Tree Planters' Notes

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***Tree Planters' Notes* (TPN) is dedicated to technology transfer and publication of information relating to nursery production and outplanting of trees and shrubs for reforestation, restoration, and conservation.**

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Dear TPN Reader

Welcome to another issue of *Tree Planters' Notes*!

I'm so pleased that this issue contains three articles for TPN's ongoing "Tree Planting State by State" series. Each article in the series profiles past, current, and future reforestation and restoration activities in a State. This issue includes California (p. 4), Alabama (p. 18), and Hawaii (p. 34), bringing the total published articles in the series to 24 States plus the U.S. Virgin Islands. The series began with the Spring 2011 issue. I would love to see it completed in the next few years, but it is challenging to recruit authors. Please contact me if you would like to submit an article for one of the following States (or can recommend potential authors).

Arizona	Montana	Tennessee
Colorado	Nevada	Texas
Florida	New Hampshire	Utah
Illinois	New Jersey	Vermont
Kansas	Ohio	West Virginia
Kentucky	Oklahoma	Wyoming
Maine	Oregon	Puerto Rico
Massachusetts	Rhode Island	Pacific Islands (American Samoa, Guam, Palau, CNMI, Marshalls, FSM)
Minnesota	South Carolina	
Mississippi	South Dakota	

In addition to the three State articles, this issue contains five other articles. Morgan et al. describe propagation protocols for an endangered tropical tree species on St. Croix (p. 56), Shoemaker et al. review results from trials to evaluate avian herbivory on pine seed (p. 82), and three articles provide guidance for seed transfer of tree species in the Eastern United States (red pine, yellow birch, and northern red oak on pages 63, 69, and 76, respectively).

I'm certain you will find something of interest within these pages.

Until next time,

Diane

Diane L. Haase

When one plants a tree, they plant themselves.
Every root is an anchor, over which one rests with grateful interest,
and becomes sufficiently calm to feel the joy of living.

— John Muir.

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Tree Planting in California

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Abstract

California has a wide diversity of forest types and species involved in tree planting and subsequent management to maintain healthy and productive forests. California has over 31 million ac (12.5 million ha) of forests, approximately half of which is in parks, reserves, wilderness areas, or very low-productivity areas. California's forests vary from the highly productive coastal forests dominated by fast-growing redwoods (*Sequoia sempervirens* [Lamb. ex D. Don] Endl.), to sparse ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson) forests on the dry side of the Sierra Nevada mountains, to extensive hardwood-dominated forests at lower elevations. California's forests grow in climates with extreme hot and cold temperatures and a long, dry season. Wildfires have increased significantly in recent years resulting in a growing incidence of high-mortality crown fires. About half of forest acreage in California is classified as productive timberlands dominated by numerous conifer species. Most tree planting in California occurs in these timberlands. The three major ownership classes (large private owners, small private owners [concentrated on the north coast], and the U.S. Department of Agriculture [USDA], Forest Service) have historically practiced very different reforestation approaches. Around half of the large private owners practice even-age management and plant mostly conifer seedlings. Smaller private landowners mainly use uneven-aged management and plant relatively few seedlings relative to their land area. The USDA Forest Service manages more than half the timberlands in the State but has lower levels of timber harvesting compared with private landowners, mainly uses uneven-aged management, and has been less active in tree planting after wildfires. As California grapples with increasing tree mortality from wildfires and other mortality events, the importance for all landowners to apply lessons learned from local best practices will be more critical than ever if their respective forests are to remain productive into the future.

California's Forests

Forest land is defined by the the U.S. Department of Agriculture (USDA), Forest Service's Forest Inventory and Analysis (FIA) program as a land base with at least 10 percent tree cover (Brodie and Palmer 2020). California has the highest percentage of its forests in reserve or park status among all States except Alaska. Each of California's conifer forest types has a considerable level of microsite species diversity. Reforestation activities are concentrated on timberlands outside of parks, reserves, and wilderness areas (table 1).

Table 1. Current forest types on California timberlands by owner group in millions of acres (total numbers are rounded).

Forest type	USDA Forest Service	Corporate	Family	Other Government	Total
	Acres (millions)				
California mixed conifer	4.2	1.6	0.5	0.1	6.5
Ponderosa pine	1.2	0.4	0.4	0.0	2.1
Douglas-fir	0.2	0.3	0.3	0.0	0.9
Fir/spruce/mtn. hemlock	1.1	0.2	0.1	0.0	1.4
Redwood	0.0	0.4	0.2	0.0	0.7
All other species	2.2	1.3	1.5	0.2	5.1
Total timberlands	8.9	4.3	3.0	0.4	16.6
Timberlands as a percent of all forest lands	58%	85%	41%	11%	53%

Source: Brodie and Palmer (2020). 1 million ac = 404,686 ha.

Figure 1. California forest landownership is divided among large private owners, small private owners, and USDA Forest Service. (Source: CAL FIRE Fire and Resource Assessment Program 2018)

In California, conifer forests are the dominant forest types in the State. Oak-dominated (*Quercus* spp.) forests in the low-rainfall foothills are extensive but these forests have very little active tree planting outside of specific restoration projects. Timberland is the subset of forest land where sustainable timber harvesting is feasible and legally allowed. The FIA program measures a range of forest characteristics on plots laid out on a 3-mi (4.8 km) grid across all forest lands. The three major ownership classes that undertake reforestation are large private owners, small private owners (concentrated on the north coast), and USDA Forest Service timberlands (figure 1). The California Department of Forestry and Fire Protection (CAL FIRE)

Figure 2. Conifer ecosystems dominate much of California's forests such as this mix of even-aged and uneven-aged mixed conifer stands on Blodgett Forest Research Station near Georgetown, CA. (Photo by William Stewart, 2012)

Figure 3. High conifer tree mortality and low hardwood tree mortality in the Southern Sierra Nevada has resulted from years of drought conditions. (Photo by William Stewart, 2018)

owns approximately 100,000 ac (40,470 ha) of forests. Most other Government-owned forests are in parks or reserves where active reforestation is usually limited to small-scale projects.

Mixed conifer forests (figure 2) dominate the Sierra Nevada, Cascade, and Klamath mountain ecosystems and represents about half of all timberland acres in California. This forest type is the touchstone for forest policy and regulations requiring reforestation with a mix of species. California mixed conifer forests consist of a mix of pines (*Pinus* sp.), Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), true firs (*Abies* spp.), and incense cedar (*Calocedrus decurrens* [Torr.] Florin), as well as minor components of various hardwood species. The hardiest and least shade-tolerant species within the mixed conifer forests is ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson). Decades of preferential harvesting of higher value species and relatively few wildfires have led to a substantial increase in the proportion of white fir (*Abies concolor* [Gord. & Glend.] Lindl.ex Hildebr.) from natural reseeding. Most active reforestation projects now prioritize planting more pine and Douglas-fir seedlings that do not naturally reproduce in the understory. Pure pine forests are common in drier sites within these ecosystems, especially in those with hotter temperatures and lower rainfall. The higher elevation forests with red fir (*Abies magnifica* A. Murray bis), mountain hemlock (*Tsuga mertensiana* (Bong.) Carr.), and Engelmann spruce (*Picea englemannii* Parry ex Engelm.) are mainly in Federal ownership where there is relatively limited tree planting. Droughts during the 2010s had a major effect on conifers in the southern Sierra Nevada (figure 3) and shifted many forests towards hardwood-dominated stands.

On California's north coast, forest stands range from nearly pure redwood stands (*Sequoia sempervirens* [Lamb. ex D. Don] Endl.) on lower elevation sites near the ocean to stands with an increasing Douglas-fir component further inland. The north coast also has many stands with high densities of tanoak (*Notholithocarpus densiflorus* [Hook. & Arn.] P.S. Manos, C.H. Cannon, & S.H. Oh), laurel (*Umbellularia californica* [Hook. & Arn.] Nutt.), and Douglas-fir that resulted from natural regeneration following past harvests. Landowners with access to their own capital or Government cost-share funds often replant these stands with well-spaced redwood and Douglas-fir seedlings to increase the future value of these forests.

Although giant sequoia (*Sequoiadendron giganteum* [Lindl.] J. Buchholz) seedlings have good survival and growth when planted on private or university lands across the Sierra Nevada (York et al. 2013), the more famous naturally occurring sequoia groves cover less than 40,000 ac (16,187 ha) and are concentrated in the southern Sierra Nevada on Federal lands (Willard 2000). Natural regeneration within historic giant sequoia groves is the preferred Federal strategy.

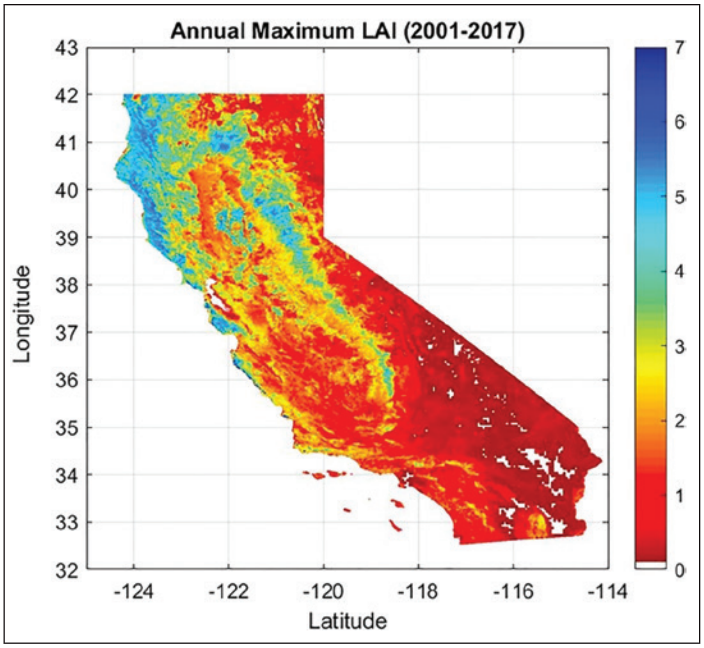

Figure 4. The map of maximum leaf area index (LAI) across California can provide insights into forest productivity. (Source: Baldocchi et al. 2019)

Climate Determinants of Forest Productivity

One way to understand highly variable forest productivity in California is through high-resolution satellite maps of average annual maximum leaf-area index (LAI; the ratio of leaf area per unit of ground) over recent decades (figure 4). LAI is highly correlated with water transfer, carbon dioxide transfer, and gross growth rates. Coastal forests with warm temperatures and high rainfall are characterized as highly productive (LAI above 5) whether they are in old growth reserves or managed stands. These forests are dominated by redwood and Douglas-fir trees where competition for light, not moisture, is the major factor affecting seedling survival and growth. The more extensive interior forests have an LAI between 3 and 5 and are characterized by less-dense vegetation. In those forests, competition for moisture is the dominant factor affecting seedling survival and growth. Forests with LAI measurements between 2 and 3 have lower productivity and are common on the low-elevation dry forests and the high-elevation alpine forests.

By comparing the forest ownership map with the LAI map (figures 1 and 4), a few factors relating to tree planting stand out. On the north coast, the most productive forests are mostly owned by large, private timberland owners, while smaller, private timberland owners have less productive forests located further from the Pacific Ocean. In the interior forests of northern California with relatively high LAI, forest ownership is mixed across large private, small private, and Federal managers. Much of the forest land in the southern Sierra Nevada has relatively low LAI and is primarily in Federal ownership at higher elevations and in small private ownership at lower elevations.

Forest Structure

The distribution of forest area by stand age and recent planned and unplanned disturbances provides a useful perspective on the scale of California's reforestation needs for forest managers (figure 5). Large private or corporate owners of conifer forest lands plant most of the conifer seedlings in California. Planting has been concentrated on clearcut acres, smaller units with poor natural regeneration within uneven-aged managed forests, and areas where crown fires killed most trees. Large, private owners have been more active in conducting both salvage logging operations (figure 6) and successful reforestation than neighboring USDA Forest Service lands burned in the same fires (figure 7). Compared with Oregon and Washington, the conifer forests owned by large, private owners in California use longer, even-aged rotations and have more areas managed with uneven-aged silviculture. This management approach requires less active reforestation acres compared with total acres (figure 8).

Small, private forest owners in California depend more on natural regeneration than active reforestation to maintain forest productivity; their management goals do not always focus on high rates of financial value appreciation. Compared with large, private forest owners, the lower percentage of total area in young stands demonstrates the greater dependence on natural regeneration with relatively less planted area. The need to replant stands owned by small, private owners following crown fires and high levels of mortality was relatively limited according to FIA data, but has increased after the severe 2020 and 2021 fire seasons.

The USDA Forest Service timberlands are roughly equal in area to the combined large and small private timberland ownerships in the State. These Federal lands have had a much different pattern of disturbances over the past decade due to less harvesting

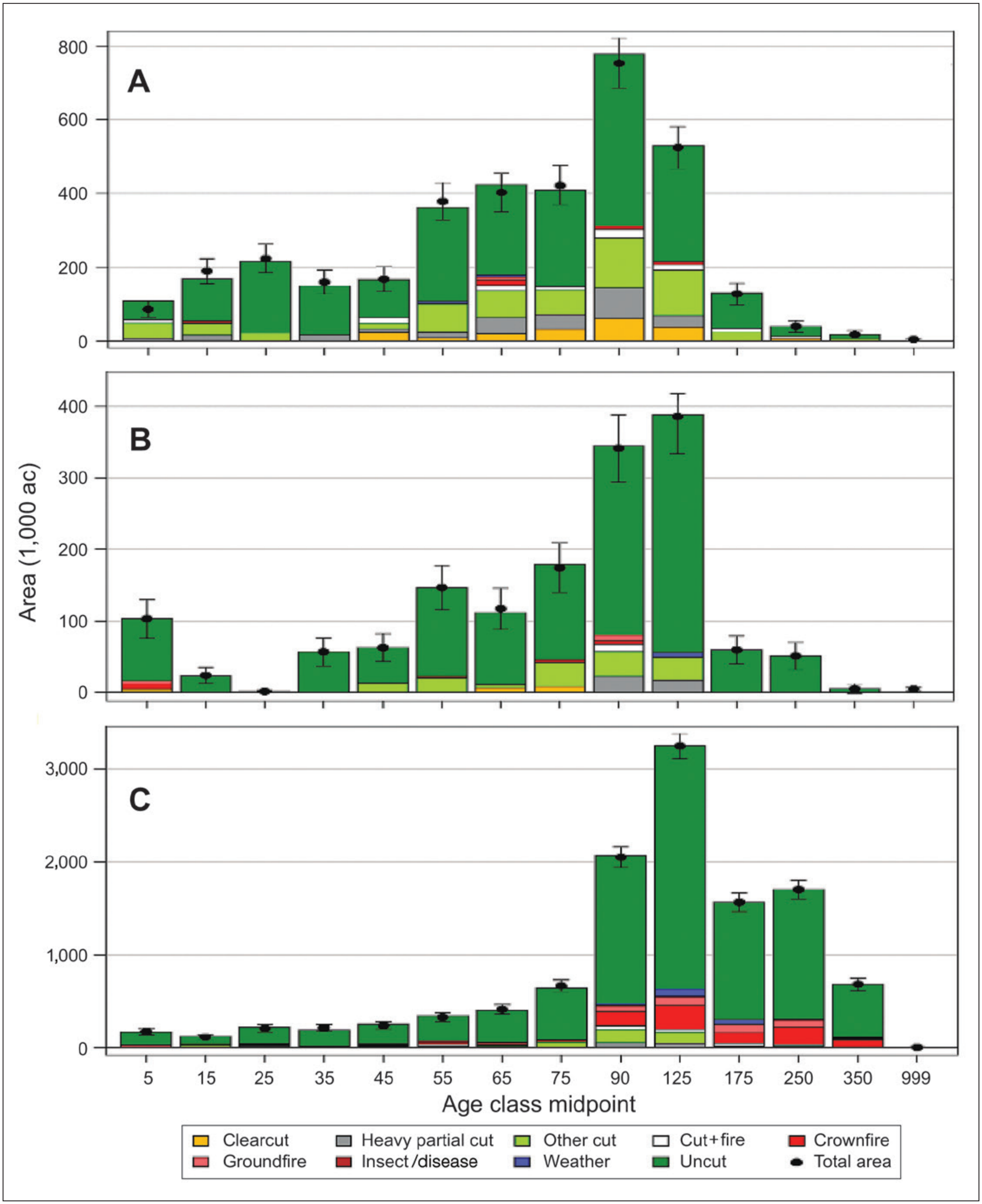

Figure 5. Mixed conifer forest stand age and status (2008–2018) in California varies among (a) large private, (b) small private, and (c) USDA Forest Service landowners. (Source. Andy Gray, USFS PNW FIA)

Figure 6. Forest management strategies differ based on land ownership. This photo shows salvaged private forest land to be replanted in between Federal timberlands that were not salvaged or replanted following the 2007 Moonlight Fire. (Photo by William Stewart, 2009)

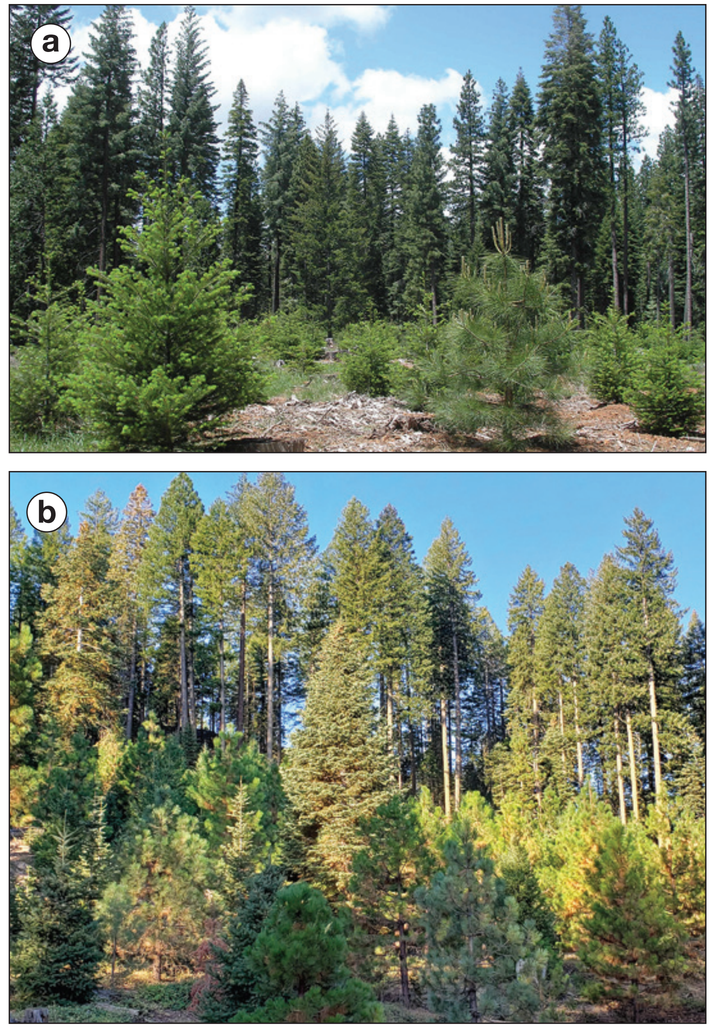

Figure 8. Many large, private landowners in California manage with uneven-aged silviculture that include ± 2-ac (0.8-ha) group selection units in forests such as these in (a) Shasta County and (b) Plumas County. (Photos by Bob Rynearson)

before the 1990s and significant reductions in harvesting and subsequent reforestation since the mid-1990s. From 2008 to 2018, thinning and clear cuts on USDA Forest Service lands were limited. By far the areas of Federal timberland that could potentially benefit from reforestation are those extensive areas affected by crown fire, severe insect and disease mortality, and major weather-related mortality in 100- to 250-year-old stands. The large wildfires of 2020 and 2021 added approximately 2 million additional acres of USDA Forest Service timberland to the total areas impacted by crown fires identified in figure 5 that could benefit from reforestation. Without successful replanting, much of the area burned by crown fires will probably regenerate with a predominant mix of montane chaparral species, lesser amounts of other nonforest types, and some natural conifer regeneration in the shady understory.

Figure 7. Prompt planting and control of competing vegetation on private land resulted in successful, mixed-species reforestation (left), whereas delayed planting and no vegetation control resulted in a shrub-dominated condition on National Forest land (right) following the 2000 Storrie Fire. (Photo by William Stewart, 2020)

Reforestation in California

History

Social and political concerns about the need for reforestation in California date back more than a century. In 1884, an interim State Forestry Commission reported to the Governor of the need to replant land “denuded of redwoods,” to plant “new land in suitable forest trees,” and to collect useful information on the “best mode of

Figure 9. Civilian Conservation Corps (CCC) planted many trees in the 1930s. In this photo, CCC crew are carrying seedling transplants to the field on the Shasta National Forest. (USDA Forest Service archives, wikimedia.org, USFS photo #413770)

planting, caring for, thinning, and general treatment of growing timber trees" (Coleman et al. 1884). By 1887, the State was producing nursery stock of 150,000 seedlings annually and had established experimental plantations in all regions. Considerable forest tree planting work was also carried out by the Civilian Conservation Corps (CCC) during the 1930s depression era (figure 9), with "tree and plant disease control" performed on nearly 800,000 ac (323,750 ha) in the State (Merrill 1981).

After World War II, both the State and Federal Governments established large, public forest nurseries that produced millions of seedlings per year throughout the 20th century. By the 21st century, however, many of these public nurseries have been closed or reduced in annual seedling output.

Low survival rates for planted seedlings have been a long-standing challenge in California's long, dry summers. Before 1953, only about 31 percent of plantings were successful (Zillgitt 1958). Low survival rates are still common when competing vegetation is not successfully controlled. Average third-year plantation survival on USDA Forest Service lands was only 57 percent in 2004, the last year this statistic was published in national reports (Barrett 2014). In comparison, conifer seedling establishment rates as high as 95 percent for pines and more than 80 percent for Douglas-fir are now common on larger, private forest land ownerships (Baldwin 2022). These high establishment rates are attributed to substantial improvements in nursery and planting technology and practices from seed collection to planting and management of the growing trees (Stewart 2022).

Five Principles of Reforestation in California

Private-sector forest management practitioners in California developed five primary principles for successful reforestation in the State (Baldwin 2022).

1. Use tree species from known, appropriate seed sources which can be established and grow vigorously on the site without irrigation.

Figure 10. California has 85 tree seed zones based on physiographic and climatic regions. Each zone is further divided into 500-ft (152-m) elevation bands. (Source: CAL FIRE Fire and Resource Assessment Program 2019)

2. Control vegetation that would otherwise compete with planted seedlings for limited soil moisture during the critical first, and possibly the second, year after planting.
3. Use seedlings that are able to withstand the conditions on the site when planted and are able to rapidly grow new roots after planting.
4. Properly handle, transport, store, and plant seedlings and plant them when conditions on the site are best to allow for rapid root growth.
5. Protect seedlings from damage by animal and insect pests, if necessary.

Seed Zones of California

The first step in the reforestation process starts with seeds collected in the wild or bred in seed orchards grown from seeds collected from known locations. Based on the work of the Forest Tree Seed Committee that built on earlier maps, California is divided into 6 major physiographic and climatic regions, 32 sub regions, and 85 Tree Seed Zones (Buck et al. 1970) (figure 10). Within the individual zones, conifer seed collections are catalogued by separate elevation bands with every 500-ft (152-m) rise in elevation (Griffis 2022). All conifer seeds collected and stored in California's three major conifer seed banks follow the same seed zone designations.

California does not have a sophisticated seed-transfer system such as those used in British Columbia (MFLNRORD 2020) or the Pacific Northwest (Howe et al. 2009). The current strategy used by most practitioners in California is similar to conclusions from a recent analysis of a Douglas-fir heredity study that indicated seeds collected from relatively small seed zones can retain good, long-term survival and productivity within an environmental range of 3.6 °F (2 °C) (St. Clair 2019). Interviews with private-sector reforestation practitioners suggest that they consider good seedling quality and tree management after planting to be more important than shifting seeds to zones that may be similar to future climates for maintaining long-term growth.

Seed Banks

California has three seed bank systems that have some degree of overlap. The USDA Forest Service maintains a seed bank at its Placerville nursery facility in the central Sierra Nevada where they currently have approximately 120,000 lb (54,430 kg) of conifer seed. They often trade with CAL FIRE's seedbank when either agency has deficiencies in viable seed for a zone where significant reforestation is planned. CAL FIRE's seed bank in Davis has a seed inventory of approximately 20,000 lb (9,070 kg) for large, private landowners who pay storage fees and another 20,000 lb (9,070 kg) collected by CAL FIRE. Smaller forest landowners rarely collect seeds from their own lands so they are mostly dependent on the CAL FIRE collections following wildfires or other mortality events. CalForest Nurseries (Etna, CA) is the largest independent nursery in California and stores around 40,000 lb (18,145 kg) of seeds for private forest landowners plus a smaller amount of their own seed. Overall, an estimated 60 percent of seedlings used by large, private forest owners come from cooperative-improved tree seed programs (Griffis 2022). Recent activities of these cooperatives build on improved seeds and focus more on activities to increase survival and growth of planted seedlings. The recent large wildfires have created seed demands far above the available improved seed and have required use of more wild-collected seed when available. California's conifer seed banks will need considerable new investments in collection and storage if increased incidence of major mortality events continues.

Seedling Nurseries

During the 2020 planting year, California nurseries produced more than 24.5 million seedlings, nearly all of which were container-grown conifers (Haase et al. 2021) (figure 11). Only two of the numerous State and Federal seedling nurseries that operated in the 20th century are still operational today. The USDA Forest Service Placerville Nursery produces approximately 4 million seedlings per year but may receive funds to increase annual production capacity up to 15 million seedlings (California Forest Management Task Force 2021). Actual production will continue to be limited by the scale of preorders from National Forests that have cleared the extensive planning requirements necessary for reforestation on National Forest lands. Several years after its closure, CAL FIRE restarted their conifer nursery in Davis. This State nursery serves State forests, State-funded ecological restoration projects, forest landowners with 50 to 1,000 ac

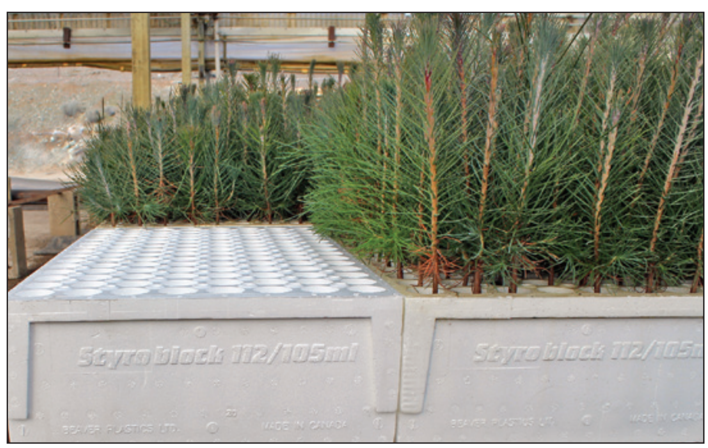

Figure 11. Most seedlings in California are grown in containers. Styroblock™ containers are manufactured with many different sizes of cells and density. (Photo by Tom Jopson, CalForest Nurseries, 2019)

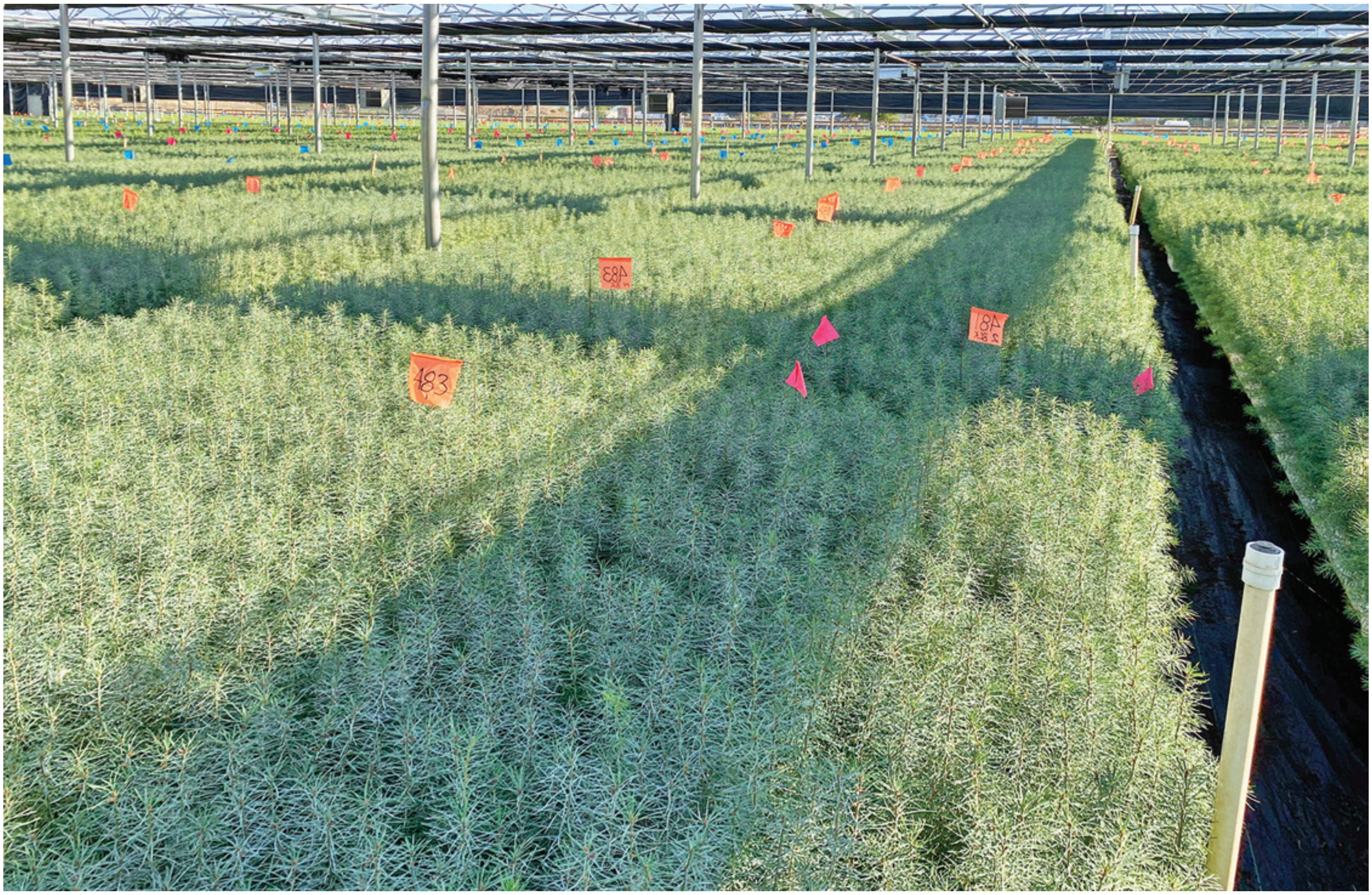

Figure 12. CalForest Nurseries is the largest private conifer seedling grower in California and grows millions of seedlings annually at its Etna, CA facility. (Photo by Tom Jopson, CalForest Nurseries, 2019)

(20 to 405 ha) who only order 100 to 5,000 seedlings at a time, and small landowners organized under Resource Conservation Districts. In 2021, the nursery produced approximately 250,000 seedlings but plan to increase annual production to 1 million seedlings within a few years.

