AMERICAN ELM (*ULMUS AMERICANA*) IN RESTORATION PLANTINGS: A REVIEW

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Abstract.—The development of disease-tolerant American elm (*Ulmus americana*) trees has led to a need for reintroduction and restoration methods for the species. Here we review the current state of experimental work to inform reintroduction biology and restoration ecology of American elm. Much of this work is ongoing, and within several years the results will provide guidance for managers to use the species in restoration plantings. We identify additional research needs and opportunities to consider in development of American elm restoration strategies.

Introduction

Pests and pathogens have caused massive mortality events in multiple tree species around the world. The American chestnut (*Castanea dentata* [Marsh.] Borkh.), American beech (*Fagus grandifolia* Ehrh.), hemlock (*Tsuga canadensis* L. Carr.), butternut (*Juglans cinerea* L.), North American ash species (*Fraxinus* spp.), and American elm (*Ulmus americana* L.) are iconic species of the forests of the eastern and midwestern United States whose populations have been greatly affected (Wheeler et al. 2015). As new exotic insects and diseases continue to emerge through accidental introductions, additional tree species will be threatened. As trees succumb to these threats, the ecosystem services provided by forests will also be affected.

To respond to these threats, government, university, and nonprofit groups have led efforts to select and breed trees with resistance or tolerance to pests and pathogens (reviewed in Wheeler et al. 2015). Programs for different tree species are in varying stages of development and progress, depending on how long the effort has been ongoing and the particular challenges of the system. These tree improvement programs are critical to species adaptation to long-term threats to forest health (Wheeler et al. 2015). Many efforts share the goal of producing a genetically diverse suite of trees with tolerance to specific pests or pathogens, which then may be used in plantings in urban and natural areas. Restoration strategies and silvicultural requirements of the species will need to be determined in order to successfully establish founder populations of these species in natural areas. Once genetically diverse material and planting strategies are developed, operational reintroduction paired in some cases with ecosystem restoration should occur.

As efforts to restore American elm move forward, reintroduction strategies and silvicultural requirements are being tested. This review summarizes the ongoing efforts in testing restoration strategies for American elm and identifies gaps and opportunities in the restoration effort. The program to restore American chestnut provides a useful comparison for American elm restoration, as the work on American chestnut is in later stages. As the goal of developing blight-resistant American chestnut seedlings neared achievement (Steiner et al. 2017), work to understand the silvicultural requirements of the species and develop management strategies was initiated to improve reintroduction success.

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The biological characteristics of American chestnut, including response to light, soil nutrients and moisture, and competition are being considered with respect to operational planting strategies (Jacobs 2007). Knowledge of these species characteristics are necessary to select appropriate silvicultural and site preparation strategies (Clark et al. 2014). Test plantings of American chestnut have examined different planting methods and stock types in different climatic regions (Clark et al. 2014). These experiments have been valuable in identifying barriers to survival and establishment, primarily involving white-tailed deer (*Odocoileus virginianus*) browsing, infection by the root-rot pathogen (*Phytophthora cinnamomi*), and insect damage, but also including damage from *Pythium* root rot and drought. Planting high quality stock may be an important approach for overcoming these barriers (Clark et al. 2014). Researchers have identified pathways by which abiotic environmental conditions will affect biotic factors, including deer, disease, and insect damage, which will interact with the genetic makeup and the quality of tree seedlings to ultimately affect performance in the field (Clark et al. 2014).

American chestnut researchers also took a critical look at their program and identified gaps, opportunities, and challenges encountered by the restoration effort. Consideration of both the social and ecological contexts of programs is also important (Jacobs 2007, Jacobs et al. 2013). Understanding the social context guides the formulation of restoration planting goals and allows identification of policy, economic, or social barriers or constraints. Additional gaps in the ecological context, including seed zone testing, the incorporation of different sources of resistance, and combating invasive exotic insects were identified as areas for additional study (Clark et al. 2014). The long-term impacts and dynamics of reintroduction on forest ecosystems were considered, including questions about how plantings including American chestnut would be managed over time and how the species may spread from plantings (Jacobs 2007). Potential future challenges, including deployment strategies, were identified (Jacobs 2007).

