth
0
200
400
600
800
1000
1200
1400
1600
Quercus alba
Fraxinus pennsylvanica
Quercus prinus
Pinus strobus
Castanea dentata
Ulmus americana
Acer rubrum
Fraxinus americana
Juglans cinerea
Pinus rigida
Quercus rubra
Tsuga canadensis
Fagus grandifolia
Acer saccharum
Populus tremuloides
Thuja occidentalis
Populus grandidentata
Picea mariana
Pinus resinosa
Betula alleghaniensis
Picea rubens
Betula payrifera
Abies balsamea

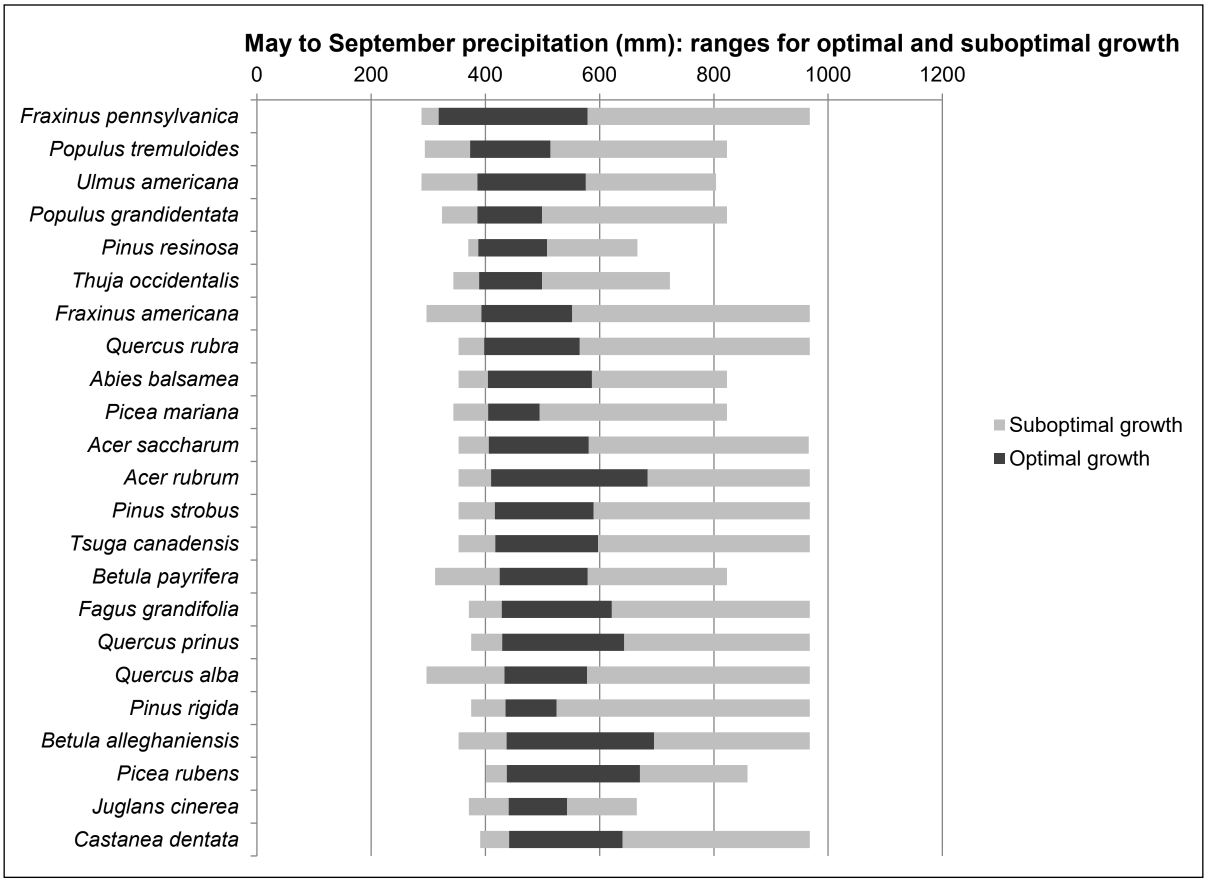

Slope gradient (%): ranges for optimal and suboptimal growth
0
5
10
15
20
25
Picea mariana
Thuja occidentalis
Populus tremuloides
Pinus resinosa
Fraxinus pennsylvanica
Populus grandidentata
Ulmus americana
Pinus rigida
Abies balsamea
Betula payrifera
Quercus rubra
Acer rubrum
Fraxinus americana
Quercus alba
Acer saccharum
Pinus strobus
Tsuga canadensis
Fagus grandifolia
Picea rubens
Betula alleghaniensis
Juglans cinerea
Castanea dentata
Quercus prinus
Suboptimal growth
Optimal growth