Private nurseries produce most of the seedlings grown in California. On the north coast, one clonal nursery and one traditional nursery grow redwood seedlings for timber companies that own large areas of second- and third-growth forests. CalForest Nurseries (figure 12) can now produce 15 to 25 million seedlings per year depending on the wildly fluctuating post-fire orders. Additional seedlings are grown in several nurseries in Oregon from seed collected in California.

Planting

Based on timber harvest statistics over the past decade, 40,000 to 60,000 ac (16,190 to 24,280 ha) of private forest lands per year have had silviculturally driven reforestation to meet post-harvest stocking requirements. Recent increases in wildfire, insect, and drought mortality have added 30,000 to 50,000 ac (12,140 to 20,235 ha) that could potentially be reforested if the damage is severe enough and the landowners have the necessary investment funds (Baldwin 2022). Large, private timberland owners must finance reforestation without access to any Government cost-share programs. Small landowners can utilize Government limited cost-share funds but often lack tree-planting expertise since they primarily practice uneven-age silviculture that depends on natural, rather than planted, regeneration.

According to annual reforestation and timber stand improvement reports (USDA Forest Service 2011 to 2020), the USDA Forest Service has averaged around 3,000 ac (1,214 ha) per year of reforestation in California with effective control of competing vegetation and a similar amount of area planted without control of competing vegetation. Much of the 2 million (~809,400 ha) of Federal timberlands in California that burned during the 2020 and 2021 fire seasons

Figure 13. Delivery of seedlings to the outplanting site must be done in a manner to maintain seedling quality (Photo by Mark Gray, Sierra Pacific Industries, 2016)

will also need active reforestation if significant forest growth rates are to be reestablished. The success rate for natural regeneration in reestablishing conifer forests in California's Mediterranean climates is often low (Welch et al. 2016), and without planned and successfully implemented reforestation efforts, it is common for conifer forest areas burned in severe wildfires to remain dominated by shrub species for decades (Bohlman et al. 2016, Stephens et al. 2020).

Reforestation foresters select the best mix of species to be planted after considering which species have historically done well on the sites and which species will thrive throughout forest development. Ensuring that the seedlings go from climate-controlled facilities to the planting site with the least delays requires an efficient logistical operation (figure 13). To optimize survival after planting, crews use hoedads or shovels to plant the seedlings (figure 14) in microsites that ensure sufficient soil moisture and prevent excessive evapotranspiration (figure 15). On north-facing slopes, species with relatively more shade tolerance such as Douglas-fir, red fir, or white fir may be more successful. Species that are highly sensitive to hot temperatures and sunscald need to be planted in the most favorable microsites, using

Figure 14. Planting seedlings with a hoedad is common on California reforestation sites. (Photo by Bob Rynearson, 2015)

Figure 15. Microsite planting on this site resulted in shading for Douglas-fir seedlings and open sun for ponderosa pine seedlings. (Photo by Bob Rynearson)

natural features such as stumps, rocks, or large woody debris that provide protection to seedlings from the harsh conditions.

Reductions in Seedling Density Requirements on Private Lands

With limited markets for small-diameter trees, major improvements in seedling survival and growth among private landowners, and increasing wildfire risk posed by high live and dead fuel loads, the 2020 Forest Practice Rules (California Department of Forestry and Fire Protection, 2020) governing non-Federal lands in California substantially reduced the minimum number of surviving seedlings required per acre after reforestation. For high-quality sites, the minimum number of surviving seedlings was reduced from 300 trees per acre (TPA; 1 ac = 0.4 ha) to 125 to 200 TPA, depending on forest type. For lands with lower site index that often have less precipitation and higher fire risks, the minimum was reduced from 200 TPA to 100 TPA. Other changes allowed for even lower planting densities in designated long-term fuel breaks. These changes will require less seed per acre, may potentially increase tree survival in stands during severe wildfires and long droughts, and can align future harvests to the market demand in California that focuses on larger diameter trees.

Current Reforestation Challenges

The greatest tree-planting challenge facing California is the huge increase in conifer forest land impacted by catastrophic wildfires. Crown fires tend to kill most of the mature trees in a stand and often do not leave sufficient numbers of well-spaced, natural seedlings to ensure subsequent reforestation. The conifer timberland area burned in both the 2020 and 2021 wildfire seasons was equal to wildfire mortality over the previous decade. This large-scale fire impact has resulted in a large reforestation backlog that will become increasingly difficult to reforest as shrubs get established. Because the USDA Forest Service and small, private forest landowners shifted away from silviculture-driven replanting over the past few decades, the reforestation supply chain shrunk in its ability to meet the needs of episodic seedling purchasers. While many large, private landowners follow well-known strategies (Amacher et al. 2008) and respond rapidly with major financial investments and reforestation efforts, many other forest managers are not able to respond as quickly and face limitations when trying to access a constrained reforestation supply chain.

Looking Ahead

Of all the States with productive conifer-dominated forests, California has experienced more mortality from wildfires and subsequent conversion towards a shrub-dominated vegetation when successful reforestation is not undertaken. Expanding the entire reforestation pipeline—seeds, nurseries, planting, and post-planting care (Fargione et al. 2021)—to serve the three diverse types of forest landowners will be challenging but necessary if California is to maintain its healthy and productive forests.

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Alabama’s Trees for Generations To Come

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Abstract

Alabama’s forest and reforestation efforts are a result of many different interests over decades and even centuries. These interests involve landowners, industry, markets, government agencies, universities, and the public. This report provides a snapshot of where Alabama forests have come from, where they are now, and where they will hopefully be in the future.

History of Alabama’s Forests

Some of the earliest documentation of Alabama’s forests can be found in the writings of William Bartram, a naturalist who traveled extensively throughout the southeastern United States during the 1700s. His writings provide detailed accounts of the forests and wildlife in the Southeast during this time (Bartram 1791). He described the northern half of Alabama as having pines (*Pinus* sp.) on upland sites sometimes mixed with oaks (*Quercus* sp.) and other hardwoods, including American chestnut (*Castanea dentata* [Marshall] Borkh.). The Coastal Plain was reported to have longleaf pine (*Pinus palustris* Mill.) on uplands where fires were common, hardwoods in bottomlands, pine barrens, and natural prairies. The lower Coastal Plain was covered in bottomlands with bald cypress (*Taxodium distichum* [L.] Rich.), wet prairies, and cane thickets.

By the mid-1700s, most sawmills in Alabama were located along smaller streams. These mills cut boards and other products to supply growing local communities. On December 14, 1819, Alabama became a State. Large-scale timber harvests were not common in Alabama at that time, but in the Atlantic States, tensions with England grew in part due to forest-use rights, and in the Lake States, timber harvesting pressures increased causing timber cruisers to look to Southern States for forest resources.

Before the 20th century, fires were common in almost all of Alabama’s forests and were often caused by lightning strikes. Struck trees might burn for days, then eventually fall and catch the surrounding ground vegetation on fire. Fires were often low intensity and were more of an inconvenience than a danger to settlers. These regular fires promoted growth of native grasses in the forest understory used by grazing livestock. Fires also stimulated natural regeneration and growth of longleaf pine and fire-tolerant hardwoods.

By the early 1900s, timber harvesting was at its peak in the Southeastern United States, with little regard for the future of forests or land management (figure 1). The U.S. Department of Agriculture (USDA), Forest Service saw the shortsightedness of this mentality and therefore helped States to conduct forest inventories. Alabama accepted the offer, and in 1908, J.H. Foster began inventorying the State’s remaining forests. By this time, much of the State’s forests had been harvested. The most important forest issues for Alabama identified at the time were losses from fire and livestock damage, overharvesting, lack of regeneration, and restrictive tax laws (Foster 1909). The largest areas of timber were left in southwest Alabama and the area around Birmingham where much of the land was owned by mining companies that harvested longleaf pine and shortleaf pine (*Pinus echinata* Mill.) to support the charcoal iron furnaces in the region. It was said to take 100 bushels of charcoal, which was mostly pine, to make a ton of iron (Williams 2005).

Not only was Alabama’s forested landscape drastically altered by extensive harvesting, but the role of fire

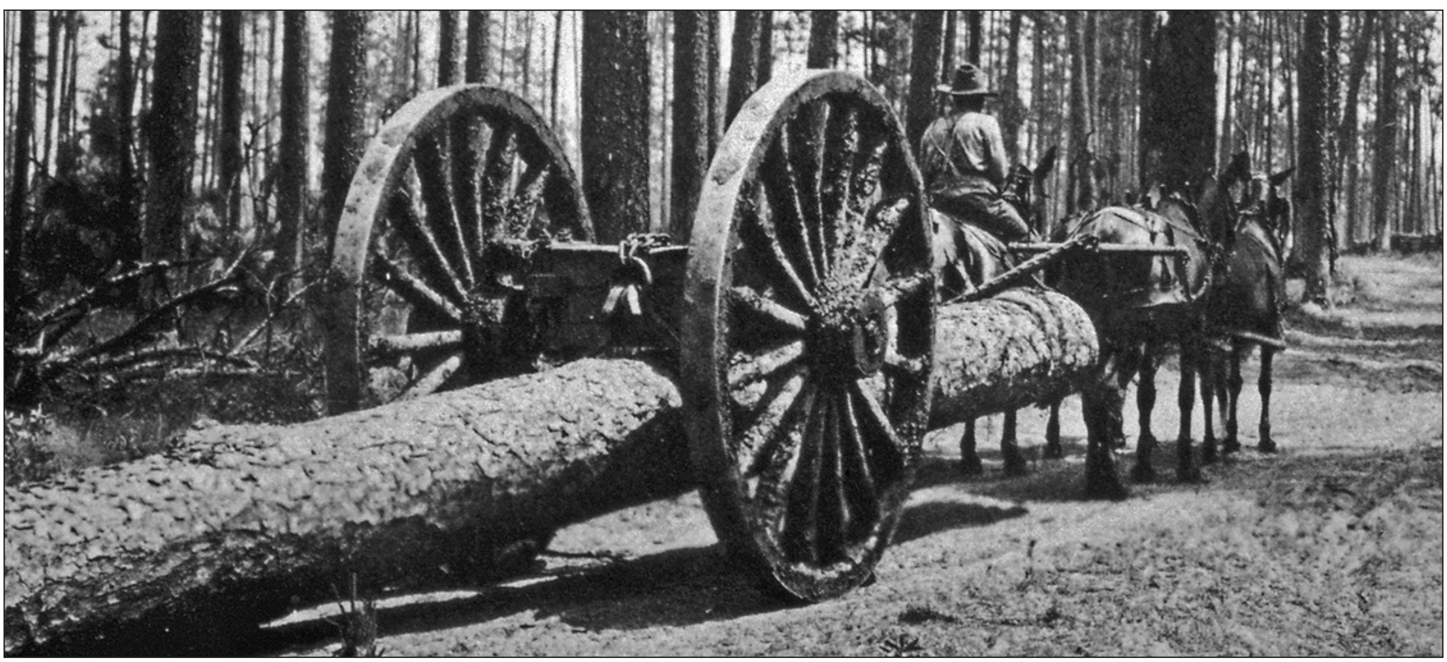

Figure 1. Extensive harvesting in the late 1800s and early 1900s drastically altered Alabama's landscape. (Photos courtesy of Alabama Forestry Commission)

on forests was altered. In 1923, the Alabama Forestry Commission (established in 1907) began to focus on fire protection. In the 1930s, members of the Civilian Conservation Corps helped with fire protection and construction of fire lookout towers. In the 1940s, 70 percent of forest fires occurred in the Southern United States. At that time, lightning fires accounted for just 1 percent of wildfires whereas smoker and arson fires were responsible for 38 and 53 percent, respectively, of all wildfires.

By the middle of the 20th century, lack of natural fire and forest regeneration failures caused land to be reforested with faster growing southern pine species, such as loblolly pine (*Pinus taeda* L.) and slash pine (*Pinus elliottii* Engelm.). The shift in forest composition, coupled with the rising use of paper and paper products (especially wrapping paper) and limited pulpwood supplies in the Lake States, resulted in paper mill developers setting up in the South. Some of the more notable companies during that time included International Paper in Panama City, FL; Westervelt Company in Tuscaloosa, AL; and the E-Z Opener Bag Company in Holt, AL (inventor of the foldable paper bag).

Companies realized that they needed to rely on landowners to assist them with sourcing trees for their mills. In 1940, Weyerhaeuser established its Clemons Tree Farm and the USDA encouraged the growth of "repeated crops of timber" on tree farms throughout the country (Randall 1954). These ideas spread to the Southern States, with Alabama being the first State to recognize tree farm landowners. In 1942, Emmett N. McCall of Dixonville, AL (near Brewton) was recognized as the first tree farmer in the State (Johnson 2012).

Current Forest Conditions

Alabama is known for its ecosystem diversity. In fact, 64 different ecosystems have been documented in the State, 25 of which are forests and woodlands (Duncan 2013). The variety of ecosystems makes Alabama the fifth most biologically diverse State in the United States. This diversity is due, in part, to the warm, moist climate, where average air temperatures range from about 36 °F (2.2 °C) in January to 93 °F (33.9 °C) in July and rainfall is abundant (an annual average of 56 in [142 cm]). Furthermore, Alabama is geologically diverse.

Alabama is generally recognized as having six physiographic regions: Interior Plateau, Southwestern Appalachians, Ridge and Valley, Piedmont, Southeastern Plains, and Southern Coastal Plain (figure 2). These regions vary in soil type, mineral resources, elevation, and topography, resulting in the unique forest types found across the State.

The Interior Plateau is in northern Alabama along the Tennessee border. Elevations are lower than the Appalachian region to the east. Limestone, chert, sandstone, siltstone, and shale compose landforms of hills, irregular plains, and tablelands in this region. Native vegetation is primarily oak-hickory forest with some mixed forest and areas of cedar glades. Springs, lime sinks, and caves are common.

The low mountains of the Southwestern Appalachians reach into northeast and north central Alabama, where forests are scattered with cropland and pasture. Forests are often limited to the deeper ravines and steep slopes, which are dominated by mixed oaks with shortleaf pine.

The Ridge and Valley region is a relatively low-lying region between the Piedmont to the east and the Southwestern Appalachians to the west. The ridges and valleys are composed of limestone, shale, sandstone, and marble. Springs and caves are common. Longleaf pine was native in the southern part of this region, and shortleaf and loblolly pines naturally regenerated cutover areas and old fields. Loblolly pine was generally found naturally only in stream margins and was considered low-value and susceptible to rot.

The Piedmont is a transitional area between the more mountainous regions of the Southwestern Appalachians to the northwest and the relatively flat Southern Coastal Plain to the southeast. Longleaf pine forests were common until most of this region was harvested and heavily farmed in the late 1800s. As farms were abandoned, this region reverted to loblolly pine and hardwood forests. The soils tend to be more clayey and eroded than those in the coastal plain region.

The Southeastern Plains region has an assortment of cropland, pasture, woodland, and forest. Natural vegetation is mostly oak-hickory-pine forests. Elevations are higher than in the Southern Coastal Plain, but generally lower than in much of the Piedmont. Streams in this area are low and sandy. This region also contains prairie areas with distinctive chalk and

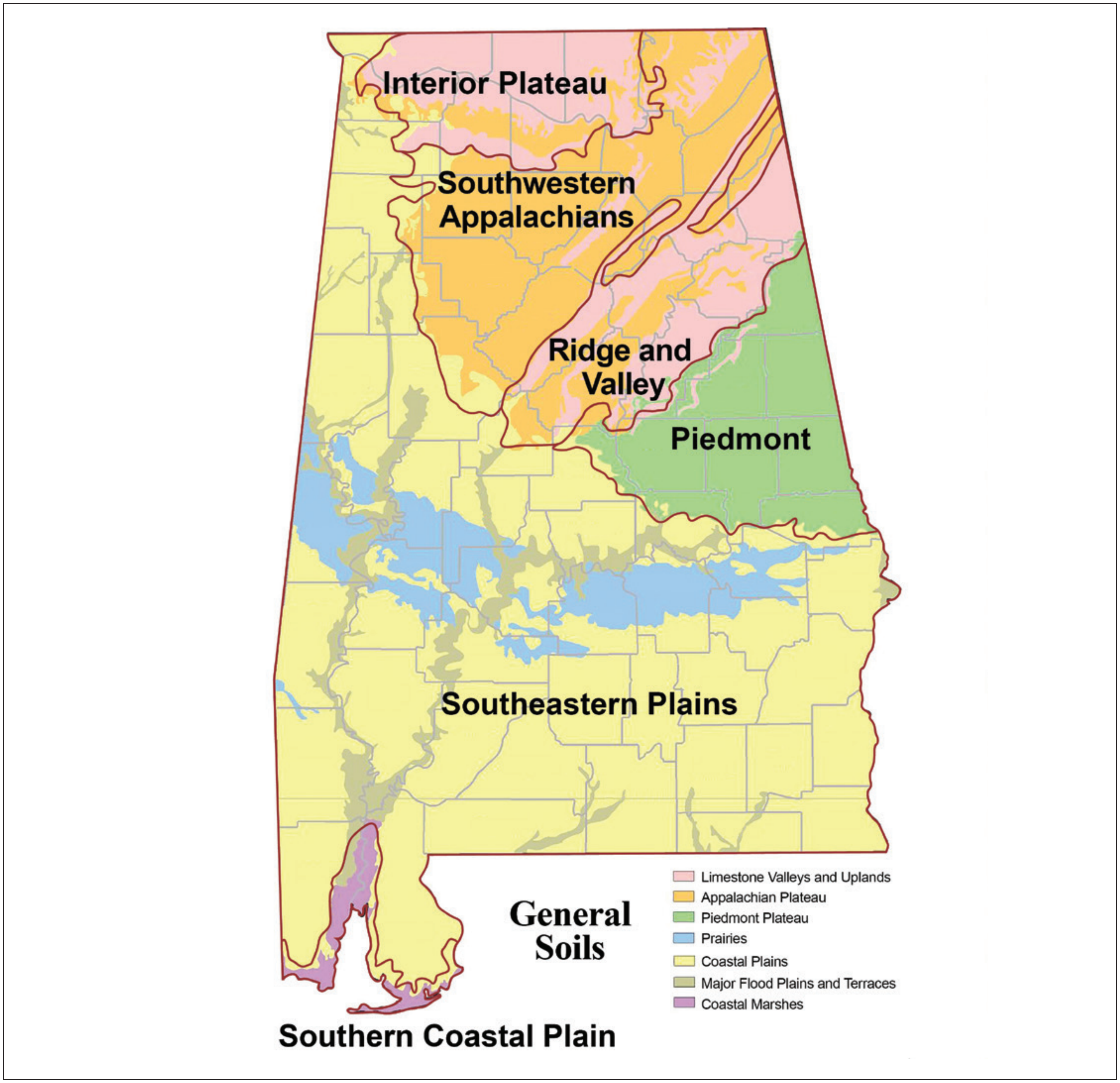

Figure 2. Alabama has distinct physiographic regions and a diversity of soil types. (Adapted from general soils map produced by Department of Geography, University of Alabama)

clay soils. These soils tend to shrink and crack when dry and swell when wet. Native prairie vegetation is mostly sweetgum (*Liquidambar styraciflua* L.), post oak (*Quercus stellata* Wangenh.), and eastern redcedar (*Juniperus virginiana* L.), along with patches of bluestem prairie species.

The Southern Coastal Plain extends along the Gulf coast lowlands of the Florida Panhandle, Alabama, and Mississippi. This region is generally low in elevation and flat with wet soils. Once covered by longleaf pine, slash pine, pond pine (*Pinus serotina* Michx.), American beech (*Fagus grandifolia* Ehrh.), sweetgum, southern magnolia (*Magnolia grandiflora* L.), white oak (*Quercus alba* L.), and laurel oak (*Q. laurifolia* Michx.) forests, land cover in the region is now mostly slash pine and loblolly pine with oak-gum-cypress forest in some low-lying areas.

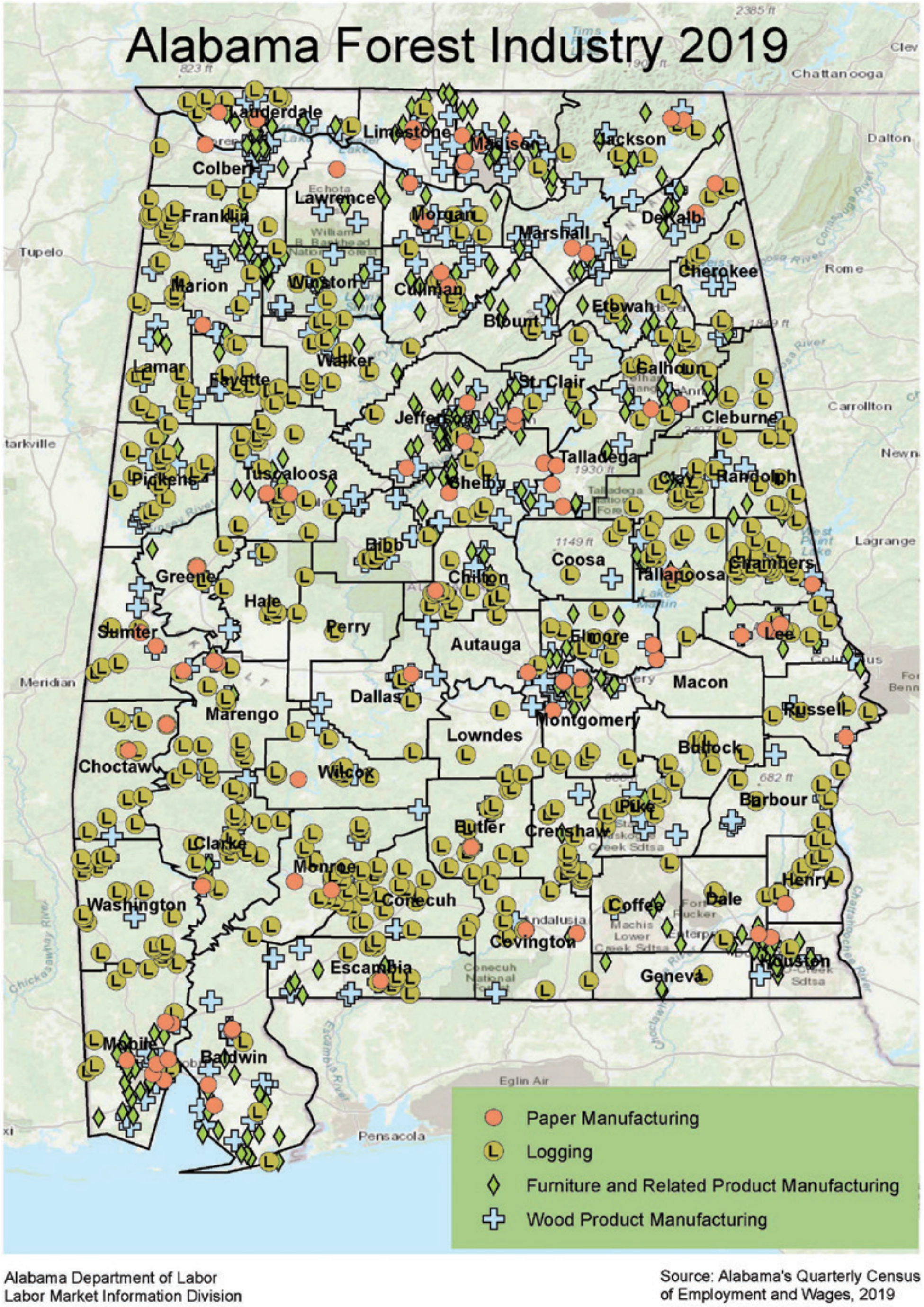

Figure 3. Alabama's forest industry is a major economic contributor to the State, the Nation, and beyond. (Map source: Alabama Department of Labor, Labor Market Information Division, 2019)

The Forest Economy

Alabama's forestry industry is exceptional for the State's economy due to its massive, sustainable timberlands (Fickle 2014). The industry ranks in the top five nationally for lumber and pulp and paper/paperboard production and in the top ten when including panels. The forest industry is a key component in the State's extensive fiber value-added supply chain and is among the top three manufacturing sectors within the State (Fickle 2014). Further, it is the State's most important rural manufacturing industry (figure 3).

Forest economic numbers in Alabama are impressive: 123,477 jobs, \$6.6 billion labor income, \$27.7 billion economic output, \$1.3 billion in exports, total value-added of \$11.1 billion, and 1,472 payrolled industry locations (Alabama Forestry Commission 2021). Alabama's forest industry job concentration is 2.57 times the national average, with average regional job earnings of $65,100. In addition, Alabama ranks in the top five States in electricity generated from biomass (nearly all of which is from the forest products industry) (U.S. Energy Information Administration 2021).

Harvested timber is distributed as follows in the State: 51 percent pulpwood, 31 percent sawlogs, 6 percent composite panels, 5 percent bioenergy and fuelwood, 6 percent veneer logs, and 1 percent poles (USDA Forest Service 2021). The majority of total roundwood production is softwood (southern yellow pine).

To support the State's forest industry, the Alabama Forest Workforce Training Institute established the first and only workforce development program specifically dedicated to the forest industry (https://www.forestryworks.com/). The forest industry sector is also a priority in the State's strategic plan (Alabama Economic Development Alliance 2017).

Alabama's contribution to the Nation's wood product markets is significant. The State's forests continually sustain fiber, create jobs, provide economic contributions for communities, and manufacture products for use not only by the Nation, but by the world as well.

Alabama's Forest Agencies and Partners

The Alabama Forestry Commission

The 1900 census data revealed that forested areas in Alabama at that time was 24.5 million acres (Alabama Forestry Commission 2020). With decreasing longleaf pine stands that once covered 50 percent of the forest canopy, Alabama had significant forested areas that needed to be protected and sustained. Thus, the Alabama Forestry Commission (AFC) was established in 1924, primarily to protect the State's forests from wildfires. Under the Forestry Act of 1923, Alabama established a statewide commission that appointed Colonel Page S. Bunker as the first State forester to head the agency (Yahn 2019). Eventually, the agency's responsibilities to the State's forests expanded beyond fire suppression and included conservation management and public education.

Today, the AFC's organizational structure and eminent mission remain relatively the same. The agency's mission has three basic goals: to protect the forests from harmful agents such as pests and wildfires, to assist landowners in responsible forest management on their property, and to educate the public on the value of Alabama's forests. Wildfires, insects, diseases, and invasive plants are detected by various means from ground reconnaissance to aerial surveys. The AFC encourages landowners to be responsible stewards of their properties through forest certification programs that promote sustainable management practices. These conservation regimes may include monitoring for threatened and endangered species, implementing harvesting activities that maintain water quality, and managing sensitive habitat for aquatic animals and terrestrial wildlife. The AFC also provides forest landowners with financial and technical assistance through cost-share programs and management services, as well as direct services such as prescribed burns, fire lane maintenance, and drone mapping. The AFC's educational programs are not only designed to inform landowners but all citizens about the value of the State's forests. AFC representatives give presentations to schoolchildren through programs like Classroom in the Forest and Forestry Awareness Week Now. The AFC collaborates with the USDA Farm Service Agency (FSA) to present wildfire prevention programs through Smokey Bear events. The agency also produces a quarterly magazine called "Treasured Forests" that contains interesting articles on various topics of conservation management (figure 4).