Natural populations of American elm were greatly reduced due to the invasive fungal pathogens *Ophiostoma ulmi* and *O. novo-ulmi* that cause Dutch elm disease (DED), causing shifts in species composition within forest ecosystems (Barnes 1976). Indeed, DED remains an important force causing mortality of larger elms (Marks and Canham 2015). As a result, the role of American elm as a canopy species has been greatly reduced in forest ecosystems, and only smaller elms are commonly found (Marks 2017, Marks and Canham 2015). The development of DED-tolerant American elm selections, and the continued work to produce additional DED-tolerant selections, has generated considerable interest in the restoration of American elm. Research to better understand the ecology of the DED pathogen, tolerance of American elm selections, and effects of other serious pathogens (including elm yellows) is foundational to successful restoration plantings. The ultimate goal is to generate a diverse group of American elm selections with durable tolerance to disease. In addition to producing disease tolerant plants, researchers are testing restoration uses and methods for American elm. The combination of the appropriate planting stock and the knowledge of how to best use it will provide useful tools for managers.

Here we review the current experimental work both on reintroduction methods for American elm and on the use of American elm as part of a restoration strategy. The goals of reintroduction biology and restoration ecology differ: while reintroduction focuses on a single species, restoration focuses on the ecosystem. Both are important components for the success of the American elm program. Much of this work is in progress and has not yet produced results, however, this review of current work will facilitate coordination and identify areas where further work is needed. The results of these experiments will inform managers interested in the use of American elm in restoration plantings.

Reintroduction Methods for the American Elm

Very little planting of American elm has occurred in natural systems in the last century. Thus, testing of restoration methods for DED-tolerant American elm is necessary to generate best practices for successful survival and growth and to understand any constraints on its use. Testing planting methods with bare-root and containerized stock, understanding site adaptation, and addressing other potential disease issues are important steps in identifying how to best use American elm in restoration plantings.

Operational planting methods with bare root seedlings are being tested in a study spanning multiple states. Over 4000 bare-root seedlings were planted on six riparian and floodplain forest sites to compare the performance of planted elms with other planted tree species in different site types (Haugen et al. 2017). Survival ranged from 37 to 100 percent, with herbivory by deer as a major factor limiting success. More labor-intensive methods of planting containerized stock are being tested in multiple research sites (Slavicek 2013), including floodplain forests of Ohio (Knight et al. 2012). When competing vegetation was removed at planting and controlled through mulching, large containerized trees had excellent survival and rapid growth (Slavicek 2013). The floodplain experiment showed greater survival of larger containerized trees compared to smaller containerized stock, as well as benefits of caging trees to prevent deer browsing.[2]

It is pointless to plant trees in sites where they are unlikely to survive. Experiments have been initiated to address components of site adaptation of DED-tolerant American elms, including cold tolerance, flood tolerance, and shade tolerance. Cold tolerance is being addressed in multiple experiments. Progeny from crosses between DED-tolerant American elms and Chippewa National Forest survivor trees were planted at multiple sites at the Chippewa National Forest and are being tracked for growth and survival over time (Slavicek and Knight 2012, Slavicek et al. 2009). While some progeny are growing well and demonstrating sufficient cold hardiness in this harsh environment, others regularly die back during winter months, suggesting that they lack adequate hardiness.[3] Similarly, offspring from DED-tolerant and survivor elm crosses in New England have been planted at four field trial sites in northeastern Vermont.[4] These trees will continue to be tracked for winter shoot injury and will be inoculated with DED pathogens to test for DED tolerance; the trees exhibiting both DED tolerance and ample cold hardiness will be kept in these sites to serve as a seed orchard. A second experiment in northern Wisconsin (which is testing progeny from open-pollinated DED-tolerant mother trees, a known DED-tolerant selection [Princeton], and locally-collected seeds), will also yield insights into survival of elms in a northern climate.[5] A third experiment to test cold hardiness of known DED-tolerant selections is also underway to test for differences in shoot cold tolerance among maternal lines of DED resistant stock and native paternal lines from different

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plant cold hardiness zones.[6] Genetic lines with consistently greater cold tolerance could be preferentially planted in northern restoration efforts.