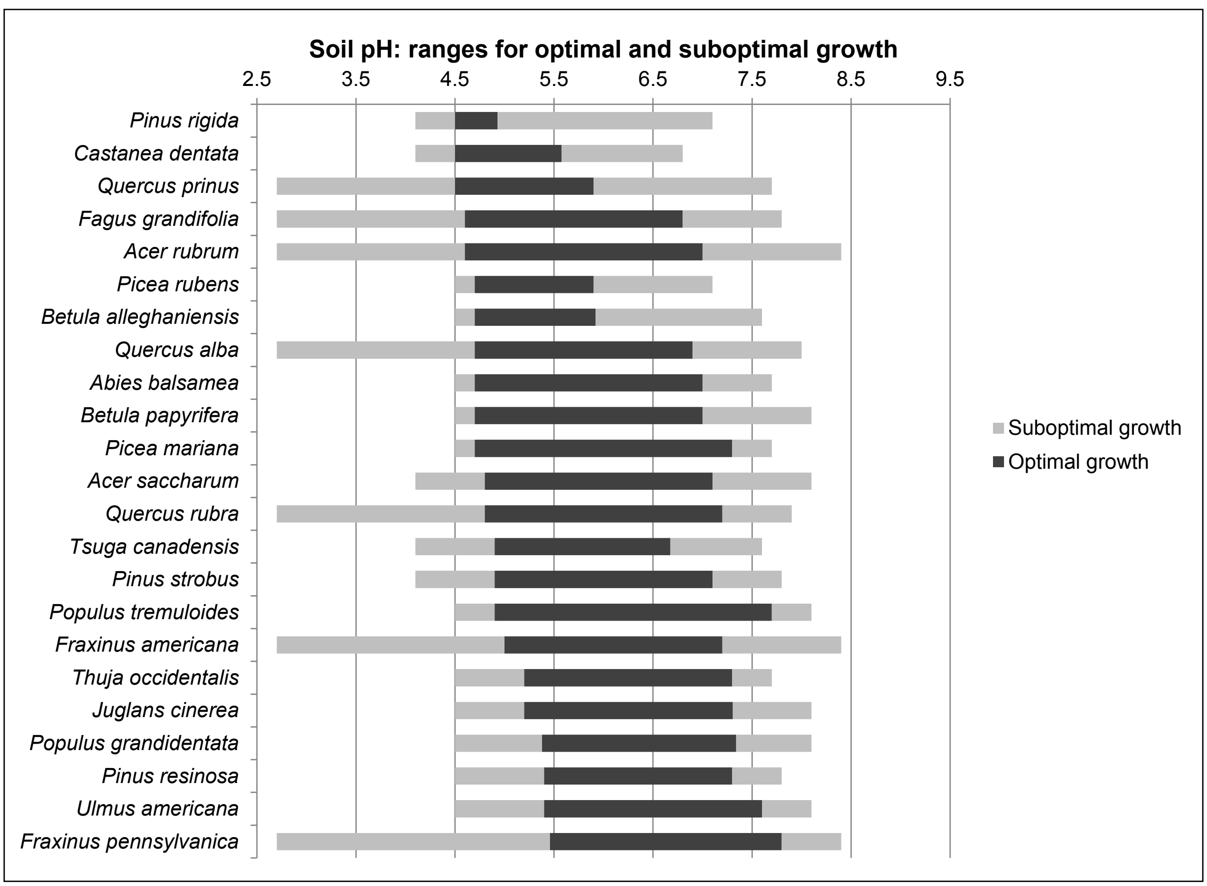

Average January temperature (°C): range for optimal and suboptimal growth
-25
-20
-15
-10
-5
0
5
10
15
20
Picea mariana
Populus tremuloides
Thuja occidentalis
Abies balsamea
Betula papyrifera
Fraxinus pennsylvanica
Betula alleghaniensis
Quercus rubra
Picea rubens
Ulmus americana
Populus grandidentata
Acer saccharum
Pinus resinosa
Acer rubrum
Juglans cinerea
fagus grandifolia
Tsuga canadensis
Quercus alba
Pinus strobus
Fraxinus americana
Castanea dentata
Quercus prinus
Pinus rigida
Suboptimal growth
Optimal growth