The AFC's obligations to tree planting and forest restoration mainly occur through internal programs and agency partnerships. The AFC administers a cost-share program that assists nonindustrial private landowners to implement management practices for pine stands that will reduce the risk of beetle infestation. Through funding from the USDA Forest Service, this financial assistance is called the Southern Pine Beetle Prevention Cost-Share Program. The management practices include noncommercial first thinning, mixed tree species planting, low-density loblolly pine planting, and longleaf pine planting. With approximately 800 ac (324 ha) planted with longleaf pine and 100 ac (40 ha) planted with loblolly pine under this program during the last 5 years, the AFC plans to continue assisting landowners and encouraging them to reestablish and maintain healthy, sustainable pine stands.

Figure 4. The Alabama Forestry Commission has published "Treasured Forests" since 1982. This quarterly publication is provided to forest landowners and is filled with technical assistance designed to assist in making informed land-management decisions. (Issues are available online: https://forestry.alabama.gov/Pages/Informational/Treasured_Forest.aspx)

For other forest management and tree planting practices, the AFC partners with the USDA Natural Resources Conservation Service (NRCS) and the FSA to assist nonindustrial private landowners under various programs. In an agreement with these Federal agencies, the AFC's role in these programs is the technical assistance provider.

The AFC conducts site visits to verify that forest stand establishment and improvement practices are being completed by the landowners enrolled in these programs. During fiscal year 2021 (October 1, 2020 to September 30, 2021), the AFC completed and verified 2,360 ac (955 ha) of tree planting under these combined programs.

USDA Forest Service

The mission of the Forest Service is "to sustain the health, diversity, and productivity of the Nation's forests and grasslands to meet the needs of present and future generations." Alabama's four national forests—Bankhead, Conecuh, Talladega, and Tuskegee—are working forests that cover more than 670,000 ac (271,140 ha) These forests are managed for multiple purposes and provide products and services to the public.

Reforestation is a top priority for national forest management and stands at the core of efforts to protect water quality both on national forests and on adjacent lands. The Forest Service and numerous partners under the America's Longleaf Restoration Initiative (ALRI) are cooperating to restore longleaf pine forests because of the species' ability to evolve and adapt to fire management. Annually, National Forests in Alabama plant approximately 700 ac (283 ha) of longleaf pine containerized seedlings (476,700 annually), 170 ac (69 ha) of containerized shortleaf pine seedlings (115,770 annually), and 75 ac (30 ha) of natural longleaf pine regeneration in support of the ALRI.

The Forest Service is committed to working with partners and communities to restore longleaf pine and takes the following eight steps to create and maintain healthy national forests in Alabama:

1. Use prescribed burning to renew vegetation growth and remove excess debris that fuel wildfire.
2. Manage forest lands that provide habitat for wildlife, clean air, and water resources.
3. Plant native trees, such as longleaf pine, that have a natural resistance to wildfire, wind, disease, and the southern pine beetle.
4. Manage understory plants to reduce nonnative invasive species, such as cogongrass (*Imperata cylindrica* [L.] P. Beauv.) and kudzu (*Pueraria montana* [Lour.] Merr.), that displace native plants essential for wildlife.
5. Manage aquatic biodiversity by altering conditions to ensure construction projects conform to habitat maintenance standards.
6. Conduct forest inventories to collect forest information for analysis.
7. Implement Geographic Information Systems (GIS) mapping to enhance ecosystem management.
8. Expand partnerships by encouraging members of the public to care for the environment by planting trees or volunteering.

Farm Service Agency

The USDA Farm Service Agency (FSA) plays a vital role in the implementation of the Conservation Reserve Program (CRP), so that environmentally sensitive land is devoted to conservation benefits. CRP participants establish long-term, resource-conserving, vegetative species, such as approved grasses and trees (known as covers) to control soil erosion, improve water quality and enhance wildlife habitat. In return, FSA provides participants with annual rental payments and cost-share assistance. In Alabama, tree planting has been one of the major uses of CRP over the past 10 years.

FSA offers three types of CRP enrollments:

1. General enrollment is announced periodically and offers are ranked at the national office to determine acceptable offers.
2. Continuous enrollment provides ongoing benefits.
3. Grasslands enrollment is a voluntary program that contracts with agricultural producers to help landowners and operations, including rangeland and pastureland, and is considered a "Working Land" program.

The Emergency Forest Restoration Program (EFRP) administered by the FSA is a contingent program that offers financial assistance to landowners for restoring forests damaged by natural disasters. The enrolled stands are restored through applied practices that include debris removal, site preparation, and forest regeneration.

Natural Resources Conservation Service

The USDA Natural Resources Conservation Services (NRCS) works at the local level to help people conserve natural resources on private lands. This assistance includes tree planting for various purposes, such as forest products (saw timber, pulpwood), energy biomass, wildlife habitat, long-term erosion control, water-quality improvement, waste treatment, reduction of air pollution, carbon storage in biomass, energy conservation, improvement or restoration of natural diversity, and aesthetic enhancements. Under the Environmental Quality Incentives Program (EQIP) administered by the NRCS, approved landowners receive financial assistance to implement management conservation practices, such as tree establishment and precommercial thinning that optimize environmental benefits for working agricultural lands. NRCS also supports three species-specific tree-planting initiatives in Alabama (see the "Tree Planting" section in this article).

Fish and Wildlife Service

The U.S. Department of the Interior (DOI), Fish and Wildlife Service (FWS) has a long-term commitment to work with private landowners seeking to improve wildlife habitats for species at risk, most visibly through their Partners for Fish and Wildlife Program. In the last 15 years, this program has established 42,632 ac (17,253 ha) of longleaf pine to improve upland habitats in Alabama, with an additional 829 ac (335 ha) planted with a variety of other tree species. These projects typically restore sites by removing offsite species and by treating unburned, mixed, and overstocked stands. Landowners who partner with FWS in this program share a commitment to improving their properties for the benefit of at-risk species, particularly the gopher tortoise (*Gopherus polyphemus*). Because the gopher tortoise is a keystone species, program activities also directly benefit several other wildlife species.

Alabama Forest Association

The Alabama Forest Association (AFA) conducts social-media marketing to connect landowners with the Alabama Landowners Resource Center. After landowners answer a few questions, they are contacted by an AFA-registered forester or certified wildlife biologist. These resource professionals typically meet with landowners on their property and make forest management recommendations based on the landowner's activities to date, priorities, and vision. Recommendations include planting trees (often southern yellow pines, but hardwood species as well). Resource professionals also direct landowners to cost-share programs that allow them to get more accomplished with limited resources of their own. Resource professionals also offer recommendations related to invasive species control, habitat management for threatened and endangered species, and improvements in habitat for game and nongame species. In addition, resource professionals encourage landowners to manage riparian zones in a way that enhances water quality and aquatic habitat.

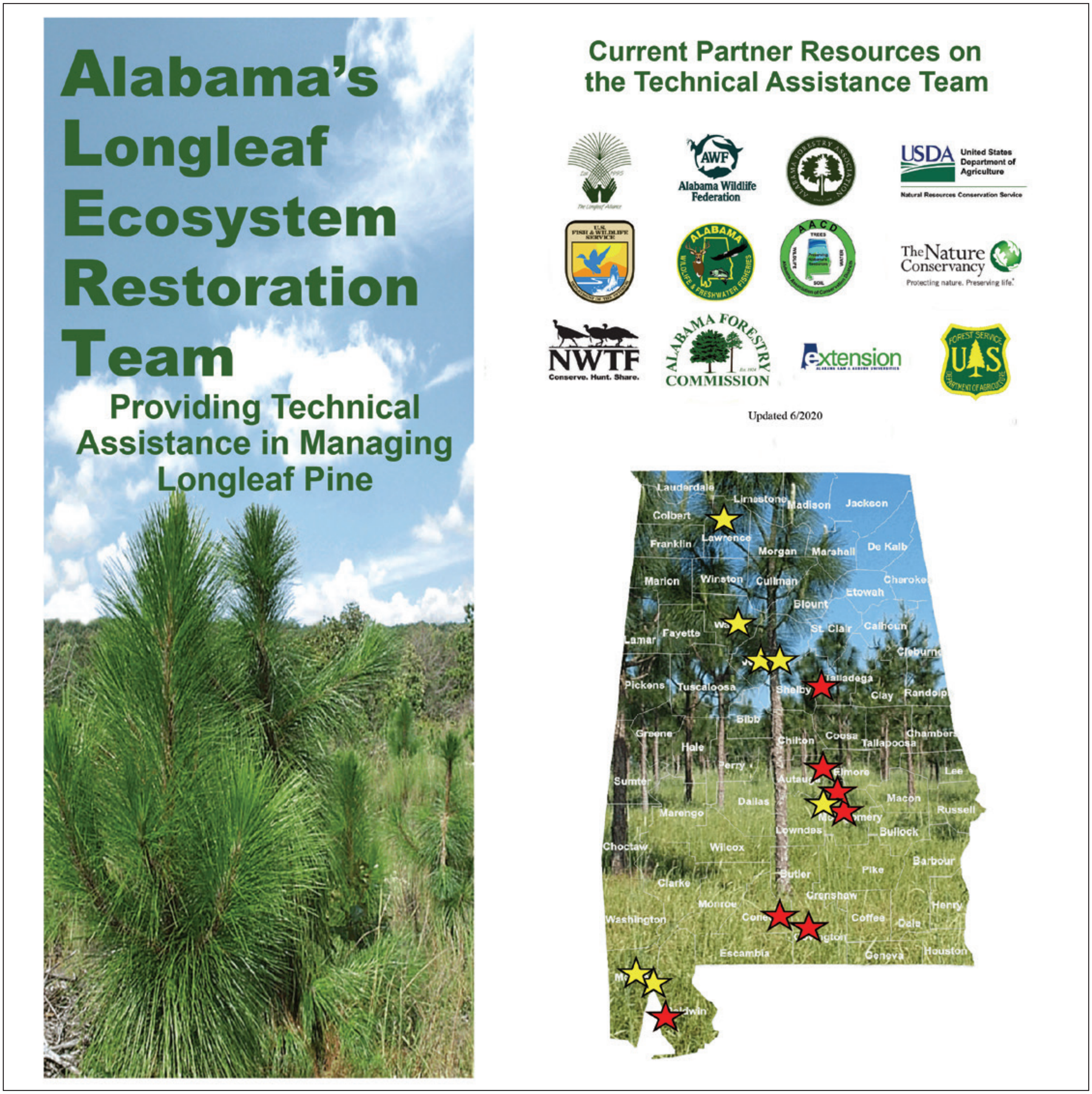

Figure 5. A technical assistance team consisting of several partner agencies and organizations assists in the implementation of the Longleaf Pine Initiative. The team provides technical guidance to help train associated partners and landowners in longleaf pine habitat management. (Images courtesy of The Longleaf Alliance)

The Longleaf Alliance

The Longleaf Alliance (TLA) was founded in 1995 and is headquartered in Alabama. TLA works throughout the Southeastern United States to guide longleaf pine restoration, stewardship, and conservation using science-based outreach, partnership engagement, and on-the-ground assistance. TLA works with all landowners, managers, and partners who share an interest in longleaf pine, helping each reach their own objectives. TLA connects landowners to the many forms of assistance available, helps to make investments more successful, and shares innovations and learnings with others facing similar challenges. Through grants and awards, TLA provides additional support to advance planting, restoration, and management activities across a variety of landscapes. TLA directly contributed to planting nearly 500,000 longleaf pine seedlings in Alabama in the 2020–2021 planting season. By reporting and sharing the combined accomplishments of all landowners and organizations engaged in longleaf pine restoration, TLA continues to grow additional support and investment for restoration of this once-imperiled species. TLA is also part of a technical assistance team that assists landowners in longleaf pine management through workshops and field days (figure 5).

The Nature Conservancy – Alabama Chapter

The goal of The Nature Conservancy–Alabama Chapter (TNC-AL) is to facilitate native, resilient, and connected habitats where ecosystems can adapt and thrive with a changing climate. TNC-AL works with The Talladega Mountains Longleaf Conservation Project (TMLCP) through a partnership of various public and private entities located in the mountains of central Alabama and northwest Georgia. The partnership helps to lead and guide restoration in this part of the longleaf pine range. The coalition consists of Federal and State partners, including the Forest Service; FWS; National Park Service; AFC; Georgia Department of Natural Resources; Alabama State Parks; Wild Turkey Federation; Alabama Department of Conservation and Natural Resources; TLA; Berry College; Alabama and Georgia chapters of The Nature Conservancy; Alabama Wildlife Federation; Munford Schools; and others. These partners work collaboratively to restore longleaf pine across the 7 million ac (2.8 million ha) of the partnership boundary. Working together, this group facilitates longleaf pine restoration through prescribed burning and annual plantings on suitable sites. Through the partnerships' work, longleaf pine has a more resilient future in this important and unique part of its range. Through the past 5 years, the partnership has awarded more than $600,000 in grant funds to complete longleaf pine restoration work across the TMLCP landscape. In addition to the TMLCP, TNC-AL also works across the vast coastal plain of the State to restore longleaf pine and its native habitat through many other avenues, such as assisting local, Federal, private, and industrial landowners, as well as through acquisition and management of ecologically significant lands within the longleaf pine range.

Nurseries

Alabama's first State nursery was established in 1926 in Sumter County and was later replaced by a new nursery near Autaugaville, later named the John A. Miller Nursery (Patterson et al. 1960). In 1949 and 1952, two more nurseries were established (Auburn Nursery and E.A. Hauss Nursery, respectively). State nursery production was approximately 27 million seedlings in 1954 and increased to nearly 141 million by 1960 (Patterson et al. 1960). Over time, however, all three of these nurseries eventually closed. A large, private nursery is now located at the site of the former E.A. Hauss nursery near Atmore (figure 6).

When the last Alabama State-owned nursery ceased operations in 2006, production of seedlings for reforestation shifted to the private sector. Mergers of forest product companies and their divestitures of land in the early 2000s further decreased the number of seedling nurseries operating in the State. Since that time, however, the number of privately owned forest-tree seedling nurseries whose primary business is seedling production has grown tremendously. Two of the largest private seedling producers in the country currently operate a total of three large nurseries in Alabama. These companies own no land-base or manufacturing facilities; their sole product is seedlings for reforestation across the Southeast. Three other large seedling producers are in Alabama along with various smaller operations serving specialized markets (figure 7).

In 2020, more than 121 million seedlings were grown by Alabama nurseries (Haase et al. 2021), providing seedlings to plant more than 220,000 ac (89,030 ha). Of the total seedlings grown, approximately 116 million were conifers and 5 million were hardwoods. The growth of containerized conifer seedling production has increased significantly during the last decade (figure 6). In 2008, only 3 percent of conifer seedlings were grown in containers in Alabama; that number grew to 24 percent in 2020 as the demand for this stock type increased. The most common conifer seedling grown in Alabama is loblolly pine (81 percent). Other major conifer species grown in the State are longleaf pine, shortleaf pine, and slash pine. All production of longleaf pine (more than 11 million seedlings) in Alabama is in containerized growing systems.

Alabama is home to the only research cooperative in the country whose sole focus is to provide relevant

Figure 6. Although Alabama's State nurseries are no longer in operation, several private nurseries provide millions of seedlings annually for reforestation, including this large longleaf pine container facility at the previous site of the State's E.A. Hauss nursery. (Photo by Tim Albritton)

research to forest nurseries in the South. The Southern Forest Nursery Management Cooperative (SFNMC) was established in 1972. The SFNMC works closely with its members to develop and disseminate new technologies for the economical production and outplanting of tree seedlings in the Southern United States. The Cooperative is comprised of four private seedling producers, three forest product companies operating nurseries, and seven State-operated nurseries. The SFNMC staff is housed at the School of Forestry and Wildlife Sciences at Auburn University (Auburn, AL).

Most SFNMC members also belong to the Tree Improvement Cooperative at North Carolina State University (Raleigh, NC), which provides research on genetic improvement of forest trees to its members.

Tree Planting

Currently the NRCS supports three initiatives in Alabama targeting special species important to the State's forests.

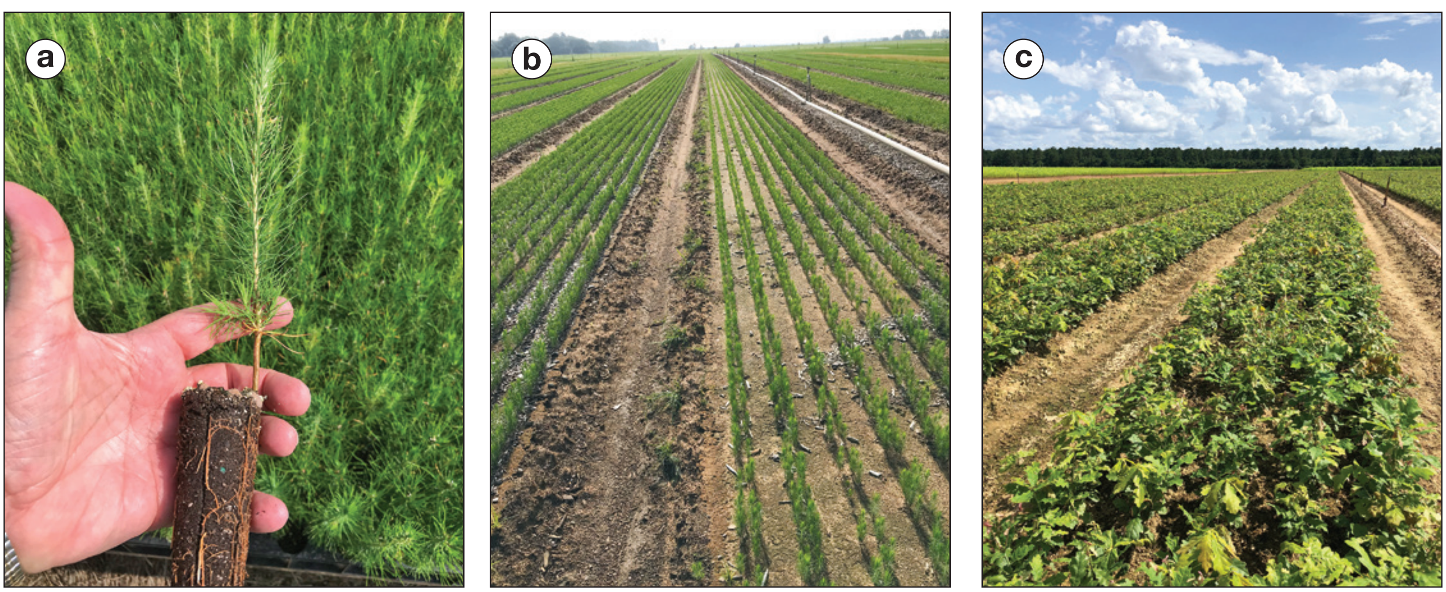

Figure 7. Alabama nurseries produce both (a) container and (b) bareroot seedlings. While most seedlings grown in the State are conifers, about 5 percent are (c) hardwood seedlings. (Photos by Tim Albritton)

Longleaf Pine Initiative

Before extensive logging in the region, longleaf pine covered about 90 million ac (36.4 million ha) from Virginia to Texas. Now, less than 4 percent remains. Thus, widespread efforts are underway to restore this important species. One of these efforts is the Longleaf Pine Initiative (LLPI), launched in 2010 to work with landowners in nine States to improve and restore longleaf pine ecosystems. In Alabama, two fund pools are available for the LLPI: Coastal Plain Longleaf and Montane Longleaf. All counties within the coastal plain longleaf area are within the nationally designated high-priority boundary. The montane longleaf area has both high- and medium-priority designations at the county level (figure 8).

The focus of the LLPI in Alabama is the management of existing longleaf pine stands. This priority is captured through the ranking process, with burning/thinning applications ranking higher than tree establishment applications. Since 2010, an increasing number of acres have been planted annually in Alabama to support the LLPI program (figure 9). Prior to planting

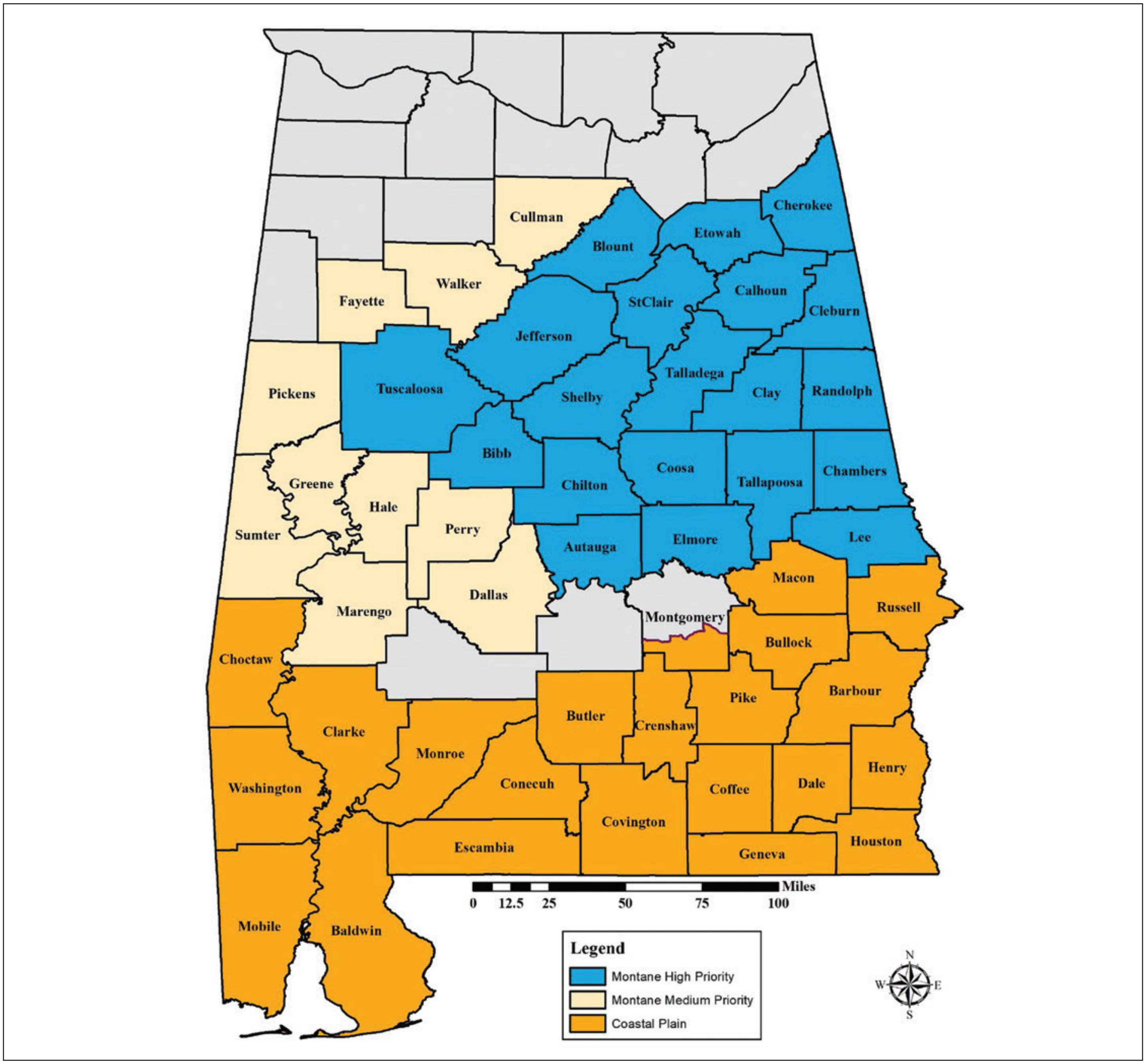

Figure 8. The Longleaf Pine Initiative determines priority areas for management of existing longleaf pine stands and planting longleaf seedlings.

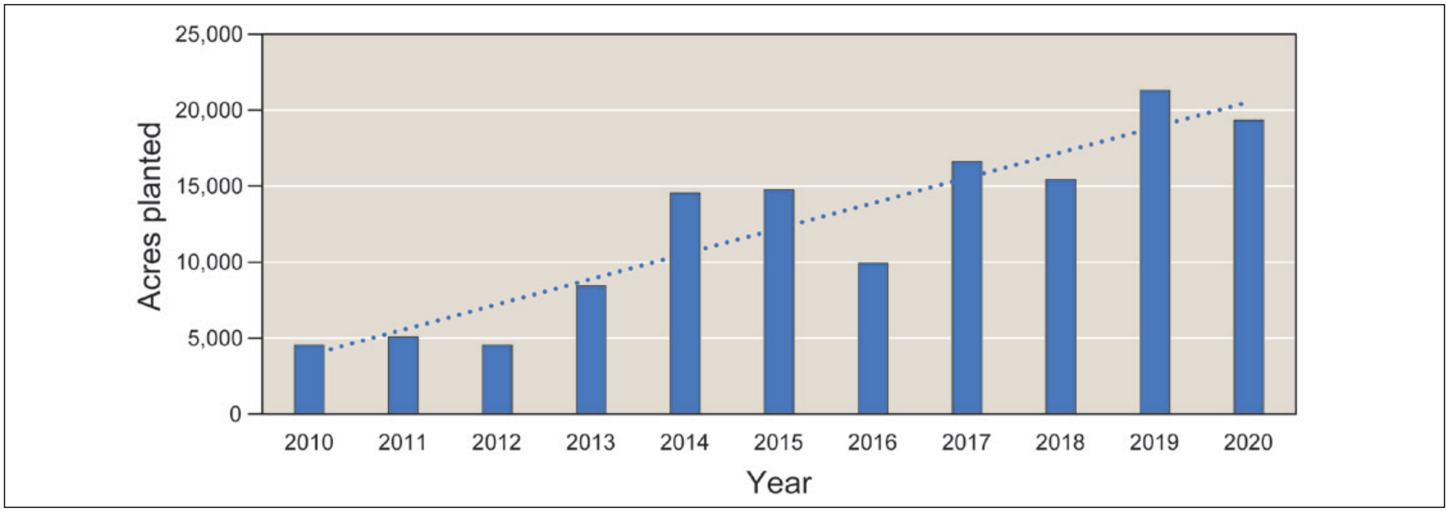

Figure 9. The Longleaf Pine Initiative has been instrumental in restoring many acres of longleaf pine stands in Alabama since it was launched in 2010.

longleaf pine, a full micronutrient soil test is done to determine suitability on sites previously managed as agricultural fields or pastures. Landowner's knowledge of recent management practices and all chemical or nutrient applications help to determine suitability and preparation needs. Soil test results may prevent planting failures due to:

1. Excess compaction.
2. High soil pH.
3. High levels of P_2O_5, which may be indicative of previous applications of chicken litter or high-phosphorus, inorganic fertilizers that can affect nutrient availability and seedling root development.
4. High levels of zinc, copper, manganese, or other micronutrients.

Shortleaf Pine Initiative

The Shortleaf Pine Initiative (SPI) was created in 2013 to address multiple threats affecting the shortleaf pine ecosystem. Shortleaf pine forests and associated habitats once covered a vast area of North America, stretching from eastern Texas and Oklahoma to the eastern seaboard (from New Jersey down to Florida). Over the last 30 years, more than 50 percent of this ecosystem has been lost with most of the decline occurring east of the Mississippi River. The SPI includes a range of public and private organizations and agencies working in the shortleaf pine ecosystem. All forestry practices within eligible counties qualify for this program; however, forest stand improvement practices of existing shortleaf pine stands and the establishment of new stands are prioritized.

White Oak Initiative

According to the Forest Service Forest Inventory and Analysis program, white oak regeneration is not keeping up with harvest of white oak sawtimber. The target landscape has mixed hardwood or mixed pine/hardwood uplands and mixed hardwood bottomlands with a significant component of white oak. Ideally, this white oak component not only includes trees in a dominant/codominant position within the forest, but also some trees in the intermediate canopy position and some regeneration in the sapling and seedling positions. Two other at-risk species in the white oak family are included in this initiative due to their high value and low recruitment of smaller size classes: chinquapin oak (*Quercus muehlenbergii* Engelm.) and swamp chestnut oak (*Q. michauxii* Nutt.). These two species can comprise up to 25 percent of white oak species planted. Within eligible counties, up to 50 percent of the planting can be composed of "trainer" tree species to be planted in alternating or third rows, such as yellow poplar (*Lirodendron tulipifera* L.), black cherry (*Prunus serotina* Ehrh.), sweetgum, shortleaf pine, or other species as approved by the NRCS State staff forester.