Other components of site adaptation, including flood tolerance, shade tolerance, and effects of competing vegetation, are also important to understand. Low seedling survival on a site with heavy flooding during the growing season (Haugen et al. 2017) raises the concern that it may be difficult to establish American elm on sites that are extremely wet. Minor variations in elevation among floodplain ecosystems can lead to very different flooding intensity experienced by planted tree seedlings. The underplanting of tree seedlings prior to harvest or mortality of canopy trees can be a successful method to establish understory trees poised to grow rapidly and fill in canopy gaps, but this strategy will only be successful if the planted seedlings are able to tolerate shading before the canopy is removed. Silvicultural guidelines list American elm as "intermediate" in shade tolerance (Myers and Buchman 1984). An experiment in floodplain forests in Ohio is examining both the flood and shade tolerance of planted American elm seedlings by testing the effects of microsite elevation and canopy openness for each of over 1000 elm seedlings planted (Knight et al. 2012). Many seedlings survived extensive spring and fall flooding; the elevation data is still being analyzed. Shade tolerance data revealed excellent survival of planted trees across a range of microsite light environments and a surprising lack of effect from competition from invasive herbaceous plants.[2]

Planting strategies for American elm may also need to consider ways to avoid risks from root grafting. While DED-tolerant elms exhibit disease tolerance when infected via beetles or stem inoculations, it is unknown how they would perform if infected via root grafts. An experiment with paired elms was initiated in 2011 to understand the risks of root grafting.[2] Inoculations will take place in several years once the trees have grown larger and formed root grafts. Additional research to understand the prevalence of root grafting in natural systems may be useful in developing planting strategies that mitigate associated risks.

It is also important to consider the "unknown unknowns"—those factors that have not yet been identified as being problematic. Two efforts have involved planting elms in many sites and tracking the trees over time. The National Elm Trials include both DED-tolerant American elm cultivars and other elm species and hybrids planted in 16 states to study growth, stress and pest resistance, and horticultural performance (Colorado State University, n.d.). Sentinel restoration sites, consisting of plantings of multiple DED-tolerant American elm selections in eight locations in four states, are being monitored to identify additional factors that may impact the success of elm restoration plantings (Slavicek 2007, 2013; Slavicek et al. 2005). These plantings may serve as an "early warning" system to identify additional pathogens of concern so that tolerance to these threats can be incorporated into the breeding program. So far, the elms are growing well at most sites. An unknown factor that was identified at one site in Ohio is a wood wasp that appears to have caused three trees to die.[3] In some Minnesota and Iowa sites, the heavy sod appears to lead to slow growth rates and high mortality of planted trees due to competition for moisture and root feeding by rodents (presumed to be the plains pocket gopher, *Geomys bursarius*).[5] Elm regeneration on the sentinel sites will be tested to understand how DED-tolerant elm may spread from plantings into surrounding landscapes.

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American Elm as a Component of Restoration Strategies

Eastern forests are impacted by many forms of disturbance, including introduced pests and pathogens, invasive plants, increases in white-tailed deer, land clearing, grazing, and climate change. American elm may be used in restoration plantings to respond to natural and anthropogenic disturbance. Its versatility and ability to thrive in a wide variety of conditions make it a useful component in both urban and natural plantings. It is one of the best species for supporting a diverse array of insect herbivores, which then support higher trophic levels including birds (Tallamy 2009). Ongoing studies are testing the use of DED-tolerant American elm in restoration plantings to address grazing in riparian areas, mineland restoration, and to compensate for ash mortality following infestation by the emerald ash borer (EAB; *Agrilus planipennis*).