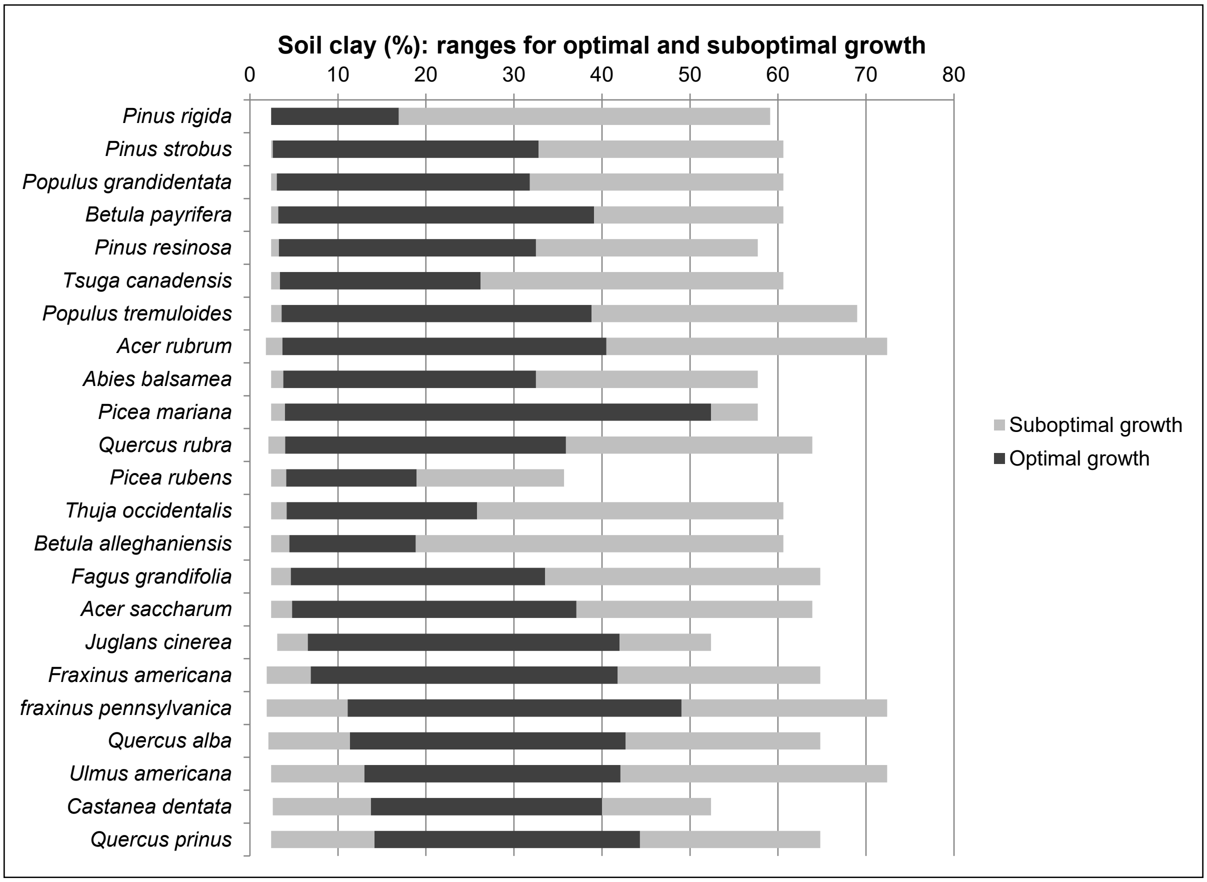

Average July temperature (°C): ranges for optimal and suboptimal growth
12
14
16
18
20
22
24
26
28
30
Picea rubens
Betula alleghaniensis
Betula payrifera
Abies balsamea
Fagus grandifolia
Picea mariana
Thuja occidentalis
Acer saccharum
Populus tremuloides
Acer rubrum
Tsuga canadensis
Pinus resinosa
Populus grandidentata
Pinus strobus
Castanea dentata
Fraxinus americana
Quercus rubra
Juglans cinerea
Quercus prinus
Fraxinus pennsylvanica
Ulmus americana
Quercus alba
Pinus rigida
Suboptimal growth
Optimal growth