Challenges

Tree planting in Alabama has many complex challenges. Many of these challenges are also opportunities for further education. Current challenges can be summarized as follows:

1. Government programs offer incentives for planting certain species, such as longleaf pine. These incentives, however, result in some people signing up for these programs who have no interest in properly managing longleaf pine with prescribed burning. Longleaf pine is a native species and should be promoted for its many benefits, but it needs to be managed with burning on a regular basis to create the desired ecosystem. Many efforts are underway to remove barriers to landowner implementation of safe and effective prescribed burning.
2. Planting projects need more diversity, but landowners often plant loblolly pine. This glut of loblolly pine causes pine prices to flatline. Thus, a more diverse approach is prudent, though convincing landowners to add species diversity to their planting projects can be challenging.
3. Staffing and staff retention within the agencies that traditionally serve landowners has been challenging to maintain. Rebuilding organizational capacity and retaining institutional knowledge in place is needed.
4. An array of markets is needed, along with growing forest inventories, to support expanding manufacturing of commodity products. Better premium markets would encourage increased management for higher quality products and thus better diversify Alabama's forest investments. Markets must include those for ecosystem services in carbon, water, wildlife, and climate.
5. Research and planning are needed to better understand and implement the establishment of more resilient and diverse future forests for a changing world, whether due to development, fragmentation of ownerships, emerging markets, climate, or social/political influences.

Growing Forward

Tree planting has progressed a great deal in Alabama over the preceding few decades. Not only do planted stands cover 67 percent more acres than they did just 30 years ago, but they are spread across a wider age and diameter range and contain significantly more volume (figure 10). Over the past 20 years, the State

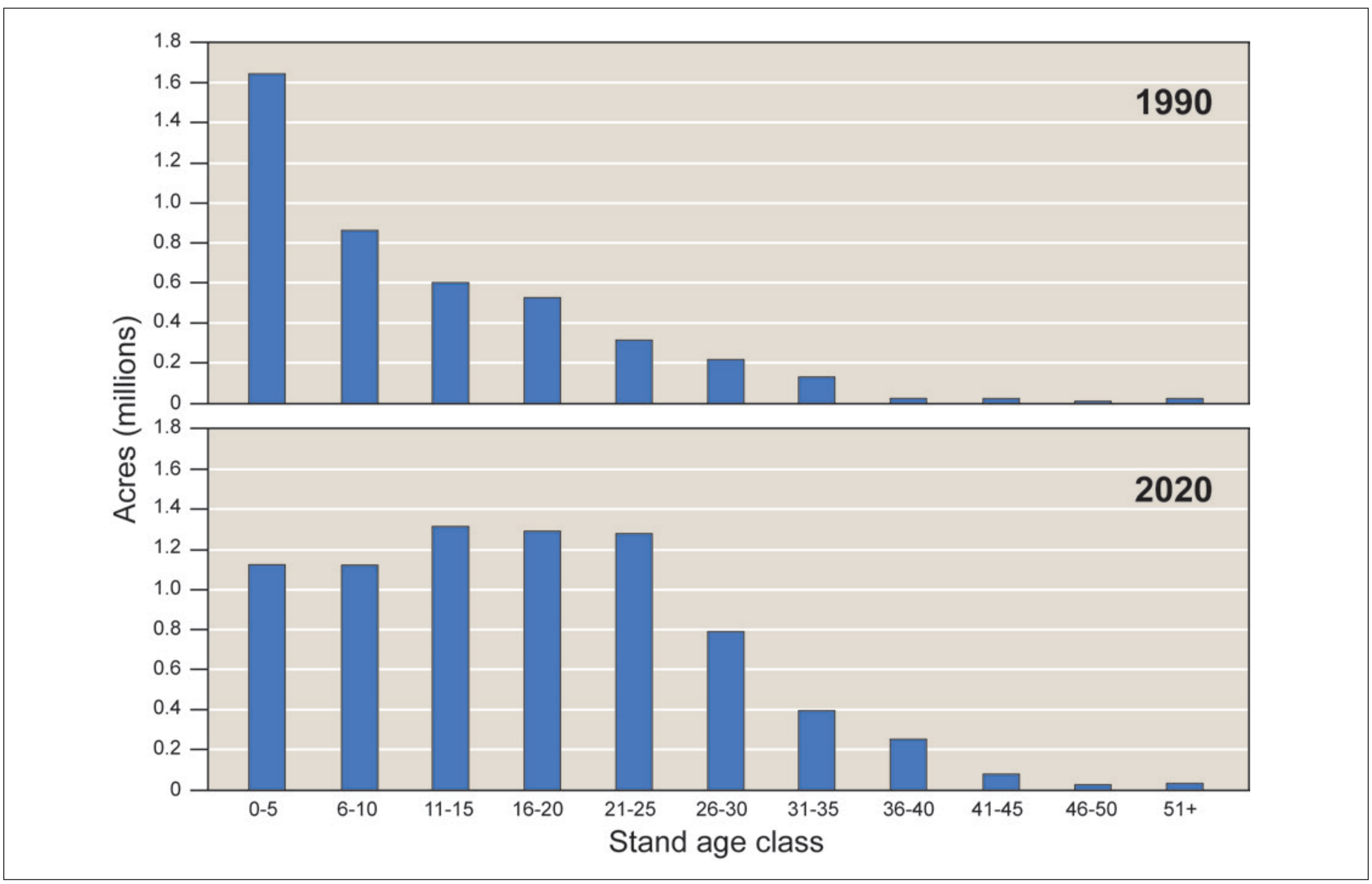

Figure 10. The amount of tree planting and the diameter range of planted forests has changed significantly in Alabama from 1990 to 2020.

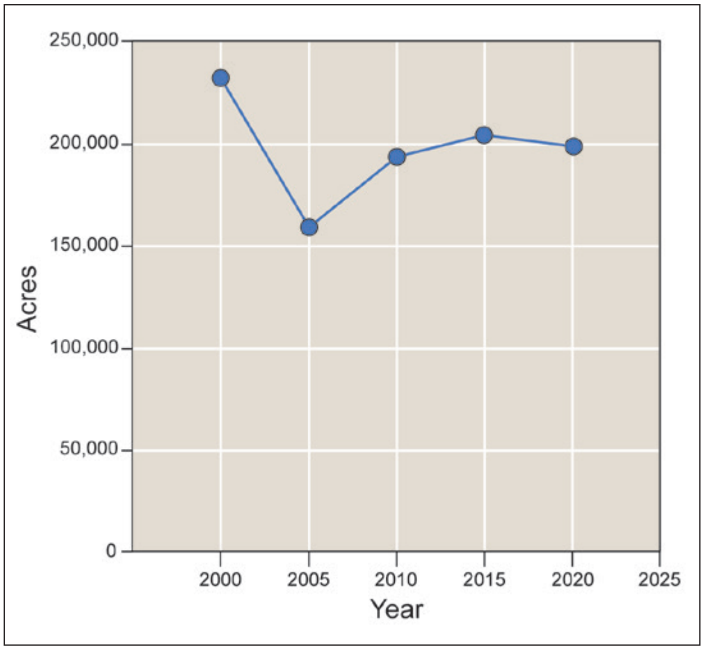

Figure 11. Approximately 200,000 ac (80,935 ha) of forest have been planted annually in Alabama in the past 20 years. (USDA Forest Service, Forest Inventory and Analysis, Evalidator program)

has planted approximately 200,000 ac (80,935 ha) per year (figure 11). Although annual planted acres were sometimes higher in the past, current planted stands tend to be maintained for longer periods than in the past (often beyond 30 years). Thus, less acres are devoted to short-rotation stands, resulting in high-volume stands.

Looking forward, Alabama expects to continue its high levels of seedling production and tree planting (figure 12). In addition, the State expects to continue building diverse markets and take necessary actions to sustain healthy forest ecosystems for generations to come.

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Figure 12. Tree planters in Alabama working hard to get trees planted. (Photo by Ted DeVos, Bach and DeVos Forestry and Wildlife Services, Inc.)

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Reforestation in the Hawaiian Islands

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Abstract

Although coconut-palm fringed beaches are the most common image of Hawai‘i, the archipelago supports a wide range of forest types, from rainforests to open-canopied dry forests to alpine shrublands. Forest types are determined by elevation, aspect (with each island having a wet windward and dry leeward side), and substrate age. Only about one-third of Hawaii's original native ecosystems remain relatively intact, and many forests today consist of a mix of native and escaped agricultural, forestry, and ornamental trees. Polynesians arrived in Hawai‘i sometime after 1,000 CE and cleared relatively small areas of land for agriculture and agroforestry. Westerners, led by Captain Cook, arrived in 1778 and made much more drastic changes to the landscape. Introduction of animals such as cattle, goats, and pigs in the late 18th century proved devastating to native forests that had evolved with no large herbivores. Tree planting to protect watersheds began as early as the 1880s during the days of the Hawaiian Kingdom. Much more widescale reforestation of lands denuded by overgrazing, fires, and unsustainable harvesting was undertaken from the 1920s through the 1960s, mainly to protect watersheds that provided a steady supply of irrigation for sugar plantations and urban areas. Most of these plantations were of nonnative tree species. Several large-scale commercial plantations, mainly of *Eucalyptus* spp., were established from the 1960s through the 1990s in hopes of developing a forest industry. Most forestry planting today is with native tree species to provide habitat for native bird and plant species. Commercial plantings with native species may be a way to provide ecosystem services such as wildlife habitat as well as economic value in the future. Local communities are increasingly becoming involved in reforestation and forest management.

Introduction

The volcanoes of the Hawaiian Islands emerged out of the sea over millions of years and developed into an archipelago of contrasts, from dry coasts to alpine deserts to rainforests. A few hundred species of plants colonized the isolated islands and evolved into hundreds of new species found nowhere else on earth. Beginning with the first Polynesian explorers, people transformed the landscape by clearing native vegetation for agriculture, ranching, and urbanization. Modern forestry arose in the 19th century out of a need to protect the watersheds rather than a desire to produce wood products.

Geography

The Hawaiian archipelago lies within the tropics, with the main islands lying between 18°54' and 22°15' north and running from 154°48' to 160°16' west. The main island chain stretches 390 mi (624 km) from the eastern tip of Hawai‘i Island to the small island of Ni‘ihau to the west. In terms of land area, Hawai‘i is 6,423 mi^2 (16,638 km^2) or about 4,110,720 ac (1,663,550 ha), larger than the State of Connecticut but smaller than New Jersey. The islands were formed from volcanoes erupting from an undersea hot spot. As the Earth's crust has slipped, the hot spot has moved to the southeast, leaving Kaua‘i, O‘ahu, and Ni‘ihau as the oldest of the main islands and Hawai‘i Island as the youngest. Hawai‘i Island is dominated by two large shield volcanoes, Mauna Kea and Mauna Loa, standing at 13,803 ft (4,207 m) and 13,679 ft (4,167 m) above sea level (figure 1). Maui is dominated by Haleakalā, at 10,023 ft (3,055 m) elevation. In addition to Kīlauea (the currently active volcano on Hawai‘i Island), Mauna Loa, Hualālai on Hawai‘i Island, and Haleakalā have all erupted in historical times. Lava erupting from the volcanoes has developed into landscapes of gradual

Figure 1. Mauna Kea is one of two large volcanoes on Hawai‘i Island. In this photo, snow-capped Mauna Kea can be seen with native 'ōhi'a forest in the foreground, native māmane-naio forest upper left, and invasive gorse (*Ulex europaeus* L.) right middle distance. (Photo by J.B. Friday, 2020)

slopes, deeply dissected by streams where soils have developed. On the older islands, millennia of erosion and occasional catastrophic collapse of volcanic slopes have resulted in a topography of knife-edge ridges surrounding deep valleys (figure 2).

Precipitation is driven by the moist northeast trade winds hitting the mountain slopes of the islands. The wettest areas on the upper slopes of windward Maui and Kaua‘i can receive over 400 in (10,000 mm) of rain annually (Giambelluca et al. 2013). Coastal lands in the rain shadow of Mauna Kea, on the other hand, typically receive less than 10 in (26 mm) of rain annually. Leeward Hawai‘i Island receives afternoon rainfall during the summer months from offshore breezes, and all the islands may be hit by “Kona” storms coming from the west during the winter months. While not as seasonal as much of the tropics, Hawai‘i typically receives more rainfall in the winter months. Studies indicate a general drying trend, with wet areas remaining constant but drier areas receiving less precipitation (Elison Timm 2015, Giambelluca et al. 2013). Near-constant trade winds keep temperatures mild near sea level, with average

Figure 2. Kalalau Valley on Kaua‘i with high sea cliffs was created by millions of years of erosion. (Photo by J.B. Friday, 2015)

highs between 80 °F and 90 °F (27 °C and 32 °C) and average lows between 65 °F and 75 °F (18 °C and 24 °C). Temperatures decrease at higher elevations and frost damage is a limiting factor to planting trees above 6,600 ft (2,000 m) elevation (Scowcroft and Jeffrey 1999).

Soils on the younger islands are dominated by Histosols, derived from organic matter and lava rock, and Andisols, derived from volcanic ash (Deenik and McClellan 2007). On the wet windward sides of the older islands of O‘ahu and Kaua‘i, the ash soils gradually weather into acidic Ultisols and Oxisols. At lower elevations on the leeward sides of the islands, Mollisols predominate and, when irrigated, form very productive agricultural lands. Of the 12 USDA soil orders, 10 are present in Hawai‘i.

Forest Types

The native flora of Hawai‘i is unusual among tropical ecosystems in that there are relatively few species, but the majority of native plant species are endemic. Over millions of years, plant propagules colonized the Hawaiian archipelago through being carried by birds, floating on the water, or being blown in the wind from ancestral homelands in the Americas, Oceania, Australia, and Asia (Price and Wagner 2018). Fewer than 300 founder species have radiated into over 1,200 native species today, about 90 percent of which are endemic (Wagner et al. 1999). Approximately 300 of these species are trees (Little and Skolmen 1989). Hawai‘i has no native conifers, figs (*Ficus* spp.), or mangroves, and only one native genus of palms (*Pritchardia*), but a large endemic diversity in the legume family (Fabaceae), coffee family (Rubiaceae), citrus family (Rutaceae), myrtle family (Myrtaceae), and hibiscus family (Malvaceae). Almost half (425 out of 940) of the plants species listed as threatened or endangered in the United States are endemic to Hawai‘i. (https://ecos.fws.gov/ecp/).

Hawai‘i has more than 35 percent forest cover, including both native and nonnative forests (Jacobi et al. 2017) (figure 3). The State of Hawai‘i is the largest

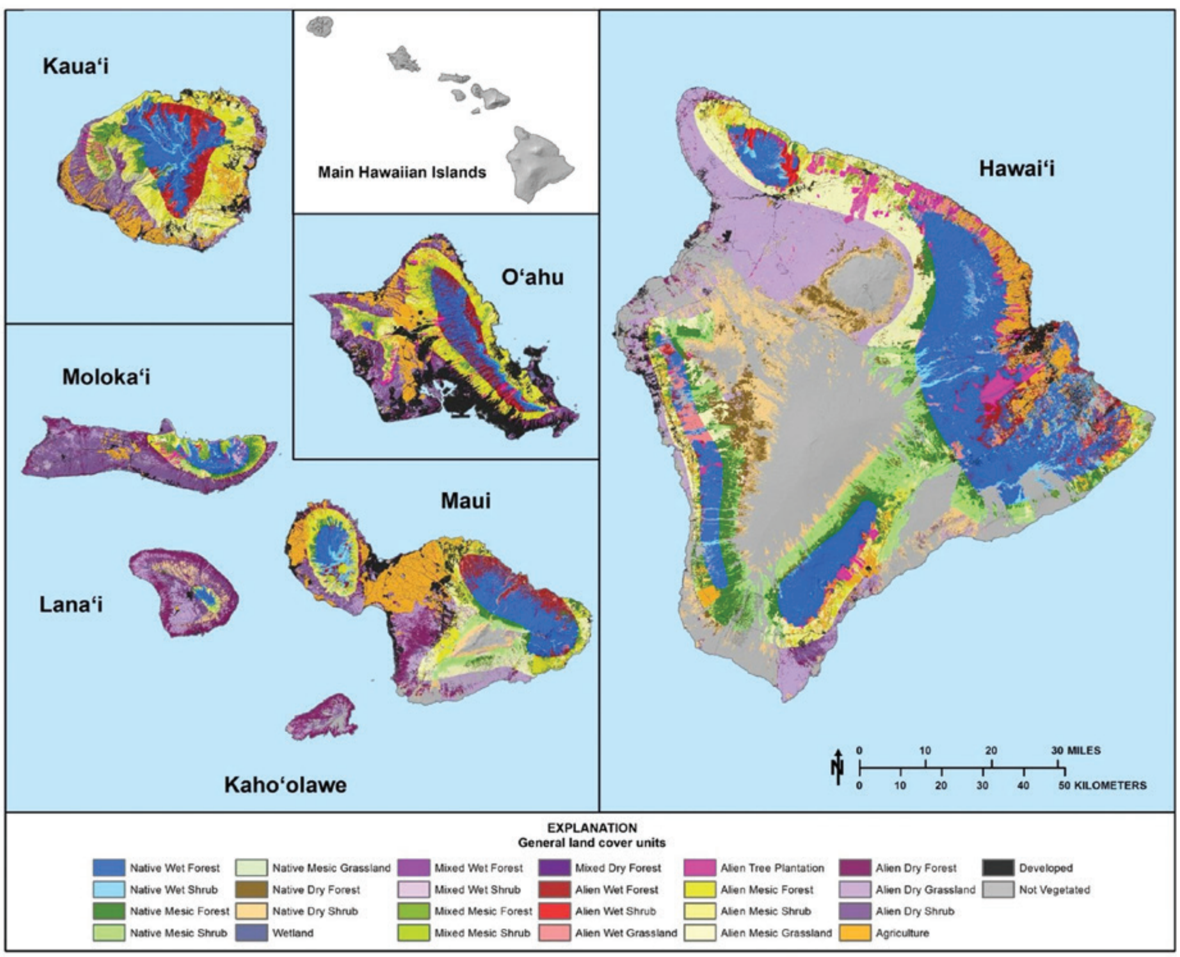

Figure 3. The land cover map of the Hawaiian Islands shows the diversity of ecological zones and the areas dominated by native and nonnative vegetation (Jacobi et al. 2017).

Figure 4. The montane wet forest of Kohala, Hawaiʻi Island, is dominated by ʻōhi ʻa (*Metrosideros polymorpha*) with an understory of hāpuʻu or tree ferns (*Cibotium* spp.). (Photo by J.B. Friday, 2009)

single forest landowner, followed by the Federal Government (mainly national parks, wildlife refuges, and military bases; there are no national forests in Hawaiʻi). About half of Hawaii's forests are privately owned (Zhang 2021). Land ownership is highly skewed: A few large estates and ranches own tens of thousands of acres, while there are thousands of private forest landowners on parcels of less than 10 ac (4 ha).

About 80 percent of native forests are dominated by ʻōhiʻa (*Metrosideros polymorpha* Gaudich.) (Gon et al. 2006) (figure 4). ʻŌhiʻa forests extend from the coastlines up to over 7,000 ft (2,100 m) elevation on the larger islands (Friday and Herbert 2006) and from young (150-year-old) lava flows on Hawaiʻi Island to the oldest weathered soils on Kauaʻi. The tallest ʻōhiʻa stands can reach 100 ft (30 m) in height on sites with deep soils and sufficient rainfall (figure 5), but trees are much smaller on young lava flows, on windswept ridges, or in bogs. In the wettest sites, which can receive over 200 in (5000 mm) of rainfall annually, ʻōhiʻa can comprise almost 100 percent of the forest canopy, interspersed with the occasional loulu palm (*Pritchardia* spp. Seem. & H. A. Wendl.) or ʻohe mauka (*Polyscias* spp. J.R. Forst. & G. Forst.). If soils are poorly drained in these forests, bogs form which are dominated by the sprawling uluhe fern (*Dicranopteris linearis* Burm. f. Underw.) under an open canopy of ʻōhiʻa. In montane wet to moderately dry forests, koa (*Acacia koa* A. Gray) is the other canopy dominant tree. At higher elevations (above 4,000 ft [1,200 m]) on Hawaiʻi Island and Maui, koa becomes the dominant overstory species.

Native subcanopy trees are much more diverse than canopy trees in the wet forests and include ʻōlapa (*Cheirodendron* spp. Nutt. ex Seem.), kōlea (*Myrsine* spp. L.), kōpiko (*Psychotria* spp. L.), and pilo (*Coprosma* spp. J.R. Forst. & G. Forst.). The understory is dominated by hāpuʻu or tree ferns (*Cibotium* spp. Kaulf.). As forests become drier toward the leeward sides of the islands or at higher elevations on Hawaiʻi

Figure 5. Tall ʻōhiʻa (*Metrosideros polymorpha*) trees, such as this one at the Hakalau Forest National Wildlife Refuge on Hawaiʻi Island, can reach 100 ft (30 m) in height. (Photo by J.B. Friday, 2013)

Figure 6. The typical dryland forest at Ka'ūpūlehu, Hawai'i Island, includes lama (*Diospyros sandwicensis*), left, and kauila (*Colubrina oppositifolia*), right. (Photo by J.B. Friday, 2008)

and Maui, both canopy and understory composition become more diverse. Canopy species can include kōlea, ʻiliahi or sandalwood (*Santalum* spp. L.), pāpala (*Pisonia* spp. L.), and mānele (Sapindus spp. L.). Understory species in the drier ʻōhiʻa forests include hōawa (*Pittosporum* spp. Banks ex Gaertn.), naio (*Myoporum sandwicense* A. Gray), and olupua (*Nestigis sandwicensis* [A. Gray] O. Deg., I. Deg. & L. Johnson).

Figure 7. The wili-wili (*Erythrina sandwicensis*), an endemic tree of the dryland forest, loses its leaves and flowers during dry seasons. (Photo by J.B. Friday, 2020)

Native dry forests are much less common than native wet forests, as most have been converted to ranches or destroyed by wildfires, but they are more diverse in tree species (figure 6). Lama (*Diospyros* spp. L.) is codominant with ʻōhiʻa on older substrates. Other tree species include māmane, naio, ʻiliahi, hōawa, wili-wili (*Erythrina sandwicensis* O. Deg.) (figure 7), and ʻohe makai (*Polyscias sandwicensis* [A. Gray] Lowry & G. M. Plunkett). A high-elevation dry forest that occurs at elevations over 6,000 ft (1,800 m) on Hawaiʻi Island is dominated by māmane and naio. A subalpine shrubland including ʻōhelo (*Vaccinium reticulatum* Sm.) and pūkiawe (*Leptecophylla tameiameiae* [Cham. & Schltdl.] C. M. Weiller) grows above the māmane-naio forest on Hawaiʻi Island and Maui.

In all but the most remote forests, native trees must compete with invasive woody species. In wet forests, the most common invader is strawberry guava (*Psidium cattleyanum* Sabine), which dominates the understory up to elevations of about 3,000 ft (910 m) (figure 8). The woody shrub Koster's curse (*Clidermia hirta* [L., D. Don]) and other shrubs and trees in the Melastomataceae family also compete with native plants for growing space. In dry forests, Christmasberry (*Schinus terebinthifolius* Raddi) is the most common invader. Escaped forest plantation trees such as silk oak (*Grevellia robusta* A. Cunn. ex R. Br.) also invade native, dryland forests.

Coastal forests usually comprise a mix of native and nonnative tree species (figure 9). The most common native species include hala (*Pandanus tectorius* Parkinson), milo (*Thespesia populnea* [L.] Sol. ex Corrêa), and kou (*Cordia subcordata* Lam.). These trees are usually found growing together with the Polynesian-introduced species coconut (*Cocos nucifera* L.), kamani (*Calophyllum inophyllum* L.), and noni (*Morinda citrifolia* L.), and modern introductions such as beach almond (*Terminalia catappa* L.). At low elevations on the dry, leeward sides of the islands a mixed nonnative forest comprised of koa haole (*Leucaena leucocephala* [Lam.] de Wit) and kiawe *(Prosopis pallida* (Humb. & Bonpl. ex Willd.) Kunth) predominates.

Figure 8. The invasive strawberry guava (*Psidium cattleyanum*) forms monospecific thickets in wet forests, as seen here on Moloka'i. (Photo by J.B. Friday, 2019)

Nonnative forests include both plantation forests and mixed forests comprised of vegetation that has regenerated after some change in land use, such as abandonment of agriculture, or disturbance such as fire. Mixed, nonnative forests dominate most islands' vegetation below about 2,000 ft (610 m) elevation and include escaped agricultural trees such as common guava (*Psidium guajava* L.), mango (*Mangifera indica* L.), and Java plum (*Syzygium cumini* [L.] Skeels); escaped forestry plantation trees such as albizia (*Falcataria moluccana* [Miq.] Barneby & J. W. Grimes) and Formosa koa (*Acacia confusa* Merr.); and escaped ornamental trees such as African tulip (*Spathodea campanulata* P. Beauv.). On the windward side of Hawai'i Island, a nonnative wet forest dominated by gunpowder tree (*Trema orientalis* [L.] Blume), bingabing (*Macaranga mappa* [L.] Müll. Arg.), trumpet tree (*Cercropia obtusifolia* Bertol.), and *Melocia umbellata* (Houtt.) Stapf has regenerated on abandoned agricultural lands (Little and Skolmen 1989). Extensive stands of kukui or candlenut (*Aleurites moluccanus* [L.] Willd.) in the backs of windward valleys are likely the remains of ancient Hawaiian agroforestry systems, where the trees were widely cultivated (Lincoln 2020) (figure 10).

Forestry plantations are dominated by eucalypt species (Nelson 1965). *Eucalyptus robusta* Sm. was the most commonly planted species in the 20th century, but plantations of *E. saligna* Sm., *E. camaldulensis* Dehnh., and *E. sideroxylon* A. Cunn. ex Woolls are also commonly encountered. *Eucalyptus grandis* W. Hill ex Maid. was planted on tens of thousands of acres of former sugar cane plantation lands in the late 1990s (figure 11). Other common plantation species include silk oak, paperbark (*Melaleuca quinquenervia* [Cav.] S. T. Blake), ironwoods (*Casuarina* spp. Adans), and tropical ash (*Fraxinus uhdei* [Wenz.] Lingelsh.). Planted conifers include pines (*Pinus* spp.), mainly

Figure 9. A typical Hawaiian coastal forest, as seen here at Pu'uhonua o Hōnaunau National Historical Park on Hawai'i Island, is comprised of native plants such as naupaka (*Scaevola taccada*), Polynesian introductions such as niu or coconut (*Cocos nucifera*), and modern introductions such as beach heliotrope (*Heliotropium arboretum*). (Photo by J.B. Friday, 2021)

Figure 10. A forest canopy of kukui (*Aleurites moluccanus*) and hala (*Pandanus tectorius*) has grown up in an abandoned agricultural site, Waimanu Valley, Hawai‘i Island. (Photo by J.B. Friday, 2021)

Koa, *Acacia koa* A. Gray

Koa trees provide the timber Hawai‘i is known for around the world. Koa wood is usually reddish but ranges from golden to dark brown in color and often has beautiful figure (Skolmen 1974) (figure 12). Today, the wood is used for high-end furniture, cabinetry, and musical instruments. Koa supplies have steadily decreased and wood prices have increased in the past 30 years. In ancient times, Hawaiians carved canoes from giant koa trees cut from upland forests (figure 13). Koa is endemic to Hawai‘i and is in the legume family (Fabaceae). Koa and ‘ōhi‘a dominate the canopy of most upland wet and mesic forests in Hawai‘i. Of the two species, koa grows much faster, often increasing 3 ft (1 m) in height annually during the early stages of growth. In mixed forests, koa, being shade intolerant, regenerates in gaps from a buried seed bank and is eventually replaced by ‘ōhi‘a (Baker et al. 2009). Mature trees on good sites commonly reach 80 ft (24 m) in height and 5 ft (1.5 m) in diameter (Friday 2010) (figure 14). In the 19th and 20th centuries, much of Hawaii’s native koa forest was cleared for pastures. Because koa is a pioneer species on disturbed sites, it is by far the most commonly planted native tree in Hawai‘i (figure 15). Wildlife plantings, mainly done on public lands, provide habitat for Hawaii’s endangered forest birds such as the ‘akiapōlā‘au (*Hemignathus wilsoni* Rothschild). Private landowners, encouraged by increases in the value of koa timber, have begun reforesting hundreds of acres of koa annually for potential future commercial harvests.

cluster pine (*P. pinaster* Aiton), Monterey pine (*P. radiata* D. Don), and slash pine (*P. elliottii* Engelm.); cypress (*Cupresses* spp. L.); and Norfolk Island pine (*Araucaria heterophylla* [Salisb.] Franco) and Cook pine (*Araucaria columnaris* [G. Forst.] Hook.).