Ash (*Fraxinus* spp.) filled in gaps left by dying American elm trees in many riparian and swamp areas (Barnes 1976). EAB, an invasive insect pest, now threatens ash trees in these ecosystems. In areas where ash trees are abundant, and few other trees are present in the understory or midstory, underplanting before ash mortality or replanting after ash mortality may be necessary to preserve hydric forests in some areas (Iverson et al. 2016). Multiple studies are testing progeny from DED-tolerant American elms as components of plantings in ash ecosystems to respond to the threat of EAB. A study in northern Minnesota is testing American elm and other native tree species planted in black ash wet forest ecosystems (Looney et al. 2015). Four overstory tree treatments simulated different management options: control, clearcut, group selection, and girdling to simulate mortality from EAB. A second study in riparian green ash forests in Ohio is testing underplanting of American elm and other tree species in forests affected by EAB. Early data indicate good initial survival of American elm in both studies, ranging from 32 percent to 93 percent across different overstory treatments in the Minnesota study, and 50 to 79 percent across different light levels in the Ohio study (Looney et al. 2015; Knight, unpublished data[2]).

Grazing in riparian areas can cause soil compaction, erosion, nutrient runoff, and impaired water quality (Kauffman and Krueger 1984). Limiting cattle access to sensitive riparian areas and restoring streamside habitat are strategies used to address these problems. Restoration plantings installed in 2015 at the Finger Lakes National Forest included DED-tolerant American elm selections and other native tree and shrub species that will test effects on aboveground and belowground ecosystem function.[7]

The Nature Conservancy's Connecticut River Program has planted 840 disease-tolerant American elm cultivars at a total of 33 sites in Vermont, Connecticut, Massachusetts, and New Hampshire between 2010 and 2016, with more planned for the future. These plantings include multiple DED-tolerant selections. Survival in these plantings has varied considerably from 30 to 100 percent depending on site factors such as ice flows, height and density of competing vegetation, climate, damage from voles, deer browsing, and others.[4]

American elm, along with American chestnut, is also being used in restoration plantings on reclaimed mine lands (Adams et al. 2015). Compacted and altered soils, coupled with invasive plants, present challenges in the restoration of these areas back to native forest. Additional plantings of American elm in a variety of contexts and ecosystem types suggest potential for its use in many situations. However, many plantings do not include regular data collection

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or experimental design to test specific hypotheses, and an inconsistency in data collection methods among researchers and across experiments hampers generalized data interpretation and synthesis. Follow-up data to understand the factors affecting the survival and growth of planted elm trees, as well as the success of achieving restoration goals such as ecosystem structure and function, are needed.

Discussion

Multiple research projects are underway to develop restoration methods for American elm and to develop recommendations for the use of American elm as part of a planting strategy to respond to disturbance. While little is published at the current time because many of these efforts are just beginning, within the next 5 to 10 years a wealth of information should be available. Guidelines regarding cold tolerance, flood tolerance, shade tolerance, response to competing vegetation, and root grafting will allow managers to maximize survival of planted elm trees. Experimental results from testing American elm as a component of a restoration strategy will also show how it may serve as a useful element to restore ecosystems after disturbance. One challenge in reintroduction is that successful guidelines may vary depending on specific situations and site characteristics such as forest type, competing species, local hydrology, etc. No protocol will work in all situations and preclude the need for adaptive management strategies. Managers will be able to use the DED-tolerant American elm selections and seeds, coupled with information from this research, as tools to restore forest ecosystems.

While the ongoing work will provide considerable information to guide restoration plantings of American elm, gaps in the research do exist and provide opportunities to proactively address potential challenges. As with American chestnut, both social and ecological contexts should be considered to guide American elm restoration strategies. Additional consideration of the social context will guide the formulation of goals, addressing questions such as the public perception and value of American elm in urban and forest areas, forest manager goals for incorporation of American elm, and municipal requirements for urban trees. There are also opportunities for expansion of ecological research. Because American elm has such a wide native range, plantings in additional parts of the range may be useful to identify potential problems (e.g., the sentinel sites) or test performance on different soil types and in different climates. Experiments to identify interactions among elm genetics and abiotic and biotic environmental variables may guide silvicultural, site preparation, and planting strategies. The long-term implications of American elm in restoration should be considered as well as the long-term durability of resistance to disease. Understanding the potential for the spread of DED-tolerant genes as planted trees reproduce and cross with local elms will provide researchers information needed to design landscape-scale strategies. Ultimately, a critical examination of the implications of different restoration strategies from social, policy, and ecological viewpoints will allow the program to take a more strategic approach toward the restoration of American elm.

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