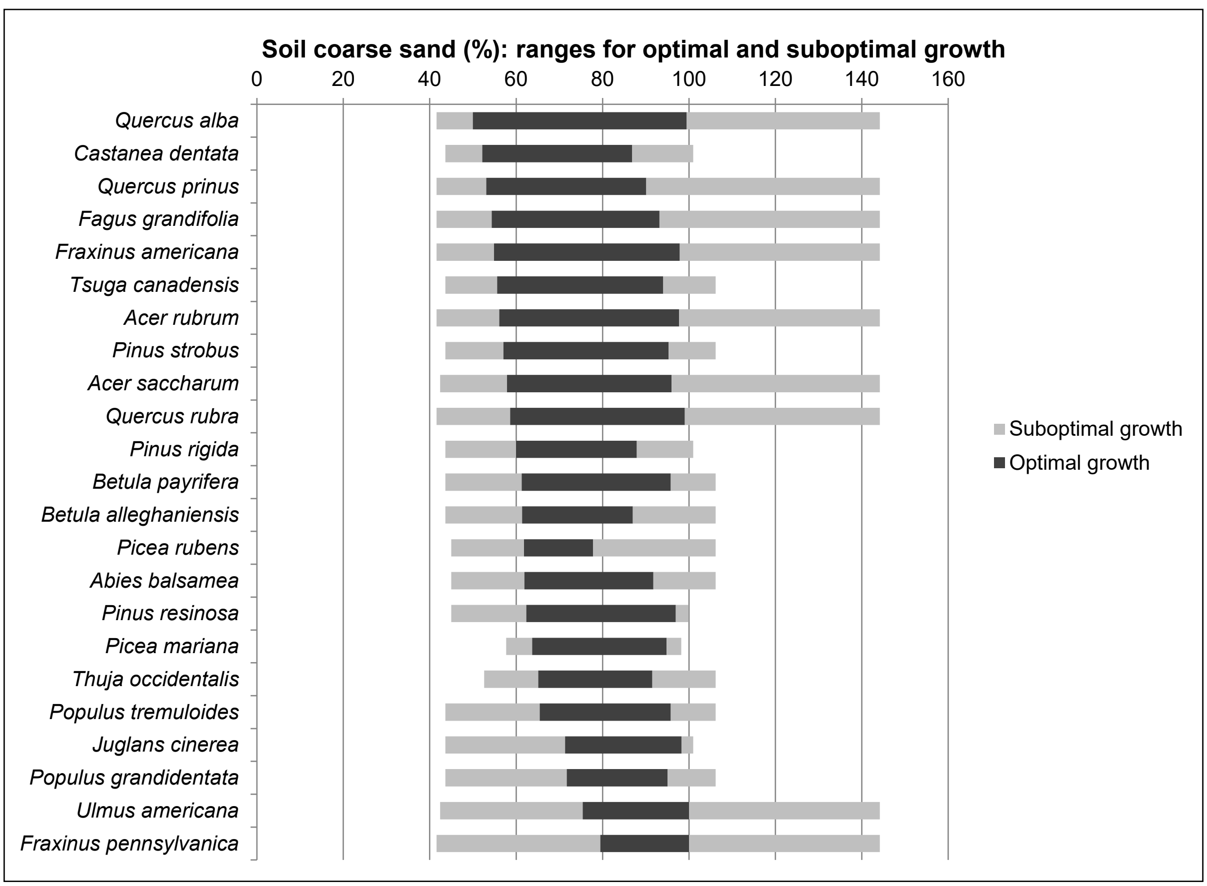

Average May-September temperature (°C): ranges for optimal and suboptimal growth
10
12
14
16
18
20
22
24
26
28
Betula alleghaniensis
Picea rubens
Betula payrifera
Abies balsamea
Picea mariana
Thuja occidentalis
Fagus grandifolia
Acer saccharum
Populus tremuloides
Acer rubrum
Tsuga canadensis
Pinus resinosa
Populus grandidentata
Pinus strobus
Quercus rubra
Fraxinus americana
Castanea dentata
Juglans cinerea
Fraxinus pennsylvanica
Ulmus americana
Quercus prinus
Quercus alba
Pinus rigida
Suboptimal growth
Optimal growth