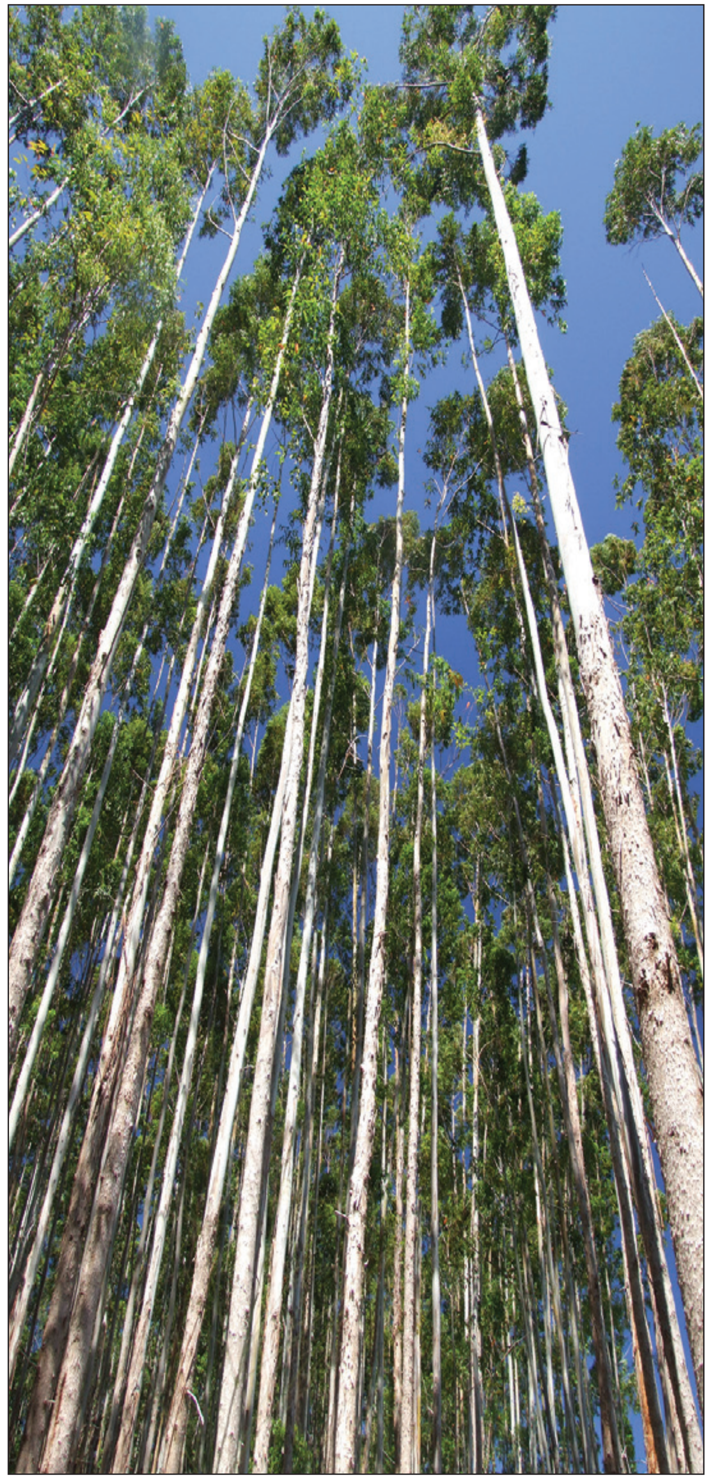

Figure 11. A 13-year-old industrial plantation of *Eucalyptus grandis*, Hawai‘i Island, is slated to be harvested for bioenergy. (Photo by J.B. Friday, 2011)

Figure 12. Koa (*Acacia koa*) veneer is made into fine furniture such as this table. (Photo by J.B. Friday, 2015)

Figure 13. Hawaiians continue the ancient tradition of racing koa (*Acacia koa*) canoes in Hilo, Hawaiʻi. (Photo by J.B. Friday, 2016)

Figure 14. Tall forest koa (*Acacia koa*) trees are rare but can provide logs for carving racing canoes. (Photo by J.B. Friday, 2009)

Figure 15. Hundreds of acres of former pasture lands are being reforested with koa (*Acacia koa*) seedlings, Hawaiʻi Island. (Photo by J.B. Friday, 2017)

Forest History

Polynesian voyagers arrived in Hawai‘i between about 1,000 and 1,100 CE, sailing up from Tahiti or the Marquesas (Athens et al. 2014). Experienced colonizers, they carried with them the plants needed to support life and begin farming in their new home. For staple crops, they carried taro (*Colocasia esculenta* L. Schott), yams (*Dioscorea* spp. L.), breadfruit (*Artocarpus altilis* (Parkinson) Fosberg) (figure 16), coconuts, and bananas (*Musa* spp. L.). The tree species they brought included kukui, from which they obtained a useful oil from the nuts; noni, which still is used medicinally; hala, for the leaves to weave mats and sails for canoes; and kamani for its beautiful wood and nuts that yield a medicinal oil. Hawaiians initially settled in wet, windward valleys, where they cultivated irrigated taro, but over the centuries, populations expanded into the upland, where they cultivated sweet potatoes in open fields and breadfruit and yams in agroforestry systems (Kirch 2019). Captain Cook estimated the population in 1778 as being up to 400,000, but other estimates of population range up to double that number, not that much lower than the current population of 1.4 million (Stannard 1989).

Although there are few native, edible fruits in Hawaiian forests, early Hawaiians were able to cut koa logs for huge, seagoing canoes, harvest ‘ōhi‘a for carving of everything from house posts to images of deities, and cut kou and milo to make fine carved food vessels. Other useful plants collected from the forest included olonā (*Touchardia latifolia* Gaudich.) for cordage, māmaki (*Pipturus albidus* [Hook. & Arn.] A. Gray) for medicinal tea, and maile vines (*Alyxia stellata* [J. R. Forst. & G. Forst.] Roem. & Schult.), and palapalai ferns (*Microlepia strigosa* [Thunb.] C. Presl) for lei. While the overall area of land cleared for agriculture was relatively small (Gon et al. 2018), the accidental introduction of the Polynesian rat had a significant impact on populations of some large-seeded species such as the endemic loulu palms, several of which are endangered today (Hodel 2012). Ancient Hawaiians described many ecological zones, but an overall understanding was that the lower elevation forests, along with agroforests and homesteads, were “wao kanaka” or the zone of people, whereas the upper elevation, pristine forests were “wao akua,” or the zone of the gods, to be entered only at need and with strict preparations.

Figure 16. Breadfruit or ‘ulu (*Artocarpus altilis*) was one of the traditional crops of ancient Hawai‘i and is regaining popularity today. (Photo by J.B. Friday, 2021)

Western contact in 1778 changed Hawaiian society drastically. Initially, sailors saw the islands as a convenient place to acquire fresh provisions. Captain Cook introduced goats to Hawai‘i, and Captain Vancouver introduced cattle and sheep in 1793. These animals were released into the forests, where, in addition to damaging the crops of local people, they began decimating the native forest vegetation. The whaling industry, which was the dominant industry in Hawai‘i in the mid-1800s, needed supplies of firewood to process the whale oil, and the slopes above the harbor towns of Honolulu and Lahaina on Maui were soon denuded by woodcutters. In the late 1700s, a sailor discovered that some of the firewood on board was actually sandalwood, which could be sold at a high price in China. The subsequent trade was a boom for merchants but a tragedy for the common people, who were forced to journey into the uplands to cut trees for the chiefs to sell to foreign traders.

Cattle ranching in Hawai‘i began expanding by the 1850s and resulted in increased forest loss. Increased flooding in urban areas and decreased stream and spring flow triggered calls for protection of remaining forests to protect water sources (Cox 1992). In 1856, William Hillebrand, a German-born botanist, blamed forest destruction mainly on cattle rather than lumbering, as local wood supplies were mostly imported from the continental United States. Hillebrand and others advocated for fencing, protection from cattle and other feral animals, and establishment of plantations. Hillebrand also imported many tree species to reforest the denuded

Figure 17. Haleakalā sandalwood (*Santalum haleakalae*) is endemic to the island of Maui. (Photo by J.B. Friday, 2018)

Sandalwood in Hawai‘i

Hawai‘i is home to 6 endemic species of ‘iliahi or sandalwood (*Santalum* spp.) out of about 25 species worldwide (Harbaugh et al. 2010) (figure 17). The discovery that this precious wood grew in quantity in Hawaiian forests set off the first big boom and bust in the modern Hawaiian economy (Merlin and VanRavenswaay 1989). Hawaiian chiefs, eager for cash to purchase Western merchandise, forced commoners up into the forests to cut wood to pay a newly imposed sandalwood tax. Western merchants then sold the wood to China for carving, cabinet making, and for its fragrant, essential oils. Ditches the dimensions of a ship's hull were dug into the ground and were to be filled with sandalwood logs before the ship's return; one of these ditches can still be seen on the island of Moloka‘i. At the peak of the trade, Hawai‘i exported over 1,000 tons (907 metric tons) per year of sandalwood. American gunboats arrived in Honolulu to enforce collection of debts, to be paid in sandalwood, from chiefs who had borrowed to purchase luxury goods. Farmers were forced to neglect their crops to complete this back-breaking labor. Stories are told of Hawaiians who would pull out any sandalwood seedling they saw, lest the trade continue and their children also be forced to cut sandalwood. By 1839, the Kingdom of Hawai‘i passed a law restricting sandalwood cutting, ostensibly to ensure sustainable harvests, but it was too late. Stocks had collapsed and trade moved on to other Pacific Islands to repeat the same cycle. While most of the dry forests that harbor sandalwood have been converted to ranches, some species, particularly *S. paniculatum* Hook. & Arn. on Hawai‘i Island, have remained relatively common, especially in parks and protected areas, although large trees are rare. In 2010, the first of several landowners in Kona on Hawai‘i Island began replanting sandalwood forests for future harvests. Although details of silviculture and rotations ages are unknown, hundreds of acres of dryland forests of sandalwood and its associated species are currently being planted.

slopes above Honolulu. In 1876, the legislature of the Kingdom of Hawai‘i passed an act to protect watersheds and create the first forest reserves. The growth of the sugar industry in the late 1800s increased local demand for firewood, exacerbating forest loss. The first Government tree nursery was established in 1882 to provide seedlings for reforestation of the slopes above Honolulu. Reforestation projects also began on Maui, Kaua‘i, and Hawai‘i Island. By 1887, over 200,000 trees had been planted to protect the watersheds above Honolulu (Walker 1887).

In 1893, the independent Kingdom of Hawai‘i was overthrown, and 5 years later, Hawai‘i was annexed by the United States. Government and Crown lands of the kingdom were transferred to the U.S. Federal Government and most were later transferred to the Territory and later the State of Hawai‘i. The new Territorial Government applied to Washington for assistance, and Ralph Hosmer, a protégé of Gifford Pinchot (first chief of the USDA Forest Service), took office as the first Territorial forester in 1904 (Cox 1992). The Territorial Forest Reserve system was established in 1906 and encompassed both public and private lands. The Forestry Division began fencing remaining forest areas; removing feral livestock, such as cattle, goats, sheep, and pigs; and planting trees. Nurseries were established on each island, not just to supply seedlings for public lands but also for distribution to private landowners. Harold Lyon, who was employed by the sugar industry, became of the strongest advocates for reforestation to ensure a steady supply of water for the plantations. Lyon, however, a plant pathologist by training, was convinced that the native forest trees were inevitably declining and could not withstand the new invasive plant species and feral animals that roamed the uplands. Lyon and botanist Joseph Rock imported trees from all over the world, which became the main species used in reforestation.

From 1910 to 1960, over 12 million trees, including 800 different species, were planted on the Forest Reserves (Nelson 1965). Tree species native to Australia topped the list, with over 2 million *Eucalyptus robusta* planted (figure 18), followed by silk oak, paperbark, and ironwoods. The foresters of that era did not totally neglect the native trees, however, and over 1 million koa were planted. Sadly, none of the koa plantations of that era seem to have survived to the present, probably destroyed by feral ungulates, competition from weeds,

Figure 18. *Eucalyptus robusta* was the most widely planted tree in the first half of the 20th century in Hawai‘i. These trees were planted in the 1930s at Kalopā on Hawai‘i Island. (Photo by J.B. Friday, 2017)

and wildfires. In the dry coastal lowlands, foresters established plantings of kiawe, a mesquite relative, and koa haole to provide forage for livestock. Seedlings were not only planted on forest reserves but distributed to private farmers and ranchers. By the 1950s, foresters began planting more potential timber trees in hopes of developing a lumber industry. Several species of true pines were planted in the uplands, and on Hawai‘i Island 12,000 ac (4,900 ha) of native forest were cleared to plant eucalyptus, Australian red cedar (*Toona ciliata* M. Roem., a mahogany relative), Queensland maple (*Flindersia brayleyana* F. Muell.), and tropical ash. With the final collapse of the sugar industry on Hawai‘i Island in the 1990s, over 20,000 ac (8,100 ha) of former sugar cane lands and marginal pastures were planted with *Eucalyptus grandis* for short-rotation biomass crops. An additional 1,500 ac (600 ha) of a mixture of *Eucalyptus deglupta* Blume and the nitrogen-fixing legume *Falcataria moluccana* were also planted on former cane lands on Kaua‘i. Markets for these trees have been difficult to find, however. About 2,000 ac (800 ha) of the Hawai‘i Island eucalyptus plantations were harvested for peeler logs that were exported to China. The plantation managers are now planning to harvest the rest for biomass energy, and the Kaua‘i plantations are also being harvested for biomass energy.

In the 1970s and 1980s, the emphasis of forestry programs moved to protecting and restoring native ecosystems. The Hakalau Forest National Wildlife Refuge was established in 1985 to protect habitat for endangered forest birds and has become the largest native forest restoration project in the State. The refuge's strategy has been to extend native forest up slope into degraded ranchlands by planting koa, which grows quickly and can overtop the introduced pasture grasses and escape frost damage during its first winter (Scowcroft and Jeffrey 1999). Once the koa has established a canopy, a suite of native understory plants is established, including fruiting species for frugivorous birds (figure 19). More recently, the refuge has obtained funding to increase populations of endangered native plants on the refuge. In the past 35 years, the refuge has planted over 600,000 native plants, mostly koa, and reforested over 4,000 ac (1,600 ha).

In addition to the Hakalau Refuge, many other native reforestation efforts have been driven by funding to provide habitat for endangered species. The Mauna Kea Restoration Project is replanting 1,000s of acres of māmane-naio forest on Mauna Kea to create additional habitat for the endangered palila bird (*Loxioides bailleui* Oustalet) (figure 20), which feeds on the māmane seeds (figure 21). In contrast, the Auwahi forest on Maui, the Ka‘ūpūlehu forest on Hawai‘i Island, and other dryland forest projects are re-establishing diverse native plant communities, including a mix of common and rare species, with intensive management on tens rather than thousands of acres.

In the last 10 years, increasing prices for koa lumber and the possibility of sustainable harvests of sandalwood have led to increased planting of these native trees. Private landowners on both Hawai‘i Island and Maui are now reforesting hundreds of acres per year with these species, and some are planting other forest trees with the goal of creating a more natural forest. Sandalwood species, in particular, require a host plant

Figure19. Students and other volunteers have planted tens of thousands of native understory plants under previously established koa (*Acacia koa*) overstory at the Hakalau Forest National Wildlife Refuge on Hawai‘i Island. (Photo by J.B. Friday, 2014)

for good growth (Speetjens 2021), and current sandalwood plantings employ a mix of host trees (figure 22).

Nurseries and Seedling Production

Seedlings for reforestation in Hawai‘i are grown by a mix of both public and private nurseries, and some public agencies contract private nurseries to grow seedlings for them. The main State tree nursery is located in the town of Waimea on Hawai‘i Island (https://dlnr.hawaii.gov/forestry/info/nurseries/), but the State forestry offices on Kaua‘i, O‘ahu, Maui, and Hawai‘i Island also have their own nurseries to produce seedlings for local projects and for sale to

Figure 20. The palila (*Loxioides balleui*), an endangered Hawaiian forest bird, is dependent on decreasing populations of the māmane tree (*Sophora chrysophylla*) for both food and shelter. (Photo by Bret Nainoa Mossman, 2021)

Figure 21. The māmane (*Sophora chrysophylla*), is an endemic tree of high-elevation forests. The seed pods comprise the main diet of the endangered palila bird. (Photo by J.B. Friday, 2018)

Figure 22. Sandalwood or ʻiliahi (*Santalum paniculatum*) is hemi-parasitic and is usually planted under a host tree, in this case koa. (Photo by J.B. Friday, 2021)

the public during Arbor Day events (figure 23). In addition, each of the four main islands also has a rare plant nursery devoted to growing the species of greatest conservation needs (http://www.pepphi.org/). These nurseries are located at higher elevations, as most of the protected habitat for these rare plants is in upland areas. More than 90 percent of the trees produced by the State tree nurseries are native species, but they also produce some nonnative species such as conifers and eucalypts for ranch windbreaks and noninvasive ornamentals for landscape use. About one-quarter of the seedlings produced by the State tree nurseries are sold to the private sector, while the rest are planted on the State forest reserves.

In 2021, the public and private forestry and conservation nurseries in Hawaiʻi produced over 470,000 tree and shrub seedlings. The State tree nurseries produced about 76,000 seedlings, other public agency nurseries (such as those at the National Parks and Wildlife Refuges) produced about 25,000, and private nurseries produced the rest (figure 24). Almost all stock is grown in dibble tubes (e.g., Ray Leach Cone-tainer™ or Deepot™; Stuewe and Sons, Inc., Tangent, OR), with the most popular size being 10 in^3 (164 cm^3), although tubes up to 40 in^3 (655 cm^3) are commonly used. The larger contain-

Figure 23. The State tree nursery in Waimea, Hawaiʻi Island, grows seedlings such as these 6-month-old ʻōhiʻa (*Metrosideros polymorpha*) for reforestation projects on State lands and for sale to the public. (Photo by J.B. Friday, 2017)

Figure 24. Kōlea (*Myrsine lessertiana*) seedlings are produced for reforestation projects using a subirrigation system at Maui Native Nursery (https://www.mauinativenursery.com/). (Photo by J.B. Friday, 2014)

ers tend to be used for rare plants or dryland species. Seedlings for urban forestry are more commonly grown in 1 gal (3.8 L) pots. Over half of the tree seedlings produced in Hawai‘i are koa, followed by māmane, ‘a’ali’i (*Dodonaea viscosa* Jacq., an indigenous shrub or small tree), ‘iliahi, and ‘ōhi‘a. Most tree species can be grown in 3 to 12 months, but a few, for example ‘ōhi‘a, may take up to 2 years in the nursery. Over 900 ac (360 ha) were reforested with native species in 2021. In addition, many nursery-grown seedlings were used for understory plantings to enrich degraded forests. Nurseries reported growing 80 native species of trees and shrubs and 35 nonnative tree species in 2021, along with many other species of native forbs and grasses.

State Forestry Programs

Forest Stewardship

The State Forest Stewardship program was established in 1991 and is funded by both the State of Hawai‘i and the U.S. Department of Agriculture (USDA), Forest Service. The program provides technical and financial assistance on a cost-share basis to private landowners to promote stewardship, enhancement, conservation, and restoration of Hawaii’s forests (https://dlnr.hawaii.gov/forestry/lap/fsp/). Participants can receive support for management planning, timber or agroforestry production, native forest conservation and restoration, fire presuppression, watershed protection, and recreation and wildlife habitat enhancement.

Urban and Community Forestry

Hawaii’s Urban and Community forestry program began in 1991 and is funded by both the State of Hawai‘i and the USDA Forest Service. The program is called Kaulunani, which can be translated as “beautiful growth” but also refers to the connections between healthy communities and the urban forest. The purpose of the program is to strengthen the capacity of communities to plan for, establish, manage and protect trees, forests, and green spaces across Hawai‘i (figure 25). The program seeks to improve the understanding of the benefits of trees in urban areas and communities, increase tree canopy cover, reduce carbon emissions, conserve energy, improve air quality and increase other environmental benefits, support community tree planting and tree demonstration projects, support Arbor Day activities, enhance the technical skills and knowledge of the urban forest industry, and expand research and educational efforts (https://dlnr.hawaii.gov/forestry/lap/kaulunani/). In 2021, the program funded the planting of 5,000 trees in urban or residential areas.

Figure 25. ʻUlu lāʻau, Waimea Nature Park (Hawaiʻi Island), is a community park funded by the Hawaiʻi Urban and Community Forestry Program, Kaulunani. The park showcases many native trees including both red- and yellow-flowered varieties of ʻōhiʻa lehua (*Metrosideros polymorpha*). (Photo by J.B. Friday, 2013)

Other Agency Programs

In addition to State-funded programs, forest landowners in Hawaiʻi have been able to use other assistance programs including the USDA Natural Resources Conservation Service's Environmental Quality Incentives Program (EQIP) and the U.S. Fish and Wildlife Service Partners programs to implement forest management activities that protect soil and water resources, control invasive species, and create habitat for endangered plants and animals. In addition, Hawaiʻi County, the local government on Hawaiʻi Island, offers lowered property taxes on land dedicated to native forest restoration.

Challenges to Successful Reforestation

Invasive plants are probably the worst threat to native wet forests. When trees are killed by pests or diseases, they are most often replaced by weedy plant species. Most wet forests below about 3,000 ft (900 m) elevation are invaded by the understory tree strawberry guava, the shrub Koster's curse, the herbaceous kahili ginger (*Hedychium gardnerianum* Sheppard ex Ker Gawl.), or other nonnative weeds. While these forests may have a native overstory, they lack any native regeneration because the understory is completely occupied by weeds. Mechanical or herbicidal control is only cost-effective in limited areas. Effective biocontrol agents seem to be the only practical way to save these forests. Biocontrol efforts have had some success, for example in controlling the banana poka (*Passiflora tarminiana* Coppens & Barney) (Trujillo et al. 1994). Recent importation and release of a new insect biocontrol that attacks strawberry guava gives some hope that the weed's advance into native forests can be stopped (USDA Forest Service, no date).

Feral ungulates, primarily pigs in wet forests; goats and sheep in dry forests; introduced deer on Maui,

Figure 26. Feral bulls cause damage to forest plantations such as this sugi pine (*Cryptomeria japonica*) grove on Hawai‘i Island. (Photo by J.B. Friday, 2017)

Moloka‘i, Lana‘i, and Kaua‘i; and cattle in some areas; continue to destroy native species and spread nonnative plants in areas where they are not excluded (figure 26). Because these animals, except for cattle, are also game species, they are not excluded from most State-managed public forests. Nonnative pests and pathogens continue to arrive in Hawai‘i, often on imported plants. The disease Rapid ‘Ōhi‘a Death was first described in 2014 (Keith et al. 2014) and has since spread over Hawai‘i Island and killed over one million ‘ōhi‘a trees (figure 27). The disease is caused by two newly described species of the fungus *Ceratocystis* (Barnes et al. 2018). Because *Ceratocystis* is a wound pathogen, wounding by feral ungulates seems to be a contributing factor in the disease's spread (Perroy et al. 2021), and fenced and protected forest areas with low feral ungulate populations have low levels of disease. Another new pathogen of concern is *Austropuccinia psidii* Beenken, a rust fungus attacking many species of trees in the myrtle family (Myrtaceae) (Uchida et al. 2006). When it was first detected, the disease mainly attacked nonnative trees such as rose apple (*Syzygium jambos* [L.] Alston), but in 2016 and 2017, it caused widespread defoliation of ‘ōhi‘a trees on O‘ahu and Moloka‘i. Populations of the endangered nioi (*Eugenia koolauensis* O. Deg.) have also been drastically reduced by the fungus. A *Fusarium* wilt of koa (*Fusarium oxysporum* f. sp. koae) (Gardner 1980)

Figure 27. Rapid ‘Ōhi‘a Death is a newly discovered fungal disease that can cause almost complete mortality of a stand of ‘ōhi‘a (*Metrosideros polymorpha*). (Photo by J.B. Friday, 2016)

causes high levels of mortality to planted koa stands at lower elevations (below about 2,500 ft [760 m]). A program to select for disease tolerance (Dudley et al. 2015) has developed lines of koa that show high tolerance of the disease and good survival even at lower elevation, warmer sites.

Hawaii's forests have long suffered from nonnative insect pests. A moth, the kou leaf roller (*Ethmia nigroapicella* Saalmueller), defoliated and killed the native kou tree across the islands after its introduction in the 1890s (Swezey 1943) (figure 28). While kou was a principal shade tree in Honolulu in the 1800s, it was largely replaced in urban forestry settings by nonnative species after the moth was introduced. A gall wasp, *Quadrastichus erythrinae* Kim, was discovered in Hawai'i in 2005 and rapidly killed almost all coral trees (*Erythrina variegata* L.) across the State (Heu et al. 2008). While *E. variegata* is not native to Hawai'i, the trees were widely planted as an urban shade species and a vertical cultivar was planted as windbreaks for agricultural fields. The native congener wili-wili (*E. sandwicensis*) is slightly more tolerant of the wasp and has likely been saved by introduction of a biocontrol agent (Kaufman et al. 2020). A thrips species (*Klambothrips myopori* Mound and Morris), which was first detected in 2009, has caused up to 80 percent mortality on naio, one of the two native trees that dominated the rare māmane-naio forest type on Mauna Kea (Conant et al. 2009).

Wildfires are an increasing threat to Hawaii's dryland forests (figure 29). While small in total acreage relative to fires on the U.S. mainland, wildfires in Hawai'i affect as large a percentage of the State as they do in the fire-prone Western States (Trauernicht et al. 2015). Almost all fires are anthropogenic, but the increase is caused by the invasion of nonnative grasslands into native dryland forests, which are not fire-adapted (D'Antonio and Vitousek 1992), and growth of grasses and other flammable vegetation on abandoned agricultural lands (Pacific Fire Exchange 2021). Climate changes predicted for Hawai'i include increased precipitation in wet areas and reduced perception in dry areas, which will increase fire risk near high-value, high-altitude forests (Elison Timm 2015, Trauernicht 2018). Effects of wildfire are multiplied by the problems of increased invasive species and climate change. To improve

Figure 28. Kou (*Cordia subcordata*) is regularly defoliated by the kou leaf roller (*Ethmia nigroapicella*). These trees have been able to recover after each defoliation. (Photo by J.B. Friday, 2017)

communication among fire scientists, land managers, and fire responders, the Pacific Fire Exchange (PFX) (http://www.PacificFireExchange), 1 of 15 Fire Science Exchanges nationally, was formed in 2011 under the Joint Fire Science Program (https://www.firescience.gov), funded by the U.S. Department of the Interior and the Forest Service. The PFX has increased understanding of wildfire problems among local communities and political decision makers. Efforts have included promoting fuels management, practices such as fuel breaks around developed areas, and use of livestock to reduce fuel loads (Pacific Fire Exchange 2016). Increasing wildfires have led to increased demand for seedlings to restore burned areas. Because these demands are unpredictable, nurseries have recently begun banking large quantities of seed of common native tree and shrub species so they can quickly ramp up seedling production following a fire (Chau et al. 2019). Each State nursery and some other agency nurseries such as the one at Hawai'i Volcanoes National Park has a seed bank.

While Hawai'i has no forest protection act, many forests are legally protected by both State and county level zoning laws. Almost all lands which are not zoned conservation have already been developed on

Kaua'i, O'ahu, and Maui, but large areas of native forest are zoned agriculture on Hawai'i Island. Conversion of forests for agriculture or residential areas is an ongoing problem on Hawai'i Island. Landowners are free to clear these forests and develop them for agriculture, ranching, or housing. Ongoing suburban development in these areas leads to forest fragmentation and ingress of invasive species.

The decline of both planation agriculture and ranching in Hawai'i since the 1980s has created the opportunity for landscape-scale reforestation of former agriculture or crop lands. To date, most native reforestation efforts have focused on creating habitat for endangered forest birds or rare plants. In the past few years, however, private landowners have begun reforesting with koa and, in some cases, sandalwood in an effort to create a sustainable forest industry based on these species. While there have been many recent harvests of nonnative plantation trees in Hawai'i, there have been very few of plantation koa and none of planted sandalwood. The silviculture of each species is still being developed (Baker et al. 2009, Speetjens et al. 2021). Nevertheless, investments by private landowners could increase the area planted annually with native trees from hundreds to thousands of acres.

Figure 29. Koa (*Acacia koa*) seedlings can regenerate from the buried seed bank after a wildfire kills the overstory trees as seen here in Hawai'i Volcanoes National Park. (Photo by J.B. Friday, 2018)

Future Directions

The most pristine native forests in Hawai'i, both public and private, will benefit from increased protection in the future. As in the past, this protection will be based on their importance for watershed protection (Department of Land and Natural Resources 2011). Priority forest areas will be fenced and have feral ungulates and weeds removed, and buffers will be replanted with native species. Hawai'i is committed to protecting 30 percent of high-priority forests protecting the islands' watersheds by 2030 (Department of Land and Natural Resources 2017). Marginal and degraded forests, however, will likely continue to suffer loss of native species because of invasive plants, damage from feral ungulates, pests and diseases, wildfires, and conversion to agriculture or other nonforest uses.

Native reforestation projects, often with trees planted by community volunteers, create opportunities for people to reconnect with the forest. Native Hawaiians, in particular, are leading efforts to restore forests not just with valuable or rare plants but also with those of cultural significance. Cultural values are being combined with biodiversity and economic values to create biocultural approaches to forest management (Gon et al. 2018, Kamelamela et al. 2022, Kealiikanakaolehaililani et al. 2018). For example, there was an old tradition from the dry uplands of the Kona side of Hawai'i Island of giving visitors lei made from flowers of the halapepe (*Dracena konaensis* [H. St. John] Jankaliski) (figure 30). In past decades, the tree has become endangered because of destruction by cattle, wildfires, and attack by new insect pests, and the tradition has died out. Local people, led by native Hawaiians, are now restoring those forests, and they have a vision that the halapepe might once again become so abundant that the tradition of using the flowers for lei can be revived. A related development is a new interest

Figure 30. Flowers of the halapepe (*Dracena konaensis*) were once used for lei by Hawaiians, but today the tree is endangered. (Photo by J.B. Friday, 2013)

in reviving traditional agroforestry systems based on breadfruit and other traditional crops for local food production (figure 31). Community groups are working to restore both social and ecological landscape functions by using a historical ecology approach, drawing on community and traditional Hawaiian knowledge as well as ecological information (Kurashima et al. 2017). This approach helps to create a working landscape with native plants and food crops that will support local communities as well as restore native flora. One of the oldest examples is the Hoʻoulu ʻĀina project in the forested valley above Kalihi, one of the most densely populated neighborhoods in Honolulu (www.hoouluaina.com). Here, urban community members, in particular native Hawaiian and other Pacific Islanders, have access to land for gardening traditional crops and participate in restoring the native forests of the valley. Whereas public and private forest lands have been centrally managed for the past century, these and other examples of community-based forest management are now being implemented. Public concern about the well-being of Hawaii's forests and involvement with forest restoration has never been higher in modern times than it is today.

Figure 31. A traditional agroforesty system at the Amy B. H. Greenwell Ethnobotanical Garden in Kona, Hawaiʻi Island includes taro (*Colocasia esculenta*, foreground), ʻawa (*Piper methystiucm*, understory), and breadfruit or ʻulu (Artocarpus altilis) trees. The garden is managed with constant help from community volunteers. (Photo by J.B. Friday, 2020)

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Propagation of Tropical Lilythorn (*Catesbaea melanocarpa* Krug & Urb.): A Federally Endangered Tree on St. Croix

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Abstract

Tropical lilythorn (*Catesbaea melanocarpa* Krug and Urb.) is a small, thorny tree with white flowers that is found on only one site on St Croix, two sites in Puerto Rico, and in a few other islands. It is a federally endangered plant species. At the University of the Virgin Islands, we are studying this species' ecology and developing propagation protocols. The goal is to plant tropical lilythorn seedlings in protected areas on the island of St. Croix because the one site where the species currently grows is not protected from development. This article summarizes nursery and field observations during propagation efforts over the previous 8 years.

Introduction

Tropical lilythorn (*Catesbaea melanocarpa* Krug and Urb.) is a thorny tree with striking white flowers. It is a member of the Rubiaceae, or coffee, family. Tropical lilythorn is a federally endangered plant species (Daley and Valiulis 2013). The Endangered Species Act forbids the destruction of these trees, and collection of botanical samples and seeds are regulated by permit. If the species were more common and not endangered, this small tree with its white flowers and black berries could be an attractive plant around buildings, on small lots, or in garden areas. At present, the most important use of the species is the provision of ecosystem services such as biodiversity, soil conservation, and pollinator habitat.

Tropical lilythorn was first botanically described on the island of Antigua in the mid-19th century and on St. Croix in 1881 (U.S. Department of the Interior, Fish and Wildlife Service 2005). Tropical lilythorn is found in one isolated site on St. Croix, two sites in Puerto Rico, the island nations of Antigua and Barbuda, the Cayman Islands, and the French Overseas Department of Guadeloupe (Rivera and Foote 2005, Lindsay et. al. 2015). On the island of Guadeloupe and another small island in the archipelago of Guadeloupe, the species occurs on the dry west coast, growing among succulents like cactus (Francius 2017). The existing population of tropical lilythorn on St. Croix is endangered by wildfires and habitat destruction because it grows on private land that is subject to development pressure and is thus outside of protected areas (Daley and Valiulis 2013).

Through a research grant provided by the U.S. Fish and Wildlife Foundation, the agroforestry and biotechnology program of the University of the Virgin Islands (UVI) is studying the phenology, population distribution, and propagation techniques of tropical lilythorn to establish protected populations at the Sandy Point National Wildlife Refuge, Salt River/Columbus Landing National Historical Site, and the private Southgate Reserve on St. Croix.

Description

Tropical lilythorn is a small, thorny tree that grows up to 10 ft (3 m) tall (figure 1). It has paired, simple, oblong, and shiny green leaves 0.2 to 1 in (5 to 25 mm) long. The thorns are green and occur in pairs in the space between the pairs of leaves (figure 2). Pairs of thorns alternate between facing in the vertical or horizontal plane. Each thorn is 0.4 to 0.8 in (1 to 2 cm) long. The flowers are white and fragrant and grow solitary or paired in the angles formed by the leaf and the branch (figure 3). The fruit is a black berry about 0.25 in (5 to 6 mm) in diameter (figure 4) (River and Foote

Figure 1. Tropical lilythorn is a small tree bearing showy, white flowers. (Photo by Michael Morgan, 2014)

Figure 3. The white, fragrant flowers of tropical lilythorn grow solitary or paired. (Photo by Michael Morgan, 2020)

Figure 2. Both Leaves and thorns of tropical lilythorn occur in pairs. (Photo by Michael Morgan, 2014)

2005). From a sample of 30 tropical lilythorn fruit, we determined that each fruit weighs approximately 0.17 g and contains an average of 13 seeds. The seeds are very small (1 g contains ± 450 seeds) (figure 5).

Ecology

On St. Croix, tropical lilythorn grows on one site on the south shore. The site is a flat plain dotted with small islands of trees and has been periodically grazed, burned, and cut for hay (figure 6). Tropical lilythorn tends to grow on the edges or interior of these tree islands and are almost never found growing in the open. Trees commonly found in the tree islands are: tamarind (*Tamarindus indica* L.), divi (*Caesalpinia coriaria* [Jacq.] Willd.), logwood (*Haematoxylon campechianum* L.), and white manjack (*Cordia alba* Roem. & Schult.). The first three species are nitrogen fixers and the fourth has white, edible berries that attract birds. Seeds of logwood are dispersed by the wind. Seeds of both tamarind and divi are dispersed by ruminants, such as cattle and deer, who eat their woody pods and pass the seeds via their digestive tracts (CABI 2009, Parrotta 1990). Both ruminant species are present onsite. Fruit-eating bats may also disperse the seeds of tamarind. Occasionally, opened fruit pods can be seen still hanging from the branches of a tamarind tree. The seeds are covered in an edible, sticky sweet and sour pulp. If this pulp is attractive to people, it is likely attractive to bats as well.

Figure 4. Tropical lilythorn fruits are small, black berries containing approximately 13 seeds each. (Photos by Michael Morgan, 2013).

The tree-like cactus (*Pilosocereus royennii* [L.] Byles & Rowley) is also a frequent component of the tree islands (figure 7). Interestingly, tan-tan (*Leucaena leucocephala* [Lam.] de Wit) is not found in these tree islands, even though it fixes nitrogen and is the most common tree on St. Croix. Perhaps this is because it does not produce a bird-edible fruit and its relatively open crown is less favored by birds for perches when compared with other tree species.

Tropical lilythorn likely favors these tree islands because they provide some protection. The shade of the trees, particularly the deep shade of tamarind, inhibits growth of grasses which outcompete tropical lilythorn seedlings and young plants for light, water, and nutrients. Most importantly, inhibition of grasses also provides protection against wildfire, because grasses are an important fuel for fire when they are dry. Furthermore, the spines of logwood and the branchy forms of divi and white manjack make it difficult for large animals such as cattle, horses, (and people), to enter these tree islands, thus protecting the tropical lilythorn plants from grazing, trampling, or other damage.

Figure 5. The seeds of tropical lilythorn are very tiny. (Photo by Michael Morgan, 2013)

Tropical lilythorn rarely grows in full sun, except when an over-topping tree dies and creates a gap in the tree island or the tree island dies through senescence or fire. It is not that tropical lilythorn cannot tolerate full sun, but rather its seedlings and young plants cannot compete with tall grass. For example, we have observed that 1- to 2-ft (30- to 60-cm) tall nursery-grown plants can grow more than 3 feet (1 m) in full sunlight in 1 year if kept free of competition from grass and other weeds.

Flowering and fruiting occur year-round for tropical lilythorn. Plants can produce fruits and flowers when they are 20 in (50 cm) tall in droughty, sunlit spots. In moister, shadier sites, plants do not produce flowers and fruits until they are about 40 in (100 cm) tall. Occasional rains induce flowering, which may or may not lead to successful and abundant fruiting. In dry conditions, tropical lilythorn has been observed to flower within 1 year of outplanting.

Bees and wasps pollinate tropical lilythorn flowers that develop into purple-black berries. Seeds are dispersed by birds, which eat the berries, or the fruits fall off the tree and germinate underneath. It is unknown which bird species eat tropical lilythorn fruits, but we do know birds eat them because half-eaten fruits have been found on branches and on the ground. The island of St. Croix has a relatively low number of bird species. Some likely seed-eating bird species seen onsite are common ground dove (*Columbina passerina*),

Figure 6. On St. Croix, the federally endangered tropical lilythorn grows on the edges of tree islands in one site. The tree islands are surrounded by grassy habitat. (Photo by Michael Morgan, 2019)

zenaida dove (*Zenaida aurita*), and the pearly-eyed thrasher (*Margathrops fugatus*). Maybe the original seed disperser of tropical lilythorn is now an extinct bird species.

Tropical lilythorn seeds may also be dispersed by rodents. We placed two camera traps in a tree island and observed black rats (*Rattus rattus*) at night climbing the branches and eating the fruits (Yriogen 2021). Black rats are arboreal and can be found in the wooded areas of St. Croix. It is unknown, however, if the tiny seeds of tropical lilythorn can pass intact through the digestive tract of a rat. Both black rats and brown rats (*R. norvegicus*) are not native to the Caribbean but were established in the Neotropics soon after European contact in the 15th century. Rats are found everywhere in the Virgin Islands except some isolated cays, although brown rats appear to be more urban than black rats.

Propagation Protocols

We have successfully grown tropical lilythorn via seeds but with limited success via vegetative cuttings.

Figure 7. Tree islands where tropical lilythorn occur on St. Croix contain several species, including a tree-like cactus. (Photo by Michael Morgan, 2019)

Seed Propagation

Once berries are ripe, extract the seeds by crushing the fruit between one's fingers. Then, dry the crushed fruits for 3 days. Since the seeds are so small (figure 5), it is impossible to sow them individually. Thus, it is best to mix them with sand and sow them onto the surface of germination trays.

We sow 0.04 oz (1 g) of seed per 15- by 20-in (37.5- by 50-cm) trays filled with a 1:1 medium of sand and amended peat moss, such as Promix™ (Premier Tech Horticulture, Quakertown, PA). The sand mixed with the seeds should be fine but not too fine. The sand used in the germination trays should be coarser than the sand used to spread the seeds. Seeds and seedlings should be watered with a mister or by using the fine-spray setting on a hose nozzle whenever the planting substrate starts to dry.

Tropical lilythorn seeds will start to germinate approximately 17 days after sowing (figure 8). Typical germination is about 18 percent. Germination peaks around day 60. After one or two pairs of adult leaves emerge, seedlings should be transplanted into individual pots filled with a well-drained growing medium (figure 9). We use a 2:1:1 mix of peat moss, sand, and topsoil.

Tropical lilythorn needs fertilization during propagation because the tiny seeds have low food reserves and planting substrates like sand and peatmoss are low in nutrients. Although the plants are bright green when

Figure 8. Tropical lilythorn seeds sown onto a substrate of sand and peat will germinate in 2 to 3 weeks. (Photo by Michael Morgan, 2021)

Figure 9. After adult leaves emerge, tropical lilythorn seedlings can be transplanted into individual pots and will be ready for outplanting when they are 1 to 3 ft (30 to 90 cm) tall. (Photo by Michael Morgan,2021)

they germinate, they soon turn yellow and die unless they are periodically fertilized. It is important, however, not to over fertilize, as this species appears sensitive to high levels of nitrogen. We recommend applying a fertilizer with low NPK (nitrogen, phosphorus, and potassium) levels, such as fish emulsion fertilizer (4-1-1), Milorganite™ (6-4-0; Milorganite, Milwaukee, WI), or composted manures every 3 weeks or whenever the seedlings start turning yellow. We found that fertilizers with high NPK levels (e.g., 20-20-20 or 14-14-14) are too strong and will burn the young plants.

Depending on the planting site conditions, seedlings can be outplanted when they are 1 to 3 ft (30 to 90 cm) tall. If the site is kept clear of weeds and grass, tropical lilythorn plants growing in full sun can reach a height of 6.5 ft (2 m) in 2 years, after which they tend to become bushy.

Vegetative Propagation

We tried to propagate tropical lilythorn through vegetative cuttings, but had very limited success. Out of 216 cuttings, only 3 produced viable plants. We tested six concentrations of the rooting hormone IBA (Indole-3-butyric acid): 0, 0.01, 0.03, 0.08, 1.6, and 3.0 percent (figure 10; Hormex Rooting Powder, Maia Products, Inc., Westlake Village, CA). Cuttings were placed in planting-tray cells filled with a 1:1 substrate of sand and Promix™. Cuttings (6 in [15 cm]) were taken from sections of young branches from both previous year's growth and current year's growth. The

Figure 10. Cuttings of tropical lilythorn were treated with varying rates of rooting hormone. (Photo by Michael Morgan, 2021)

basal end of each cutting was dipped into its assigned rooting powder concentration and then planted into one of the filled planting-tray cells (figure 11). The trays were kept in a shaded location and watered daily (except for weekends) with a hose kept on the mist setting.

We considered propagation a success if the cuttings started to put out a new vertical shoot with new leaves. Two cuttings treated with 0.03 percent IBA and one treated with 0.08 percent IBA were successful. We noticed that it took a long time for cuttings to get established or to die. Cuttings were planted at the beginning of December 2020. Noticeable mortality did not occur until the beginning of April 2021, 5 months after striking into the planting substrate. In mid-May 2021, 74 of the best looking cuttings were transplanted into larger pots with an enriched planting substrate consisting of a 1:1:1 mixture of local Virgin Islands topsoil (Sion clay), sand, and Promix™. Topsoil has more nutrients than sand or Pro-mix ™. Nonetheless, cuttings continued to slowly die, and by June 2021, only three viable plants remained (figure 12). We examined each of the dead cuttings and none had callus tissue. We intend to

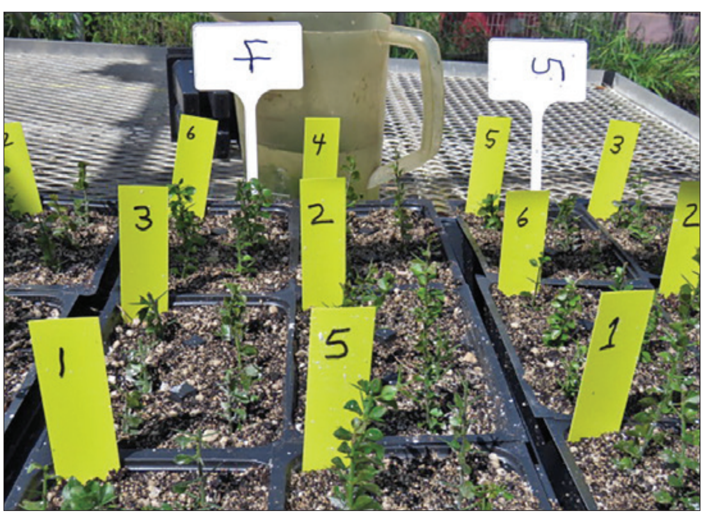

Figure 11. Tropical lilythorn cuttings were placed in individual cells after treatment with varying rates of rooting hormone. (Photo by Michael Morgan, 2021)

Figure 12. After 6 months, only 3 of 216 tropical lilythorn cuttings were viable. Research into vegetative propagation of this species is ongoing. (Photo by Michael Morgan, 2021)

continue studying vegetative propagation of tropical lilythorn, although seed propagation may be the best approach.

Conclusion

Tropical lilythorn is a federally endangered plant species. To mitigate its endangered status, we need to produce many plants and get them established into wild, protected areas. We have developed a successful seed propagation protocol, but are still working to determine if it can be successfully propagated vegetatively. Additionally, we continue to work toward a better understanding of tropical lilythorn's ecology.

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Red Pine: Guidance for Seed Transfer Within the Eastern United States

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Abstract

Red pine (*Pinus resinosa* Ait) is one of the most widely planted tree species in temperate North America. This species is native to coniferous and mixed conifer/deciduous forests around the Great Lakes, along the St. Lawrence River, and in the Northeastern United States and maritime Canada. Red pine is notable for lower genetic diversity and higher levels of inbreeding than most conifer trees, likely due to past population bottlenecks. Variation among red pine of different geographic origins is limited, but there is evidence that southern sources generally perform better than northern sources. Moving red pine between the Great Lakes and northeastern populations is not recommended, but otherwise, assisted migration is a good strategy for maintaining this species in a changing climate.

Introduction

Red pine (*Pinus resinosa* Ait) is a long-lived conifer that occurs naturally on well-drained sites in a relatively narrow band in eastern North America including the northern Great Lakes region, the St. Lawrence River Valley, and the extreme northern Appalachians in the Northeastern United States and maritime Canada. In natural settings, red pine may form single-species stands or occur in mixed-pine forests with eastern white pine (*P. strobus* L.), jack pine (*P. banksiana* Lamb), or both. Most natural red pine stands occur on dry (but not excessively so) sites with coarse-textured soil (Hauser 2008). In the upper Great Lakes region, stands dominated by natural-origin red pine may be extensive and are often associated with sandy ridges and banks near lakes and swamps. In the Northeast, red pine typically occurs as small stands on favorable sites while at its southern range edge in southwestern Wisconsin, Pennsylvania, and West Virginia, it is limited to small, exposed areas on rocky cliffs (e.g., Stephenson et al. 1986) (figure 1). Most original red pine stands were removed by logging in the late 19th and early 20th century. Red pine is one of the most widely planted tree species in the Great Lakes region of the United States and may be found in single-species planted stands on a wide range of sites (e.g., figure 2).

Figure 1. These mature red pines near the southwestern edge of the species' native range in Wisconsin are growing with oaks and white pine on a steep, sandy slope with exposed sandstone. (Photo by Nick LaBonte, 2021)

Natural regeneration of red pine is governed by its intolerance of shade and its seedlings' preference for bare mineral soil or mineral soil with a thin moss or litter layer (Rudolf 1990). Fire played a major role in determining red pine's distribution and persistence historically. Mature red pines are more fire-tolerant than jack pine or white pine (Hauser 2008), but its cones are not serotinous and seeds are destroyed by intense fire. Based on dendrochronology and analysis of fire scars (figure 3), most extant old-growth red pine stands are dominated by one or two age cohorts. Fires severe enough to remove some canopy trees, but not severe enough to eliminate local red pine seed sources, were probably involved in the origin of natural stands historically (Fraver and Palik 2012) while less severe, more frequent ground fires reduced hardwood competitors. Red pine is restricted to the least fire-prone sites in the boreal forest of Quebec, where crown fires are relatively frequent (Flannigan and Bergeron 1998).

Figure 2. This rangewide red pine provenance trial at the Cloquet Experimental Forest in Minnesota is similar in appearance to the numerous planted stands of red pine in the Great Lakes region. (Photo by Jim Warren, USDA Forest Service, 2004)

Red pine seedling establishment is most likely to occur several years after a canopy-clearing fire, after the ash layer has broken down, and in conjunction with a large cone crop, which occur at 3- to 7-year intervals (Ahlgren 1976). Seedlings grow slowly following germination, but growth increases after 4 or 5 years (Rudolf 1990). Due to slow initial growth and shade intolerance, germinating red pine seedlings are not competitive with hardwood sprouts, seedlings, or shrubs, such as hazel (*Corylus* sp.). Planted red pine seedlings are more competitive than naturally regenerated seedlings, but site preparation may still be necessary to remove competition. Red pine may be browsed occasionally but is not considered a preferred species of deer in most of its range.

Genetics

Red pine is not closely related to any other continental North American pine species and does not naturally form hybrids with its closest relatives, Eurasian hard pines such as European black pine (*Pinus nigra* Arnold). Like other Great Lakes forest tree species, red pine migrated southwards during the last glacial maximum and occupied the southernmost Appalachian uplands in Georgia (Rudolf 1990, Walter and Epperson 2005). Chloroplast DNA evidence suggests that a second refugial population of red pine existed on now-submerged land off the coast of northeastern North America (Walter and Epperson 2005). The main landscape-scale genetic distinction in red pine is between the large western population, which has a single chloroplast haplotype, and the more diverse, but smaller, eastern population. This division is notable in both chloroplast (Walter and Epperson 2005) and nuclear (Boys et al. 2005) DNA markers.

Red pine is characterized by remarkably low genetic variation, genetic diversity, and heterozygosity based on markers from the nuclear genome. Early studies (e.g., Fowler and Morris 1977) failed to identify variation in large samples of red pine using protein-based isozyme markers. Later studies identified relatively small amounts of variation at microsatellite DNA markers (e.g., Boys et al. 2005). Red pine is monoecious (figure 4) and self-compatible.

Figure 3. This old red pine growing in a mixed pine/oak forest in Wisconsin has a substantial upslope fire scar. The thick bark of red pine allows mature trees to survive low-intensity fire. Fire is a key part of the natural red pine regeneration process and is important for maintenance of mature red pine stands. A ground layer of *Vaccinium* sp. is frequently found in naturally occurring red pine stands. (Photo by Nick LaBonte, 2021)

Unlike most forest trees, however, red pine seeds resulting from self-pollination show little evidence of inbreeding depression (Fowler 1964) which may indicate that many generations of inbreeding have "purged" deleterious alleles from the genome. Despite red pine's large population, long lifespan, and wind-pollinated habit, genetic differentiation at molecular markers among natural populations is much higher than in other conifers (F_{st} ~ 0.25, Boys et al. 2005), likely due to facultative self-pollination. The unusually low genetic diversity of red pine is not a result of its heavy exploitation for timber; the population bottleneck likely involved a long-term reduction in population size (Fowler and Morris 1977) dating back to the last glacial maximum. Red pine's low genetic diversity is not shared by its closest extant relative, European black pine, although a study of trees from isolated stands in Spain and Morocco found high differentiation between the two regions (Rubio-Moraga et al. 2012). Given that no comparable barriers to gene flow exist within the native range of red pine, a tendency to produce offspring by self-pollination may be the reason red pine populations are so strongly differentiated.

Seed-Transfer Considerations

Studies that measured performance of red pine seed sources did not find strong relationships between movement distance and performance, but sources from the Northeastern United States (New England States) consistently underperform compared with Great Lakes sources (e.g., Wright et al. 1972). Variation

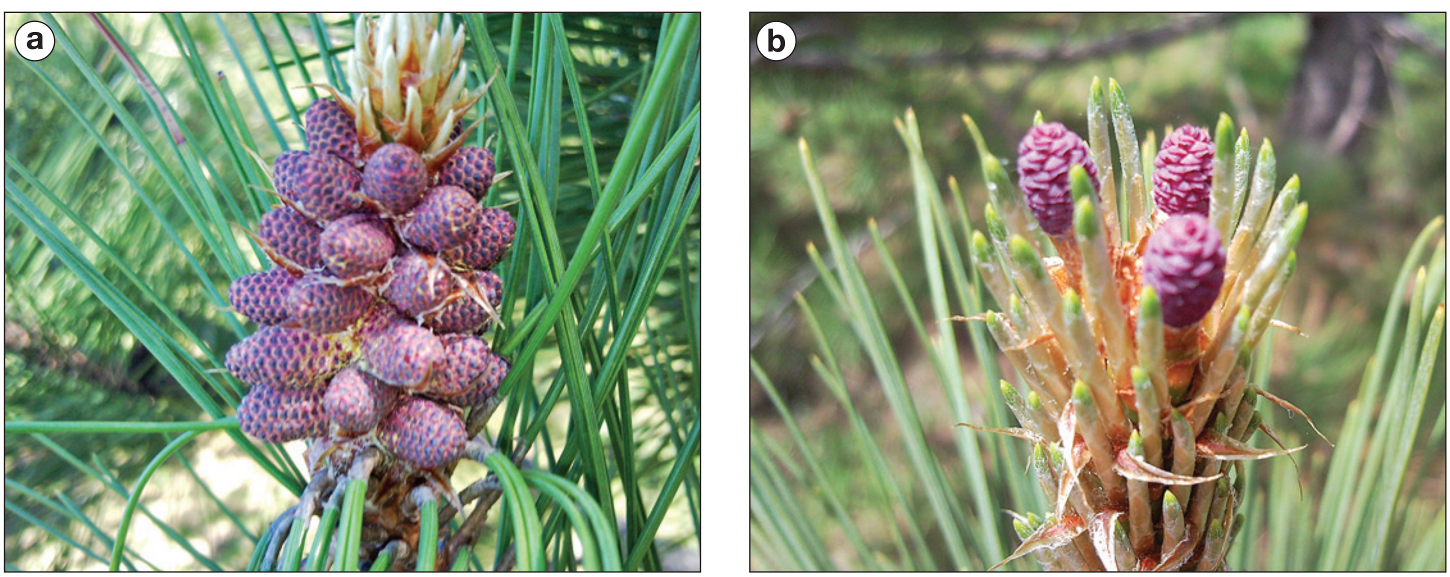

Figure 4. (a) Male and (b) female strobili of red pine in Minnesota. (Photos by Carrie Pike, USDA Forest Service, 2014)

Figure 5. Second-year cones on this red pine tree are nearly ripe enough for picking. (Photo by Nick LaBonte, 2021)

among provenances tends to be small if significant (Lester and Barr 1965), and the same sources tend to perform best at different sites (Pike and David 2007, Wright et al. 1972). Red pine is projected to cope poorly with a changing climate according to the Tree Atlas (Peters et al. 2020). Some investigators have found subtle variation in growth traits based on latitude, with sources from the southwestern part of the range performing best, indicating that assisted gene flow may be effective in helping red pine adapt to climate change (Rahi et al. 2010, Ter-Mikaelian 2014). Limited clinal variation has been noted for average seed size and some foliar traits (Rudolf 1990). Southern seed sources tend to have larger seeds, which may explain an observation of increased vigor of seedlings from native remnant populations in West Virginia when compared to seedlings from a Maine seed source (Buell 1940). A summary of considerations for moving red pine seed is contained in table 1.

Figure 6. This red pine tree has one cone near opening (purple-brown color) and a second already open with seed release in progress in September in southwestern Wisconsin. Cones at the closed and mostly brown stage are ideal to collect. (Photo by Nick LaBonte, 2021)

Table 1. Summary of silvics, biology, and transfer considerations for red pine.

Red pine, *Pinus resinosa* Aiton	
Genetics	• Genetic diversity: low • Gene flow: medium-low due to its capacity to self-pollinate; pollen and seed dispersal presumed similar to other pines
Cone and seed traits	• Small, winged seeds • 66,000 to 156,000 seeds per pound (30,000 to 71,000 per kg) • Non-serotinous cones; most seeds drop shortly after cone opening in early fall (figures 5 and 6) • Large cone crops every 3 to 7 years
Insect and disease	• Diplodia shoot blight may be problematic in young or mature stands • Other pests include red pine shoot moth, pine root collar weevil, and pine engraver • Pathogens of concern include armillaria root disease and annosum root rot
Palatability to browse	• Not a preferred food source for white-tailed deer, but seedlings may require protection in some locales
Maximum transfer distances	• Seed can be moved over a large distance (200 to 300 mi [322 to 483 km]) without significant declines in performance • Best performing sources tend to perform well at many sites • Seed sources from New England States are not recommended for planting in the Great Lakes region
Range-expansion potential	• Likely to experience northward range shift due to increased drought stress • Requirements for natural establishment put red pine at a disadvantage for natural migration into new areas

Insects and Diseases

Shoot blights are the most serious disease problem affecting red pine, causing damage to seedlings that grow near mature, infected red pines. In the Lake States, *Sphaeropsis sapinea* can induce mortality on mature trees (Nichols and Ostry 1997, Stanosz et al. 1997) or on seedlings infected at the nursery of origin (Stanocz et al. 2007). *Armillaria* sp. and annosum root rots (*Heterobasidion annosum* [Fr.] Bref) also affect red pine. A wider variety of root diseases may cause damage to red pine on sites outside its natural range of adaptability, especially on heavy and/or poorly drained soils and in forests with simplified structure such as even-aged pine plantations (Ostry et al. 2012). Red pine seedlings may also be susceptible to frost damage in frost pockets (Rudolf 1990).

Insect pests of red pine can damage stressed trees and stands but are not currently major causes of red pine mortality. Several insects cause damage to young stands, including sawflies, pine shoot moths, and pine root collar weevils. Native pine engraver beetles (Ips sp.) can kill stressed mature red pine trees. Cone beetles can cause severe damage to seed crops (Gilmore and Palik 2006).

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Yellow Birch: Guidance for Seed Transfer Within the Northeastern United States

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Abstract

Yellow birch (*Betula alleghaniensis* Britton) is a small-seeded hardwood tree native to forests across northeastern North America. Genetic diversity of this species is high due to high levels of seed dispersal and pollen flow, though few parameters that describe gene flow have been reported. Yellow birch is capable of hybridizing with other *Betula* species. Common garden studies revealed relatively weak clines for growth traits but strong variation in phenological traits, indicating that seed transfer may be deleterious if seed is moved long distances. No empirical transfer distances have been suggested, but distances of 200 mi (322 km), or roughly 3 degrees latitude northward, is a safe recommend distance to avoid phenological mismatches. Widespread yellow birch decline has been described in Canada and attributed to climatic perturbations. Few major pests impact yellow birch except for decay fungi in decadent (overmature) stands. Yellow birch is likely to persist with climate change in its current range because of its high genetic diversity and gene flow.