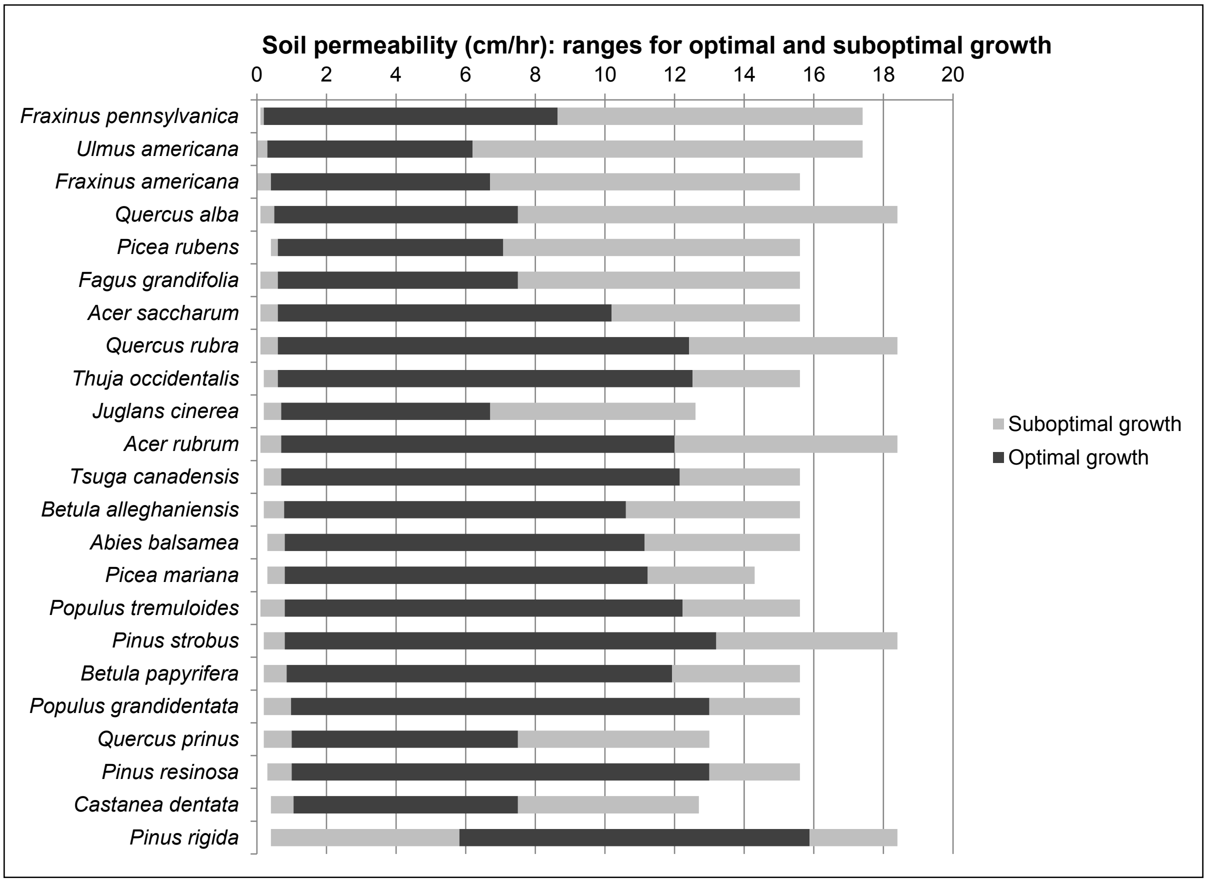

Precipitation (mm): range for optimal and suboptimal growth
0
500
1000
1500
2000
2500
Fraxinus pennsylvanica
Populus tremuloides
Ulmus americana
Picea mariana
Thuja occidentalis
Betula papyrifera
Abies balsamea
Quercus rubra
Pinus resinosa
Populus grandidentata
Juglans cinerea
Acer saccharum
Fraxinus americana
Acer rubrum
Quercus alba
Pinus strobus
Tsuga canadensis
Betula alleghaniensis
Fagus grandifolia
Quercus prinus
Picea rubens
Castanea dentata
Pinus rigida
Suboptimal growth
Optimal growth