Introduction

Yellow birch (*Betula alleghaniensis* Britton) is an opportunistic, relatively long-lived mesic hardwood that is readily found in hardwood forests of the Northeastern United States and Canada on a variety of soil types. The bark may be golden (figure 1) or brown in color (figure 2) and generally exhibits some peeling characteristics. Yellow birch has intermediate shade tolerance and is less shade-tolerant than its common associates, sugar maple (*Acer saccharum* Marshall) and American beech (*Fagus grandifolia* Ehrh.)(Beaudet and Messier 1998). Like other species in the *Betula* genus, yellow birch thrives on exposed or mixed

Figure 1. The shiny bark of this yellow birch is visibly distinguishable from other birch species in this forest. (Photo by Carolyn Pike, 2019)

Figure 2. The bark of this yellow birch tree is light brown in color and exhibits patterns of peeling similar to other trees in the genus. (Photo by Katie Frerker, USDA Forest Service, 2019)

mineral soil created by major disturbances (Caspersen and Saprunoff 2005, Kern et al. 2019) or on decayed wood debris (Marx and Walters 2008) (figure 3). Yellow birch populations are concentrated across northern portions of New York, New Hampshire, Vermont, and across Maine. The species also occurs in lower densities across the western Great Lakes region and at higher elevations along the southern Appalachians as far south as North Carolina. Three glacial lineages exist: a large eastern group (southern Appalachians to New England), a western group in the Great Lakes region, and a small group in Atlantic Canada (Thomson 2013, Thomson et al. 2015a). Introgression among *Betula* species (*B. papyrifera* Marshall, *B. lenta* L., and *B. alleghaniensis)* likely occurred during the last glacial maximum (Thomson et al. 2015a), but today the species are largely distinct (Thomson et al. 2015b). Yellow birch has experienced declines attributed to overmaturity (Woods 2000), lack of recruitment (Caspersen and Saprunoff 2005), and/or periodic freeze-thaw events (Bourque et al. 2005). Yellow birch seedlings are also prone to desiccation following lengthy periods of drought.

Yellow birch is not commonly planted because the species regenerates readily from seed. Excessive leaf litter and a lack of bare mineral soil can hamper regeneration success, especially on sites where light is limiting (Shields et al. 2007). In managed stands, natural regeneration is promoted with group or patch selection followed by scarification to expose mineral soil (Gauthier et al. 2016, Willis et al. 2015). In addition, one or more seed trees must be

Figure 3. Yellow birches grow best on bare mineral soil or any exposed surface such as the rock in this photo. (Photo by Matt Pickar, USDA Forest Service, 2021)

retained in, or near, harvest-created openings (stand basal area >1.3 m2/ha [5.7 ft2/ac]; <15 m [49 ft] away) (Caspersen and Saprunoff 2005, Willis et al. 2016). Release of advance regeneration through frequent selection cutting can also facilitate attainment of canopy positions for this species (Webster and Lorimer 2005). Seedling survival and growth are best on sites with medium to large light gaps (Kern et al. 2012, Gasser et al. 2010), although excessively large gaps can result in increased competition with shrubs or increased desiccation through temperature extremes (Hatcher 1966, Kern et al. 2013). The species' thin bark renders it highly sensitive to damage from sun scald and fires. Yellow birch root systems are generally shallow and thus sensitive to changes in soil temperature and moisture. White-tailed deer (*Odocoileus virginianus*) and snowshoe hare (*Lepus americanus*) commonly browse yellow birch seedlings. More information about the species' distribution, growth, and habitat can be found in Neesom and Moore (1998) and Erdmann (1990).

Genetics and Gene Flow

Yellow birch is monoecious and can produce male and female flowers on the same or different branches. Pollen is shed in the spring, and seeds are wind dispersed from August through September (Clausen 1973). The seeds are relatively small, with approximately 1,000 per gram (450,000 per pound) (Karrfalt and Olson 2008). The period of seed dispersal in yellow birch is more extended than other taxa with which it coexists (maple [Acer sp.] and beech [*Fagus* sp.]), resulting in a more persistent seed bank (Houle 1994) (figure 4). Production of male and female flowers may commence early in a tree's lifespan, sometimes before age 10 (Clausen 1980) but is generally much later (40 years and older) across most of its range (Erdmann 1990). Seed production increases with the age and abundance of yellow birch in the canopy (Drobyshev et al. 2014). Gene flow, measured with F_{ST} values (a ratio of genetic variation between sub-populations and the total population), has not been reported, but genetic and phenotypic variation is considered high due to effective dispersal of pollen and seed from both young and mature trees over their lifespan.

The *Betula* genus has a transcontinental range across the northern hemisphere and a complicated phylogeny (Wang et al. 2016). Yellow birch is hexaploid (Clausen 1973, Wang et al. 2016) and can hybridize with paper birch (*Betula papyrifera* Marshall, also a hexaploid), most commonly where the species ranges overlap (Barnes et al. 1974, Sharik and Barnes 1971, Thomson 2013, Thomson et al. 2015ab). Genetics studies of yellow birch have focused on the effects of introgression with other *Betula* spp., most commonly with *B. papyrifera* and less often with *B. lenta* (sweet, or black, birch). These natural hybridization events are most common in the lower Great Lake States where paper birch and yellow birch are sympatric, although the species are genetically distinct despite occurrence of hybridization events (Thomson 2013, Thomson et al. 2015b). Genetic

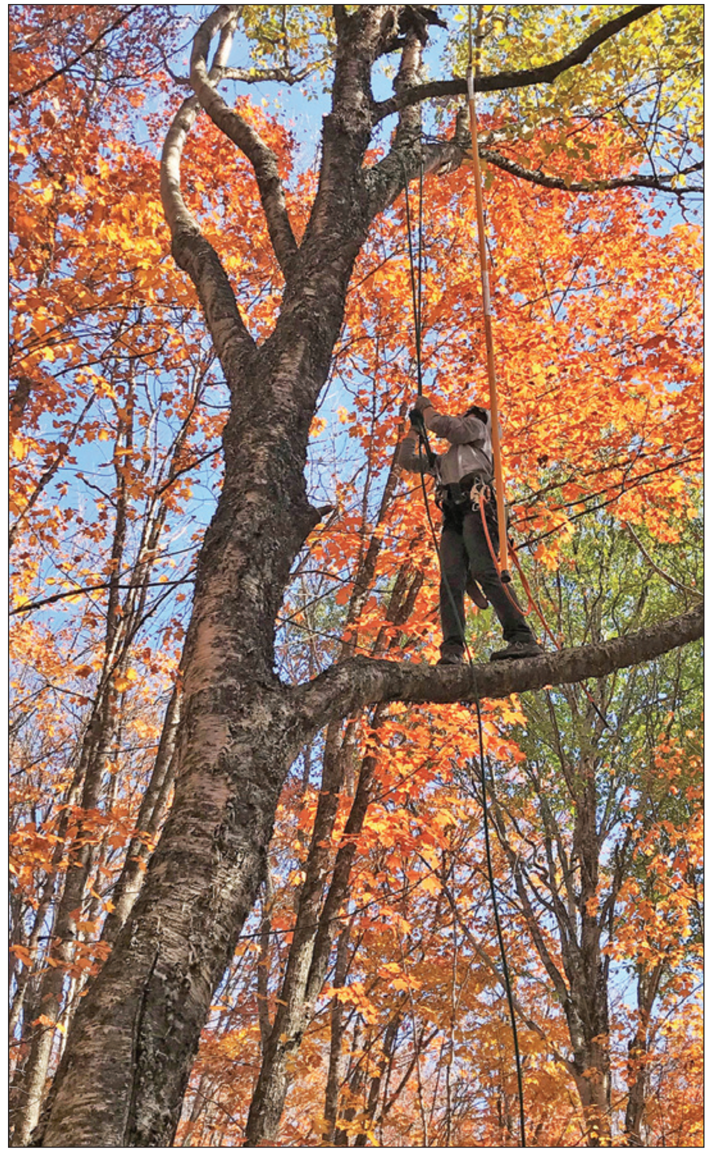

Figure 4. Yellow birch regenerates well on its own, but seeds are also collected and planted to supplement natural regeneration. (Photo by Richard Kujawa, USDA Forest Service, 2021)

diversity is highest for yellow birch in the central-western Great Lakes region where introgression with paper birch occurred historically (Thomson et al. 2015a, 2015b).

Seed-Transfer Considerations

Common-garden studies found weak clines (latitudinal or longitudinal) for growth traits in both seedlings and 5-year-old saplings (Clausen 1975, Leites et al. 2019). Growth rings, studied in stands of natural origin, were relatively insensitive to variations in climate as well (Drobyshev et al. 2014). Clinal variations along a latitudinal (north-south) gradient are more pronounced for phenological traits associated with cold tolerance than height growth, especially for young seedlings. For example, timing of growth initiation was consistently earlier for northern- than southern-origin sources while southern-origin sources extended growth longer into the late-summer months or early fall (Clausen 1968a, Clausen and Garrett 1969). This extension of the growing season into the fall may increase susceptibility to damage from fall frosts. Traits with uncertain adaptive value, such as catkin, bract, and fruit characteristics, do not follow clear geographic patterns (Clausen 1968b), implying that genetic variation is well-dispersed among stands (Clausen 1980).

A recent analysis derived critical (not to exceed) transfer distance for yellow birch and other taxa (Pedlar et al. 2021) from provenance trials by comparing mean annual temperature (MAT) of each seed source's origin to the MAT of each planting site. Tree height in yellow birch remained above the 10 percent threshold until transfer distances exceeded 7.8 °C (13 °F) to a cooler environment or 70-day shorter growing season (Pedlar et al. 2021). This critical transfer distance, based on tree height alone at a relatively small number of common gardens, may, however, overlook phenological differences that impact survival. Transfer distances of up to 200 mi (322 km) (approximately 3˚ latitude northward) is conservative but would likely avert phenological mismatches from excessively long-distance movement of seed. The 200-mi (322-km) distance is a general recommendation for white spruce (*Picea glauca* [Moench] Voss) (Thomson et al. 2010) which has undergone more extensive provenance testing and may be comparable to yellow birch because of its high genetic diversity and low clinal variation for growth traits. If yellow birch seed orchards are established, a variety of phenotypes from local areas and southerly sites should be incorporated to maximize genetic diversity. In the absence of artificial regeneration, silvicultural prescriptions that incorporate mature seed trees near exposed mineral substrates and canopy openings will improve natural regeneration of the species. As the climate changes, natural hybridization with paper birch may be exacerbated or deterred based on local weather cycles, but these events will likely be impossible to predict or avoid.

The geographic range that yellow birch occupies is not expected to change dramatically with climate change, but the quality and quantity of the habitats within its range may decline (Peters et al. 2020). Its high seed and pollen dispersal is favorable for the species to endure across a dynamic landscape in a changing climate, but fire and pests may negatively affect its habitat (Prasad et al. 2020). Yellow birch is also sensitive to summer droughts and freeze thaws in the spring and fall when trees are incompletely dormant (Cox and Zhu 2003), which may affect its survival if these conditions become more commonplace in the future. Yellow birch populations residing in its northern range edge were limited by substrate and seed availability but were otherwise relatively neutral to temperature extremes (Drobyshev et al. 2014), suggesting few barriers for its northward expansion. Genetics and seed-transfer considerations for yellow birch are summarized in table 1.

Insect and Diseases

Few major insects and diseases impact the growth and survival of yellow birch. Bronze birch borer (*Agrilus anxius* Gory) and birch skeletonizer (*Bucculatrix canadensisella* Chambers) can lead to mortality of mature trees. Birch leaves (figure 5) are also susceptible to feeding from the introduced gypsy moth (*Lymantria dispar dispar*) and the native forest tent caterpillar (*Malacosoma disstria* Hübner) which may contribute to yellow birch decline, especially in mature forests where trees experience other health issues.

Table 1. Summary of silvics, biology, and transfer considerations for yellow birch.

Yellow birch, ***Betula alleghaniensis*** Britton	
Genetics	• Hexaploid (6 sets of chromosomes) • Gene flow (pollen): high • Gene flow (seed): high
Cone and seed traits	• Small, winged seeds • 50,000 cleaned seeds per pound (992,250 seeds per kg) (Karrfalt and Olson 2012) • Seeds released in September
Insect and disease	• Bronze birchborer, nectria canker, cider conk, and skeletonizer • Decadent stands may exhibit crown dieback and decline
Palatability to browse	• High risk of herbivory from white-tailed deer and snowshoe hare
Maximum transfer distances	• No specific transfer distances have been calculated • Yellow birch should tolerate long distance transfers (200 mi [322 km], 3° latitude northward) • Potential to hybridize with paper birch or sweet birch where ranges overlap
Range-expansion potential	• Likely to expand range but requires suitable sub strate (e.g., exposed mineral soil) and sufficient light to survive (e.g., canopy gaps)

Figure 5. Yellow birch leaves are ovoid and serrated and sometimes difficult to distinguish from paper birch. (Photo by Jack Greenlee, USDA Forest Service, 2003)

No primary pathogens currently afflict yellow birch, but several decay fungi, such as cinder conk (*Inonotus obliquus* [Ach. ex Pers.]), are often found on mature or decadent trees (Brydon-Williams et al. 2021). Nectria canker (*Neonectria galligena* (Bres.) is damaging to yellow birch but is generally not destructive on a stand level (Ward et al. 2010); trees can live for many years with rather large cankers. Episodes of crown decline may occur with no clear cause, resulting in dead branches in the top of the tree and occasionally substantial crown dieback. Crown dieback may also be triggered by unusual weather events (Bourque et al. 2005) or site disturbance.

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Northern Red Oak: Guidance for Seed Transfer Within the Eastern United States

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Abstract

Northern red oak (*Quercus rubra* L.) is a large-seeded hardwood that grows in forests across eastern North America. Genetic diversity of this species is high due to high levels of seed dispersal and pollen flow and from hybridization with other species in the red oak section. Hybridization occurs readily across its range except in the northern parts of the range where other species in the red oak family are less common. Northern red oak is expected to thrive in a future climate because of its genetic diversity and inherent plasticity. Common garden studies revealed relatively weak clines for growth traits. No empirical transfer distances have been suggested, but distances of 200 mi (322 km), or roughly 3 degrees latitude northward, is a safe recommendation to avoid phenological mismatches. Oak wilt, a pathogen of concern, is slowly spreading across its range and may become more problematic in the future. Several insects impact northern red oak but are generally more problematic in older stands or stands that are weakened by other causes.

Introduction

Northern red oak (*Quercus rubra* L.) is a long-lived, mesic hardwood that is widely distributed across the eastern half of North America from Maine and the Canadian Maritimes, west to Minnesota, and as far south as Arkansas, Alabama, and Georgia. Studies of pollen records suggest that *Quercus* refugia were likely scattered across the lower Mississippi Valley and northern Florida followed by rapid recolonization concurrent with ice sheet retreat 18,000 years before present (Davis 1983). Northern red oak is associated with deep, well-draining soils but can tolerate a range of soil textures from loams to silty clay loams. Northern red oak is generally associated with north or easterly aspects and lower elevations. Regeneration of northern red oak can occur from seed (acorns) (figure 1), and stumps can also coppice. Leaves of northern red oak have pointy tips (figure 2) which are readily distinguished from the rounded tips of white oak (*Quercus alba* L.) leaves.

Figure 1. Acorns of northern red oak are oblong with a flat, scaly cap. (Photo by Carolyn C. Pike, 2018)

Figure 2. Leaves of northern red oak are oblong with toothed lobes and sharply pointed leaves. (Photos by Mark Coggeshall, 2021)

The bark of northern red oak trees is variable but is generally dark gray with shallow fissures (figure 3). Northern red oak readily hybridizes with other species in the Lobatae section including scarlet oak (*Q. coccinea* Muenchh.), northern pin oak (*Q. ellipsoidalis* E.J. Hill), bear oak (*Q. ilicifolia* Wangenh.), shingle oak (*Q. imbricaria* Michx.), blackjack oak (*Q. marilandica* Muenchh.), water oak (*Q. nigra* L.), pin oak (*Q. palustris* Muenchh.), willow oak (*Q. phellos* L.), black oak (*Q. velutina* Lam.), and Shumard oak (*Q. shumardii* Buckl.) (figure 4). Hybrids can sometimes be difficult to detect morphologically (Aldrich et al. 2003) and may require molecular assessments to confirm. Hybridization does not occur with species in the white oak section (Leucobalanus).

Northern red oak is intermediate in its shade tolerance and can tolerate light shade (Gottschalk 1994, Phares 1970). Shelterwoods are a common silvicultural practice in northern red oak stands (Dey and Parker 1996), though regeneration success can be unreliable if a strong cohort of seedlings is absent before, or immediately after, the first cut. Fencing is often required to protect seedlings from herbivory (Miller et al. 2004, Redick et al. 2020), while management to control competing vegetation (yellow poplar [*Liriodendron tulipifera* L.], red maple *[Acer rubrum* L.], or sugar maple [*Acer saccharum* Marshall]) may also be needed to enable northern red oak to survive or thrive (Morrissey et al. 2010). Northern red oak is the

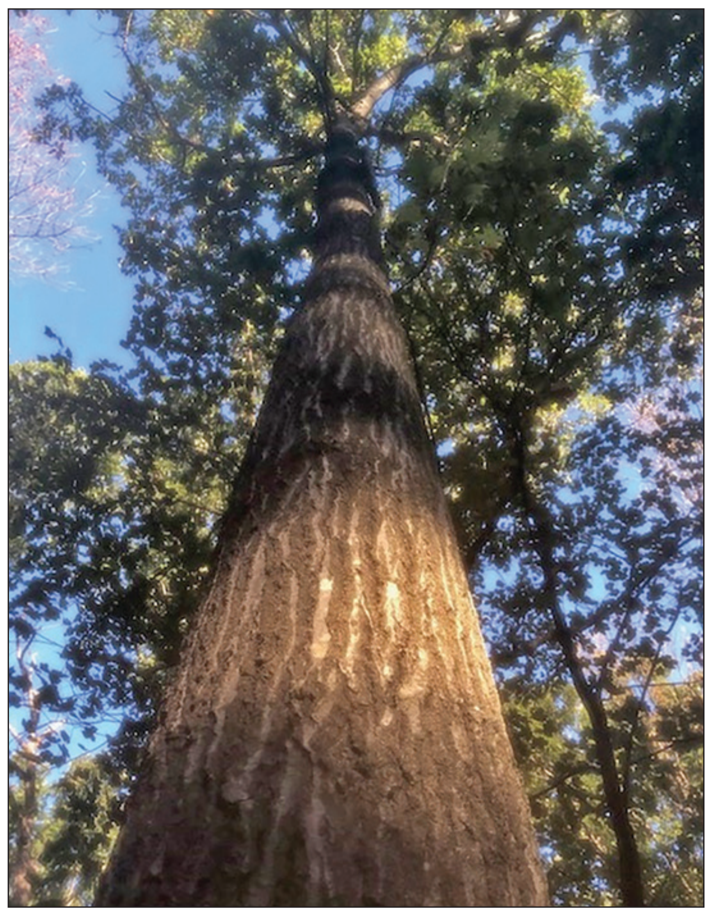

Figure 3. The bark of northern red oak is dark gray and scaly with ridges, but the species lacks the deeper fissures of others in the red oak family. (Photo by Mark Coggeshall, 2021)

most-planted hardwood tree in the Northeastern United States (Pike et al. 2018) and suitable for planting across a variety of site types including riparian areas and reclaimed minelands (Adams 2017). The species is more commonly propagated as a bareroot seedling because of its prodigious root system (figure 5).

Genetics

Genetic structure of neutral DNA markers in northern red oak is more prominent latitudinally than longitudinally (Birchenko et al. 2009, Magni et al. 2005), likely due to the northward re-colonization that followed glacial recession that was more rapid compared to other deciduous tree species (Davis 1983). Genetic diversity and gene flow in northern red oak is very high. The species is a complete out-crosser, and inbreeding is very low in natural stands (Schwarzmann and Gerhold 1991, Sork et al. 1993). The exceptionally high genetic diversity of northern red oak (compared to other hardwoods) is due, in part, to its ability to hybridize with other species in the Lobatae section, a feature that has resulted in weak phylogenetic structure, or weak differentiation, from other taxa in the red oak family (Magni et al. 2005). Despite its high gene flow, caching habits of its primary seed dispersers (squirrels) can create fine-scale genetic structure locally (Sork et al. 1993).

Northern red oak is monoecious, wherein trees may produce both male and female reproductive structures on the same individual. Pollen is wind-dispersed, and acorns can be animal dispersed, primarily by gray squirrels, fox squirrels, and blue jays. The timing of pollen shed and female receptivity may be asynchronized among trees within a seed orchard or stand. This asynchronous phenology, in which the same subset of trees share pollen from year to year, contributes to the presence of a Wahlund effect whereby pollen is not shared equally among trees (Alexander and Woeste 2017, Jones et al. 2006, Moran and Clark 2012). Such effects can reduce expected levels of genetic diversity but can be offset by mixing seed from many sources and stands within a seed lot.

Seed-Transfer Considerations

Phenotypic variation in northern red oak is generally not attributed to provenance of seed source (Deneke 1974, Kriebel et al. 1976, Kriebel et al. 1988, Leites et al. 2019) (figure 6). For example, family differences in acorn size and first-year seedling growth superseded differences among provenances, except for extreme far northern seed sources (Kriebel 1965). Even though provenance accounted for low levels of variation in older provenance trials, physiological differences in young seedlings planted in common gardens in Minnesota were detectable between northern seed sources (Etterson et al. 2020). Geographic clines (north to south) are also evident for phenological traits such as date of flushing and timing of leaf coloration in the fall, although elevation, and to a lesser extent longitude, of seed origin can also affect leaf flushing and coloration (Schlarbaum and Bagley 1981). Older northern red oak trees from southern and western provenances had thicker bark than those from northern and

Figure 4. Northern red oak can naturally hybridize with other trees in the red oak family, such as Shumard oak (*Quercus shumardii*). The hybrids, as shown in this image, can be difficult to detect morphologically as hybrids may resemble one parent or have traits of both. (Photo by Mark Coggeshall, 2021)

Figure 5. Northern red oak seedlings have prodigious root systems that thrive in bareroot culture but may also be grown in large containers. (Photo by Mark Coggeshall, 2013)

eastern provenances, which is likely a fire adaptation attributed to sources originating from drier portions of its range (Russell and Dawson 1994). Radial growth in natural stands was most significantly correlated with early-season moisture from May through July (LeBlanc and Terrell 2011).

No studies to date have empirically assessed seed-transfer distances, but northern red oak is highly tolerant of long-distance seed transfers (Schlarbaum 2021). A reassessment of older provenance trials revealed local adaptation in which southern sources were best in mild environments and northern sources were most suited to cool environments (Leites et al. 2019). Height growth in common gardens was most strongly correlated with maximum summer temperatures; correlations with minimum temperatures and growing season length were not significant (Leites et al. 2019). Assisted migration (i.e., moving seed sources at least one zone northward) may help offset adaptation lags. Western edge populations that are adapted to drier climates may be favored for areas where droughts are predicted to be more prevalent. Northward transfer distances of 200 mi (322 km), or roughly 3 degrees latitude, is likely a safe recommendation to avoid phenological mismatches but has not been explicitly tested. This distance is also recommended for conifers such as white spruce (*Picea glauca* [Moench] Voss), where genetic diversity is high among families but low among provenances (Thomson et al. 2010). Considerations for seed transfer are summarized in table 1. Northern red oak is well suited for planting in the future because of its high genetic diversity, plasticity, fecundity from high seed production, and ability to regenerate from both stumps and seed. It also has strong juvenile growth allowing it to quickly establish on a new site.

Insect and Diseases

Red oak is often defoliated by insects, such as the nonnative gypsy moth (*Lymantria dispar*). Periodic outbreaks of native defoliators, such as fall cankerworm (*Alsophila pometaria*) and forest tent caterpillar (*Malacosoma disstria* Hubner), can feed on northern red oak in the spring leading to stress and predisposition to decline from other factors (Asaro and Chamberlin 2019). Drought events can stress northern red oak, rendering it more vulnerable to red oak borer (*Enaphalodes rufulus* [Haldeman]) and two-lined chestnut borer (*Agrilus bilineatus*), especially

Table 1. Summary of silvics, biology, and transfer considerations for northern red oak..

Northern red oak, *Quecus rubra* L.	
Genetics	• Genetic diversity: high • Gene flow: high to moderate • Does not readily inbreed and will not self-cross • Readily hybridizes with other oaks in the red oak section
Cone and seed traits	• Large seeded: 75 to 255 cleaned seeds per pound (165 to 561 per kg) (Bonner 2012) • Mammal dispersed
Insect and disease	• Defoliating insects: gypsy moth, two-lined chestnut borer • Pathogens: oak wilt is a growing threat
Palatability to browse	• High risk of browse from deer; seedlings often require protection
Maximum transfer distances	• No empirical transfer distances have been calculated • High tolerance to long-distance transfer • Transfer of 200 mi (322 km) (3° latitude from south to north) is likely well tolerated
Range-expansion potential	• Northward potential is high • Likely to maintain populations in current range

Figure 6. This range-wide provenance trial (17 years from planting) is one of several common gardens analyzed to study the geographic patterns of variation in northern red oak. (Photo by Mark Coggeshall, 2008)

following defoliation events. Oak wilt (*Ceratocystis fagacearum*) is also a concern and can limit management efforts from mid-March through mid-July due to activity of insect vectors like bark beetles and ambrosia beetles (*Scolytinae*) and picnic beetles and sap beetles (*Nitidulidae*). Oak borers (*Enaphalodes rufulus*) are active in late spring/early summer and will attack wounded (pruned) trees and others in close proximity. Bacterial leaf scorch (*Xylella fastidiosa*) of northern red oak has symptoms similar to oak wilt, but trees will decline in health over several years before they succumb and die.

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Determining Avian Herbivory Patterns at Sowing Using Loblolly and Longleaf Pine Seed

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Abstract

Avian herbivory of pine seeds is a leading cause of seedling loss in container nurseries. Practices currently used to prevent herbivory are not fully effective and have not changed much in the last 60 years. Because no clear avian herbivory patterns of seeds have been documented, two trials were conducted to determine effects of: (1) container cell color and growing medium depth using longleaf pine (*Pinus palustris* Mill.) seeds at two sites, and (2) genetic quality of longleaf pine and loblolly pine (*P. taeda* L.) seeds at two sites. In the first trial, fewer seeds were consumed after 5 days from cavities filled to two-thirds of operational capacity compared with those filled to operational capacity, but by day 10, birds foraged in all cavities regardless of medium depth. In the second trial, birds showed no preference for pine species or genetic quality of seeds. Birds tended to avoid an open field area. Birds also recognized where containers had been placed for a previous trial, which led to earlier and faster seed consumption in the subsequent trial.

Introduction

Tree seedling production using containers has increased almost 5,000 percent over the last 40 years across the Southern United States (Starkey et al. 2015). Currently, more than 230 million conifer seedlings are grown in containers each year in the South (figure 1) (Haase et al. 2021). Increasing seed efficiency is a primary objective of nursery managers to ensure each container cavity produces a seedling from each pure live seed sown. When a container cavity does not produce a seedling, seed efficiency is reduced, and the nursery incurs economic losses. The cost of seeds, wasted growing medium left in the container cavity, and fewer seedlings available to sell at the end of the growing season all contribute to lost revenue by the nursery.

In a 2012 survey, 80 percent of container seedling nursery managers reported birds as the largest factor contributing to reductions in seed efficiency with a 1.33-percent seedling loss (Starkey et al. 2015). Avian herbivory leads to more seedling loss than pre- and post-emergence damping-off or insects (Starkey et al. 2015). To put that into economic perspective, if a container nursery with a capacity to grow 40 million seedlings endures a 1.33 percent loss, and seedlings are priced at 20 cents each, production loss will be 532,000 seedlings or $106,400 in revenue.

Avian herbivory of seeds is not a new problem in tree seedling nurseries. Reines and Greene (1957) described a single bird consuming 67 seeds in less than 1 minute at a Georgia nursery. Nursery managers have implemented preventive measures to curb damage from birds for more than 60 years. Kingsley (1958) tested thiram and anthraquinone on loblolly (*Pinus taeda* L.) and slash pine (*P. elliotti* Englm.) seed and had good protection from birds while also reducing labor costs associated with patrolling the nursery. Thiram and anthraquinone are still recommended as seed treatments against birds in container nurseries (Landis et al. 1998). Suspending shade cloth over container sets during the germination phase is another practice currently used to prevent birds from reaching seeds. Issues with this method include birds getting trapped under the shade cloth leading to increased feeding (Starkey et al. 2015) and the cost of the shade cloth necessary to cover large areas (up to 40 ac [16 ha]). In addition, removing the shade cloth must coincide with a certain stage of germination, which can vary depending on the conifer species and genetic sources within species (Clouse

Figure 1. Many conifer seedlings are grown in container production systems in the South. (Photo by Paul Jackson, 2021)

2021). Noise-making devices such as propane-fueled exploders have been used to prevent herbivory, but they require frequent maintenance, can be dangerous to handle, and birds become accustomed to their presence (Jackson 1991). The use of cover crops such as soybeans (*Glycine max* L.) and sorghum (*Sorghum bicolor* L.) have been successful luring birds away from seeded areas when grown in close proximity to the nursery (Dorward 1965).

In 2018, avian herbivory of seeds was a problem in a longleaf pine (*Pinus palustris* Mill.) trial conducted to detect Sonderegger pine (*Pinus x sondereggeri* H.H. Chapm.) seedlings during the germination phase (Bolner at al. 2019). Birds were observed foraging only on seeds sown in container cavities that were filled with medium to operational levels (within 0.4 in [1 cm] of the top) compared with those filled to two-thirds capacity (within 3.6 in [4.8 cm] of the top) (figure 2). After these observations, the authors contacted Mike Coyle, Container Operations Manager at International Forest Company (IFCO, Moultrie, GA) to learn if he had observed any seed foraging patterns during daily operations. His observations were: (1) birds tend to forage more heavily on longleaf pine seeds compared with other pine species, (2) birds seem to forage on seed lots bred for improved genetic quality compared with open-pollinated or wild-collected seed lots, (3) different avian species often forage on fall-sown seeds compared with those that forage on spring-sown seeds, and (4) birds tend to forage in containers located along the edges near tree lines compared with more open areas of the nursery.

Using the information gathered from the 2018 trial and from Mike Coyle at IFCO, and knowing that current preventive methods against avian herbivory still result in significant seed loss (Starkey et al. 2015), two trials were designed. The objectives for Trial One were to determine if container medium depth, container color, and site surroundings such as an open field or tree-lined edge affected avian herbivory of seeds. The objective of Trial Two was to determine if sowing loblolly pine and longleaf pine seeds from different genetic sources affected avian herbivory.

Figure 2. In a 2018 longleaf pine trial, seed castings were left behind as a result of avian herbivory. (Photo by Paul Jackson, 2018)

Materials and Methods

Trial One

Non-treated longleaf pine seeds were sown singly into Ray Leach Cone-Tainer™ cells (RL98 Stubby, 6.5 in^3 [107 cm^3], Stuewe and Sons, Inc., Tangent, OR) on October 23, 2020 at Louisiana Tech University (Ruston, LA). Containers were filled with a peat moss-based growing medium (Pro-Mix®, Premier Tech Horticulture, Quakertown, PA). Two container colors (white or black) and two medium fill levels (operational level within 0.4 in [1 cm] of the top or two-thirds of operational level within 3.6 in [4.75 cm] of the top) (figure 3) were evaluated in the trial for a total of four treatments. Two geographic locations were selected to set out containers: an open field site (32°31'02" N, 92°39'05" W) and an area adjacent to a wooded fencerow (32°30'58" N, 92°39'13" W). Each tray of 49 cells served as a replication with 3 trays per treatment at each location for a total of 24 trays and 1,176 cells. Trays were placed in a completely randomized block design on three nursery tables at each

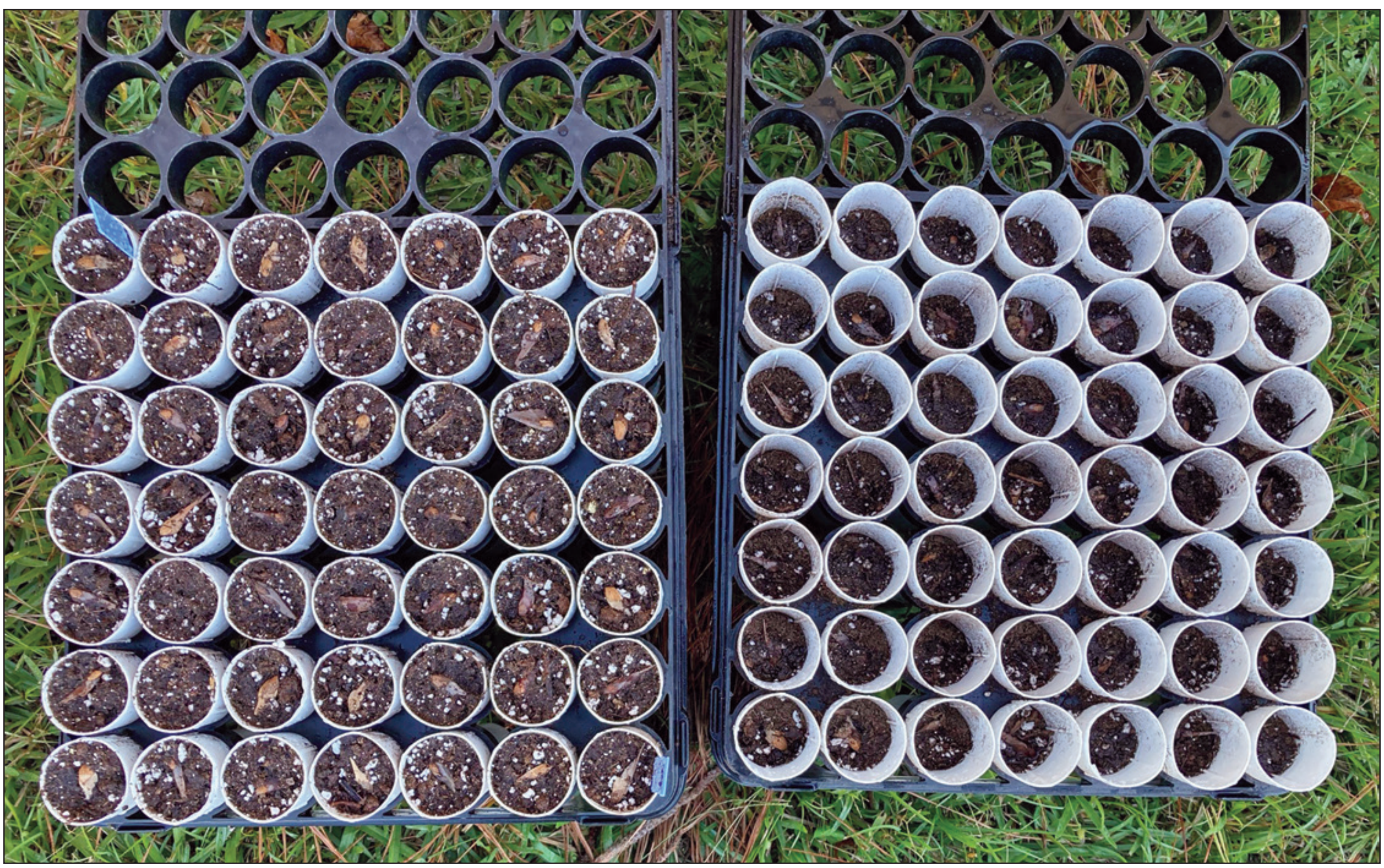

Figure 3. For Trial One, container cells were filled with medium to operational levels (left) or to two-thirds capacity (right). (Photo by Paul Jackson, 2020)

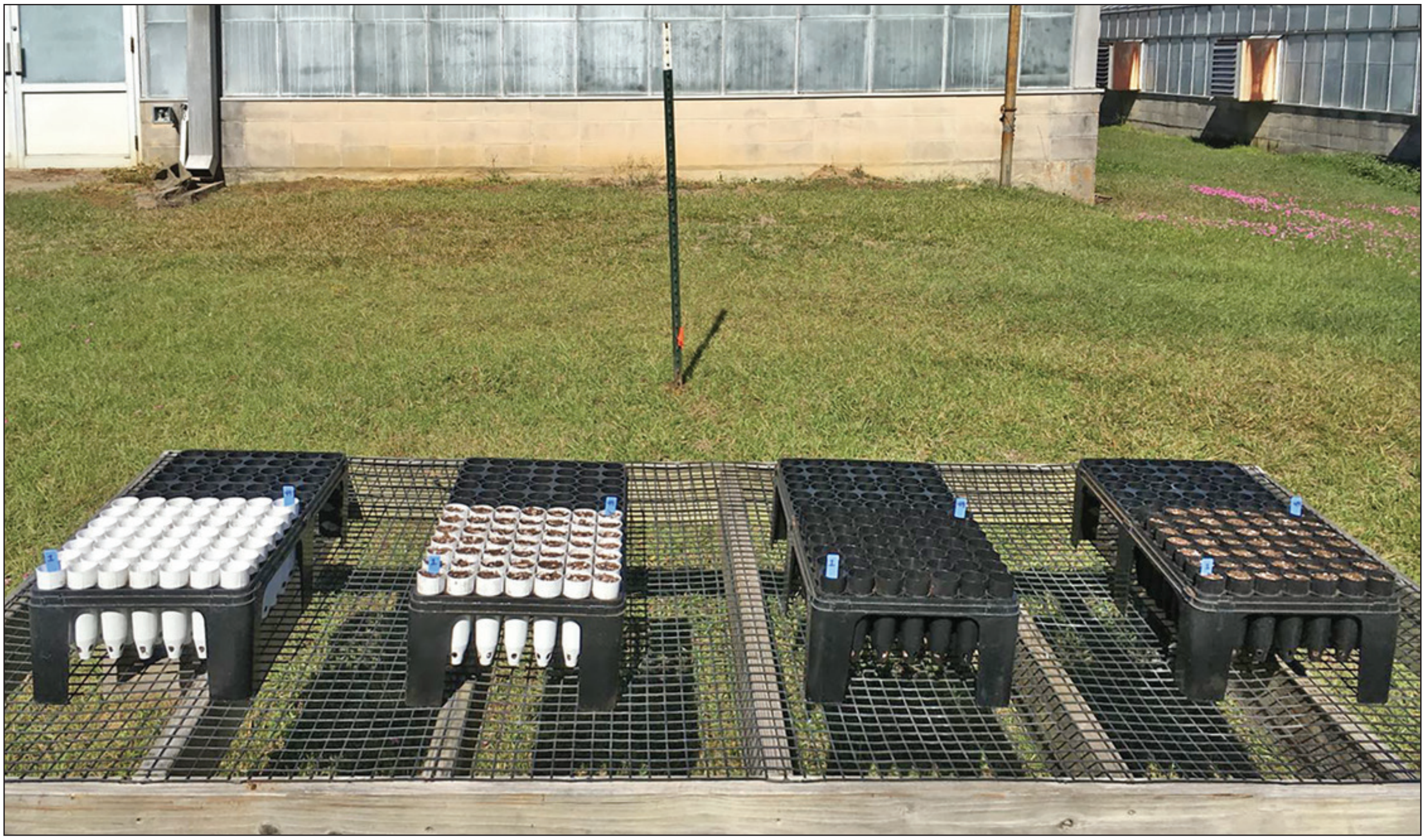

Figure 4. Trial One was set up in a randomized complete block of trays set out on a nursery table. (Photo by Kelsey Shoemaker, 2020)

location (figure 4). Beginning on October 24, 2020, container cells were checked daily for 10 days to determine if seeds were present or consumed (figure 5). A seed was considered consumed if completely missing or if feeding was evident, such as seed castings remaining in the container (figure 6).

Figure 5. To assess avian herbivory, containers were checked daily for the presence or absence of seeds. (Photo by Paul Jackson, 2020)

Trial Two

Black IPL Rigi-Pots™ (IPL-110, 6.7 in^3 [110 cm^3] cells, Stuewe and Sons, Inc., Tangent, OR) were filled to operational levels with a Pro-Mix® growing medium on April 6, 2021 at Louisiana Tech University. Containers were sown singly with two seed lots of longleaf pine and three seed lots of loblolly pine for a total of five treatments in the trial. Longleaf pine seed lots were either collected from

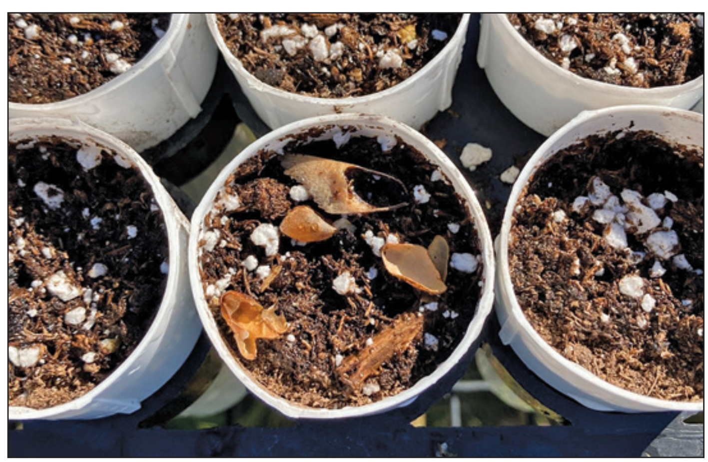

Figure 6. Seed castings left in the container cell are an indicator that seeds were foraged. (Photo by Paul Jackson, 2020)

a wild source and not genetically improved (low quality) or collected from a genetically improved family (high quality). Loblolly pine seed lots were either a C-grade, second-generation selection (low quality); an A-grade, second-generation selection (medium quality); or a controlled, mass-pollinated seed lot (high quality). Grades for the low- and medium-quality loblolly pine seed lots were assessed based on selection factors associated with tree volume, straightness, and forking potential.

Two geographic locations were selected: the area adjacent to a wooded fencerow (same as in Trial One) and a tree line near the edge of a pasture (32° 30' 49" N, 92° 39' 08" W). Each IPL Rigi-Pot™ container (45 cells) served as a replication, and there were 4 containers per treatment at each location for a total of 40 containers, 720 longleaf pine seeds, and 1,080 loblolly pine seeds used in the trial. Trays were set out in a completely randomized block design on four nursery tables at each location (figure 7). Similar to Trial One, container cells were checked to determine if seeds were present or consumed during a 15-day period.

Avian herbivory was observed at each site using passive, infrared, motion-activated trail cameras throughout the trial. Afterwards, photographs were reviewed for avian herbivorous events. Documented data from these events included avian species, sex (if identifiable), the seed lot at which the bird was observed, site, date, and time. To compare avian species photographed consuming seeds to all species in the area, SM4 Song Meters (Wildlife Acoustics, Inc., Maynard, MA) were placed at each site (figure 8). These devices were set to record during the peak of daily avian activity—approximately 10 minutes before and 10 minutes after sunrise each morning (Robbins 1981) during data collection. Avian species heard singing or calling during each 20-minute recording period were documented.

Data Analyses

For both trials, an analysis of variance was conducted using a General Linear Model, and multiple comparisons of means were conducted using Duncan's Multiple Range Test using SAS statistical software (9th ed., SAS Institute, Cary, NC). Analyses were conducted on data collected every 5 days during each trial.

Figure 7. For Trial Two, tables and containers were arranged in a randomized complete block as shown at the pasture edge site. (Photo by Kelsey Shoemaker, 2021)

Figure 8. The SM4 song meter (left) and a motion-activated trail camera (right) were used to document avian herbivory in Trial Two. (Photo by Heidi Adams, 2021).

Results

Trial One

At the open field site, a total of 24 of the 588 longleaf pine seeds were completely missing from cells regardless of medium level or container color, and another 19 seeds were located in nearby cells or between cells in the tray. We speculate that these seeds were displaced by wind or rain because seed castings or evidence of feeding was not apparent.

After 5 days of observation at the wooded fencerow site, cells filled with medium to operational levels endured more herbivory than those filled to two-thirds capacity. By day 10, herbivory of seeds was similar between medium levels. Container color had no significant effect on seed herbivory (figure 9).

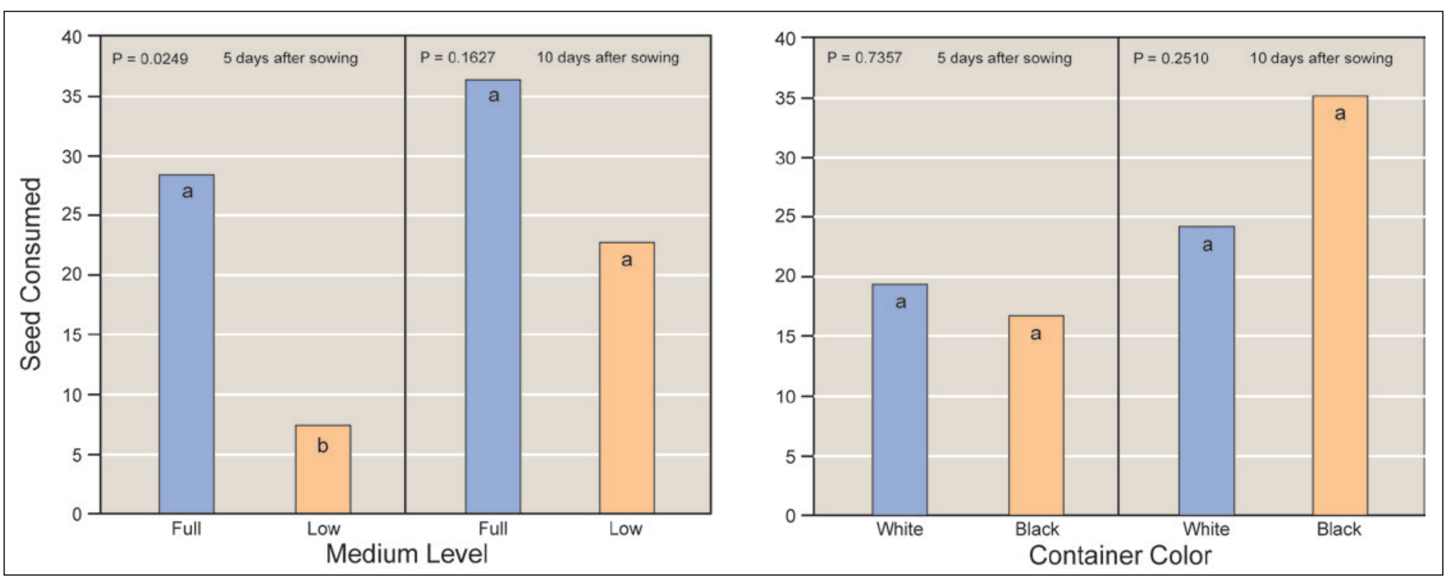

Figure 9. The average number of longleaf pine seeds consumed at the wooded fencerow site were compared 5 and 10 days after sowing (a) between containers filled to operational levels or to two-thirds capacity and (b) between black or white container cells. After 10 days, avian herbivory did not differ by either treatment. Means within each treatment and evaluate date with the same letter are not significantly different based on Duncan's Multiple Range Test.

Trial Two

At the wooded fencerow site, seed herbivory began immediately. Two days after sowing (DAS), there seemed to be a preference for high- and medium-grade loblolly pine seed compared with other seed lots (table 1). By day 4, almost all seeds were consumed regardless of pine species or seed grade.

At the pasture edge site, less than 5 seeds were consumed after 5 days regardless of species or seed grade (table 2). By day 10, herbivory of loblolly pine seeds was more than double that of longleaf pine but not statistically different. Herbivory appeared to be indiscriminate tray to tray. For instance, seeds in one high-grade longleaf pine tray and one high-grade loblolly pine tray were completely consumed by day 10, while no seeds were consumed in other trays of the same seed grade and pine species. By day 15, almost all seeds were consumed regardless of pine species or seed grade.

Table 1. Average number of loblolly pine and longleaf pine seeds of various genetic quality consumed in Trial Two at the wooded fencerow site 2 and 4 days after sowing (DAS).

Pine Species	Seed Grade	Average # seeds consumed	
		2 DAS	4 DAS
loblolly	high	31.0	44.0
	medium	33.5	41.5
	low	18.8	44.5
longleaf	high	10.8	43.8
	low	18.5	44.8
P-value		0.5632	0.8449

Table 2. Average number of loblolly pine and longleaf pine seeds of various genetic quality consumed in Trial Two at the pasture edge site 5, 10, and 15 days after sowing (DAS).

Pine Species	Seed Grade	Average # seeds consumed		
		5 DAS	10 DAS	15 DAS
loblolly	high	1.5	33.8	44.5
	medium	3.0	44.0	45.0
	low	0.5	32.5	44.5
longleaf	high	1.0	16.5	43.5
	low	1.0	16.8	43.8
P-value		0.2095	0.3658	0.2883

During the trial, there were 13 audio recordings from the wooded fencerow site and 19 audio recordings from the pasture edge site. Based on a review of these recordings, 30 total avian species were in the vicinity of the trial locations: 22 at the wooded fencerow site, 25 at the pasture edge site, and 17 at both sites (table 3). Northern cardinals (*Cardinalis cardinalis*) accounted for 95 percent of the photographed herbivory events at the wooded fencerow site and 100 percent at the pasture edge site (figure 10). The remaining 5 percent of photographed herbivory events at the wooded fencerow site were blue jays (*Cyanocitta cristata*).

Nine mammalian species were also photographed in the vicinity of the trial sites: eastern cottontail (*Sylvilagus floridanus*), feral cat (*Felis catus*), gray fox (*Urocyon cinereoargenteus*), nine-banded armadillo (*Dasypus novemcinctus*), North American raccoon (*Procyon lotor*), red fox (*Vulpes vulpes*), striped skunk (*Mephitis mephitis*), Virginia opossum (*Didelphis virginiana*), and white-tailed deer (*Odocoileus virginianus*). None of these mammals, however, disturbed the seeds.

Discussion

In Trial One, fewer longleaf pine seeds were consumed from container cells filled to two-thirds capacity. However, herbivory remained an issue as seeds sown at lower medium depths were eventually consumed. Even if this treatment had shown more promise in preventing herbivory, the root plugs that would develop in the container cavities with a smaller volume of medium may not have met nursery quality standards for good outplanting performance. Container color was not a significant factor in deterring herbivory even though more

Figure 10. A pair of northern cardinals were captured by a trail camera foraging on seeds at the wooded fencerow site in Trial Two. (Photo courtesy of Heidi Adams 2021)

Table 3. Number of avian herbivory events and audio detections at both Trial Two locations by species.

Avian species	Wooded fencerow		Pasture edge	
	Herbivory events	Audio detections	Herbivory events	Audio detections
Northern cardinal (*Cardinalis cardinalis*)	93	13	89	19
Blue jay (*Cyanocitta cristata*)	5	9	0	12
American crow (*Corvus brachyrhynchos*)	0	12	0	17
Carolina chickadee (*Poecile carolinensis*)	0	11	0	17
Carolina wren (*Thryothorus ludovicianus*)	0	10	0	13
Red-bellied woodpecker (*Melanerpes carolinus*)	0	9	0	10
Brown thrasher (*Toxostoma rufum*)	0	10	0	5
Tufted titmouse (*Baeolophus bicolor*)	0	8	0	7
White-eyed vireo (*Vireo griseus*)	0	2	0	13
Ruby-throated hummingbird (*Archilochus colubris*)	0	7	0	6
White-throated sparrow (*Zonotrichia albicollis*)	0	9	0	4
Common grackle (*Quiscalus quiscula*)	0	10	0	1
Northern mockingbird (*Mimus polyglottos*)	0	10	0	1
Brown-headed cowbird (*Molothrus ater*)	0	0	0	8
Blue-gray gnatcatcher (*Polioptila caerulea*)	0	0	0	7
American robin (*Turdus migratorius*)	0	5	0	1
Red-winged blackbird (*Agelaius phoeniceus*)	0	4	0	2
Pine warbler (*Setophaga pinus*)	0	5	0	0
Wood thrush (*Hylocichla mustelina*)	0	2	0	3
Eastern phoebe (*Sayornis phoebe*)	0	0	0	4
Fish crow (*Corvus ossifragus*)	0	1	0	3
Red-tailed hawk (*Buteo jamaicensis*)	0	0	0	4
Cedar waxwing (*Bombycilla cedrorum*)	0	2	0	0
Indigo bunting *(Passerina cyanea*)	0	2	0	0
Killdeer (*Charadrius vociferus*)	0	0	0	2
Red-eyed vireo (*Vireo olivaceus*)	0	0	0	2
Eastern bluebird (*Sialia sialis*)	0	1	0	0
Eastern meadowlark (*Sturnella magna*)	0	0	0	1
Eastern wood-pewee (*Contopus virens*)	0	0	0	1
Mourning dove (*Zenaida macroura*)	0	1	0	0

seeds remained in white cells. Because seedlings are typically grown in black containers across the South, changing to white containers would not be economical unless seed herbivory had been dramatically different between black and white containers.

The idea of testing the potential for herbivory among seed lots of various genetic levels came from previous observations in an operational nursery. In Trial Two, almost all seeds were consumed regardless of seed grade or pine species. This herbivory occurred during what would be a normal 2-week germination window in the nursery. This trial differed, however, from operational procedure because multiple seed grades were sown in close proximity on the same tables. Seed lots of various genetic qualities are typically sown together in large compartments throughout the nursery. Therefore, if birds prefer seeds based on genetic quality, this behavior may be better observed in areas of the nursery where seeds of the same genetic grade are sown together in high quantities.

During Trial One, only 43 of 588 seeds were missing or found outside of the containers at the open field site compared with 356 of 588 seeds consumed at the wooded fencerow site. This disparity is likely due to edge effects at the wooded fencerow site. Northern cardinals were photographed during Trial Two at the wooded fencerow site and observed on containers from afar during Trial One. These birds and other passerines are known to be prey to a variety of predators and likely avoided the open field area. Several potential predators photographed or recorded during the trial included feral cats, gray and red fox, and red-tailed hawks (*Buteo jamaicensis*). Foraging in an exposed area like the open field site exposes small birds to greater predation risks. For example, Horn et al. (2003) determined the proximity to cover was inversely related to the number of birds visiting a bird feeder. Similarly, Kross et al. (2020) discovered avian damage to sunflower (*Helianthus annuus* L.) was higher at a field's edge compared with 160 ft (49 m) or more from the edge.

Northern cardinals are opportunistic granivores, feeding on seeds and other vegetative matter for most of the year (Halkin and Linville 1999, Hamel 1992). The pattern observed in Trial One fits an opportunistic approach as foraging increased in cavities with less medium after the more accessible seeds sown in operationally filled cavities were no longer available. In the fall, these birds will feed on fruit and insects during their pre-basic molt, acquiring carotenoids that will turn their developing plumage red (Halkin and Linville 1999). Northern cardinals tend to be solitary most of the year, but will form a monogamous pair bond during the reproductive season. At this time, the pair will be very territorial (Halkin and Linville 1999). This territory can range between 0.5 to 6.5 ac (0.2 to 2.6 ha) depending on food resource availability (Halkin and Linville 1999).

Northern cardinals have a good memory for food acquisition. Just as in mammals, the avian hippocampus functions in learning and memory. In a study evaluating the volume of the avian hippocampus, for instance, northern cardinals had a greater hippocampal volume-to-body mass ratio than 18 of the 22 other avian species examined (Sherry et al. 1989). This anatomical feature allows northern cardinals to better remember food resources, such as the seedling containers used in this study. Herbivory events at the wooded fencerow site during Trial Two began much sooner than at the pasture edge site. The likely reason for this is the wooded fencerow site was used previously during Trial One, and the northern cardinals recognized the available food source shortly after seeds were placed at the site. Foraging began there almost immediately, and there was no preference for a certain pine species or seed grade.

Several tactics may be used to deter northern cardinals from feeding on pine seeds in the nursery, though it is important to note that one single method may not be entirely effective. One tactic is to establish decoy food plots or feeding stations around the perimeter of container sets, particularly in areas in close proximity to habitat edges (e.g., wooded fencerows). This technique is not used to sustain the northern cardinal population but provides a food source more appealing than pine seeds, such as bird feeders filled with black-oil sunflower seeds. This tactic has been effective in other scenarios, including the reduction of blackbird (Icteridae) damage to sunflower crops (Linz et al. 2011, 2015).

The use of avicides is also a common technique to reduce avian damage to crops. Anthraquinone has been used to reduce dickcissel (*Spiza americana*) damage to rice (*Oryza sativa* L.; Avery et al. 2001) and sandhill crane (*Antigone canadensis*) damage to corn (*Zea mays* L.; Barzen and Ballinger 2018). Methyl anthranilate was effective in reducing avian damage to Colorado corn crops, North Dakota sunflower crops, and Washington State cherry (*Prunus avium* L.) crops (Askham 2000). Caffeine has also been used as a deterrent, contributing to a reduction in rice consumption by red-winged blackbirds (*Agelaius phoeniceus*) in Louisiana (Avery et al. 2005). Before using avicides to treat pine seeds, a trial test should be conducted to evaluate product efficacy and environmental safety.

Other methods to manage avian herbivory include auditory (e.g., propane cannons) and visual (e.g., reflective ribbons or mirrors, drones) deterrents (Dolbeer 1990, Rivadeneira et al. 2018). Lethal measures to address avian herbivory of pine seeds should be avoided as northern cardinals—along with many other avian species—are protected under the Federal Migratory Bird Treaty Act of 1918 (16 U.S.C. 703–712, MBTA). The list of all species protected under the MBTA can be found in the Code of Federal Regulations under Title 50 Part 10.13. Additionally, this tactic has several drawbacks, including low acceptance among the general public, low cost-effectiveness, and the risk of species misidentification, putting non-target species at risk (Linz et al. 2015).

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