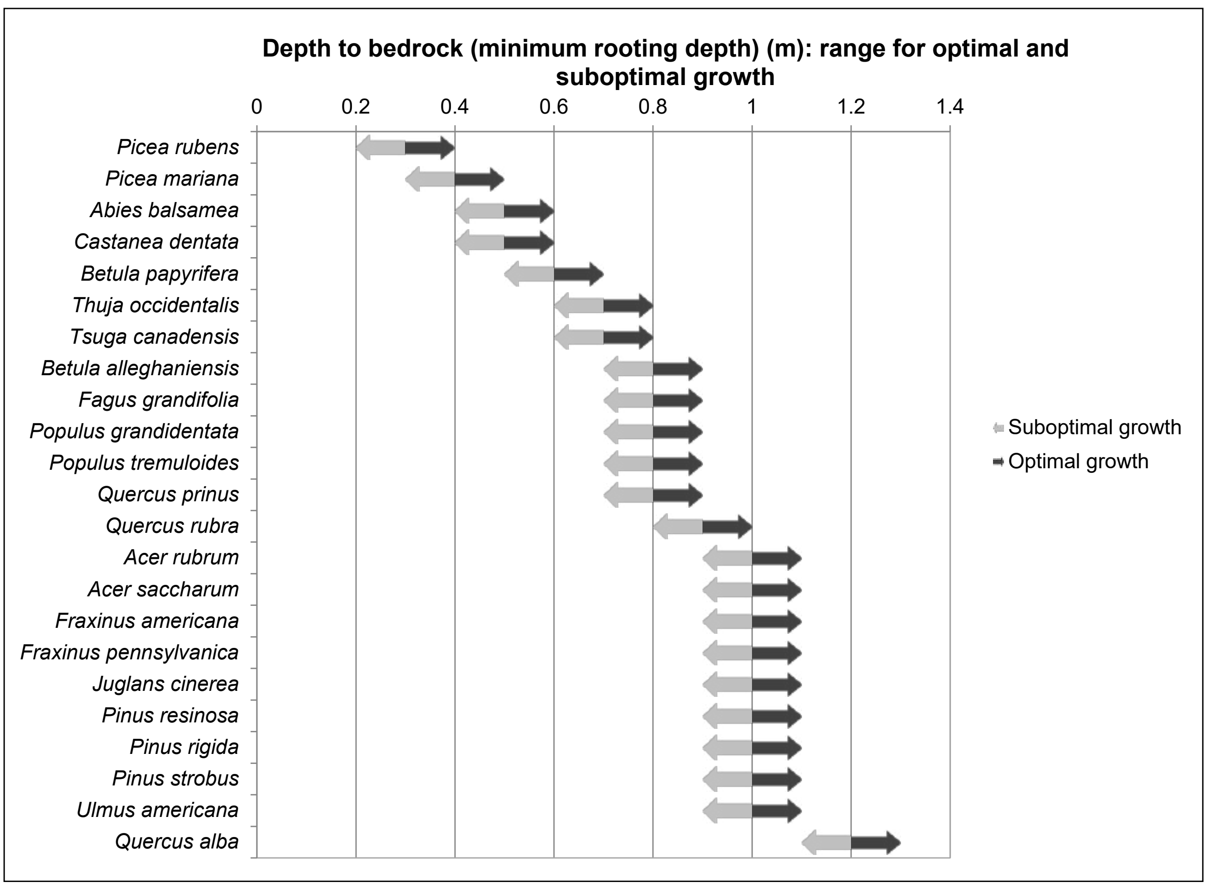

May to September precipitation (mm): ranges for optimal and suboptimal growth
0
200
400
600
800
1000
1200
Fraxinus pennsylvanica
Populus tremuloides
Ulmus americana
Populus grandidentata
Pinus resinosa
Thuja occidentalis
Fraxinus americana
Quercus rubra
Abies balsamea
Picea mariana
Acer saccharum
Acer rubrum
Pinus strobus
Tsuga canadensis
Betula payrifera
Fagus grandifolia
Quercus prinus
Quercus alba
Pinus rigida
Betula alleghaniensis
Picea rubens
Juglans cinerea
Castanea dentata
Suboptimal growth
Optimal growth


Soil pH: ranges for optimal and suboptimal growth
2.5
3.5
4.5
5.5
6.5
7.5
8.5
9.5
Pinus rigida
Castanea dentata
Quercus prinus
Fagus grandifolia
Acer rubrum
Picea rubens
Betula alleghaniensis
Quercus alba
Abies balsamea
Betula papyrifera
Picea mariana
Acer saccharum
Quercus rubra
Tsuga canadensis
Pinus strobus
Populus tremuloides
Fraxinus americana
Thuja occidentalis
Juglans cinerea
Populus grandidentata
Pinus resinosa
Ulmus americana
Fraxinus pennsylvanica
Suboptimal growth
Optimal growth


Soil clay (%): ranges for optimal and suboptimal growth
0
10
20
30
40
50
60
70
80
Pinus rigida
Pinus strobus
Populus grandidentata
Betula payrifera
Pinus resinosa
Tsuga canadensis
Populus tremuloides
Acer rubrum
Abies balsamea
Picea mariana
Quercus rubra
Picea rubens
Thuja occidentalis
Betula alleghaniensis
Fagus grandifolia
Acer saccharum
Juglans cinerea
Fraxinus americana
fraxinus pennsylvanica
Quercus alba
Ulmus americana
Castanea dentata
Quercus prinus
Suboptimal growth
Optimal growth


Soil coarse sand (%): ranges for optimal and suboptimal growth
0
20
40
60
80
100
120
140
160
Quercus alba
Castanea dentata
Quercus prinus
Fagus grandifolia
Fraxinus americana
Tsuga canadensis
Acer rubrum
Pinus strobus
Acer saccharum
Quercus rubra
Pinus rigida
Betula payrifera
Betula alleghaniensis
Picea rubens
Abies balsamea
Pinus resinosa
Picea mariana
Thuja occidentalis
Populus tremuloides
Juglans cinerea
Populus grandidentata
Ulmus americana
Fraxinus pennsylvanica
Suboptimal growth
Optimal growth


Soil permeability (cm/hr): ranges for optimal and suboptimal growth
0
2
4
6
8
10
12
14
16
18
20
Fraxinus pennsylvanica
Ulmus americana
Fraxinus americana
Quercus alba
Picea rubens
Fagus grandifolia
Acer saccharum
Quercus rubra
Thuja occidentalis
Juglans cinerea
Acer rubrum
Tsuga canadensis
Betula alleghaniensis
Abies balsamea
Picea mariana
Populus tremuloides
Pinus strobus
Betula papyrifera
Populus grandidentata
Quercus prinus
Pinus resinosa
Castanea dentata
Pinus rigida
Suboptimal growth
Optimal growth


Depth to bedrock (minimum rooting depth) (m): range for optimal and suboptimal growth
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Picea rubens
Picea mariana
Abies balsamea
Castanea dentata
Betula papyrifera
Thuja occidentalis
Tsuga canadensis
Betula alleghaniensis
Fagus grandifolia
Populus grandidentata
Populus tremuloides
Quercus prinus
Quercus rubra
Acer rubrum
Acer saccharum
Fraxinus americana
Fraxinus pennsylvanica
Juglans cinerea
Pinus resinosa
Pinus rigida
Pinus strobus
Ulmus americana
Quercus alba
Suboptimal growth
Optimal growth

Robin-Abbott, Molly J.; Pardo, Linda H. 2017. **How climatic conditions, site, and soil characteristics affect tree growth and critical loads of nitrogen for northeastern tree species.** Gen. Tech. Rep. NRS-172. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 149 p.

Forest health is affected by multiple factors, including topography, climate, and soil characteristics, as well as pests, pathogens, competitive interactions, and anthropogenic deposition. Species within a stand may respond differently to site factors depending on their physiological requirements for growth, survival, and regeneration. We determined optimal ranges of topographic (elevation, aspect, slope gradient), climatic (average temperature for January, July, and May to September; annual and May to September precipitation), and soil (pH, percent clay, percent coarse sand, permeability, depth to bedrock) parameters for 23 tree species of the northeastern United States. We primarily used importance values (a measure of how dominant a species is in a given forest area under existing site conditions) from a published analysis of more than 100,000 U.S. Forest Service Forest Inventory and Analysis plots to set optimal ranges for the abiotic factors. The region included in this assessment is defined by level 2 ecoregions: mixed wood plains in the Eastern Temperate Forest Ecoregion; Atlantic highlands and mixed wood shield in the Northern Forest Ecoregion. In addition to summarizing ranges for abiotic modifying factors, we also determined the critical load of nitrogen—the deposition below which no harmful ecological effects occur—for each species. The information can be used in forest health assessments to determine whether species growth at a site is expected to be optimal or suboptimal, and can also be used to modify critical load ranges for each species based on site conditions.

KEY WORDS: nitrogen deposition, topography, precipitation, temperature

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