Embedding Research Into Restoration: A Case Study Illustrating the Value of Applied-Academic Partnerships

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Abstract

Conservationists are increasingly dependent on restoration as a means of expanding natural areas as the availability of natural habitats for preservation declines. The uptick in number and scale of restoration projects provides an opportunity to learn about how to restore habitats most effectively. This information is especially valuable in an era of climate change where restoration ecologists and foresters are already implementing mitigation strategies, such as assisted migration. Here, we advocate for the establishment of applied-academic partnerships that can be used to glean the most information possible from revegetation projects. Our work was conducted in the context of assisted migration into a boreal forest that is already under decline with climate change and is a model for achieving both applied and academic goals. We outline the value of collaborative initiatives that create translational research with real-world impact. We also underscore key steps that can lead to productive partnerships that achieve both restoration and research goals. This paper was presented at the Joint Annual Meeting of the Northeast Forest and Conservation Association, the Southern Forest Nursery Association, and the Intertribal Nursery Council (Walker, MN, July 31–August 3, 2017).

Introduction

As the availability of intact, native habitats declines, conservationists are increasingly dependent on restoration as a means of expanding the number and size of natural areas (Maunder 1992, Miller and Hobbs 2007). Habitat restoration typically starts with reestablishing the vegetation by either planting new populations or augmenting existing populations (Temperton 2004). Although plant establishment is an essential first step, the success rate of these efforts is rarely known (Deredec and Courchamp 2007), except for some cases of endangered plant species reintroductions (e.g., Bottin et al. 2007). This reality is underscored in a survey of the plant restoration literature showing that only 14 percent of studies reported restoration success after seeding or planting (Ruiz-Jaen and Mitchell Aide 2005). Moreover, it is possible that this scant information is biased toward positive results (Fanelli 2010). Based on the published studies, the success rate of plant species introductions is 78 percent, which contrasts sharply with a success rate of 33 percent based on a survey of restoration practitioners (Godefroid et al. 2011). Although additional information on success rates may be available in the gray literature, this body of work is not widely accessible. Overall, the collection, analysis, and publication of lessons learned from successful and unsuccessful revegetation approaches is the exception rather than the rule. To address this gap in our understanding, we suggest the establishment of translational ecology partnerships (Enquist et al. 2017) to maximize the learning potential from habitat restoration and management.

The coupling of methodological and outcome information is critical both to advancing the science of restoration ecology and identifying ways to improve restoration success in the establishment of functional communities. Although previous papers (Menges 2008) and publications from restoration organizations (McDonald et al. 2016) have outlined best practices for evaluating restoration success, these methods are rarely implemented, and, when they are, assessments are typically based on few metrics (Ruiz-Jaen and Mitchell Aide 2005; see also Guerrant and Kaye 2007). Valid reasons exist for this lack of follow-through. For example, restoration projects are rarely active for more than 5 years (Ruiz-Jaen and Mitchell Aide 2005), which may be a shorter timeframe than is necessary to collect relevant data, especially for long-lived species. Financial resources may also be a very real and severe limitation. Moreover, restoration practitioners may not have the time or incentive to collect, analyze, and publish this information. The situation, although understandable, amounts to a lost opportunity for learning and improving the practice of restoration.

It is especially important to track the success of restoration efforts in an era of climate change. Globally, mean land surface air temperatures have increased by a rate of 0.092 °C (0.17 °F) per decade from 1880 to 2012. These rates have increased dramatically during the past 30 years (0.26 °C [0.47 °F] per decade, 1979 to 2012; Field et al. 2014). Climate change is imposing a natural experiment on the world's biota that will require wild and restored populations of organisms to adapt to the changing environment or face extinction (Davis et al. 2005). Although plants and animals faced such environmental challenges during previous time points in Earth's history (Zachos et al. 2001), human-induced climate change is expected to occur faster than in the past (Pachauri et al. 2014). Moreover, rapid climate change is superimposed on other anthropogenic factors that already imperil native organisms and have made restoration efforts necessary. Namely, wild and restored populations are often isolated in a matrix of altered habitat that may reduce the opportunity for range shifts. Populations may be cut off from input of novel genetic variation through pollen flow and seed dispersal that might promote adaptive responses (Kremer et al. 2012, Swindell and Bouzat 2006). For many species, contemporary populations are smaller than in the past, which may cause genetic diversity to be lost by drift and inbreeding and may increase susceptibility to extinction by stochastic environmental events (Heschel and Paige 1995). Habitat degradation may also facilitate invasion of exotic species that compete for resources and compound stress (Strauss et al. 2006). Furthermore, positive interactions between organisms (for example, between plants and pollinators) may be decoupled as species respond to climate change in different ways (McCarty 2001), which also threatens the long-term persistence of these populations. Thus, whether wild or restored, the long-term fate of populations will depend on a multiplicity of interacting factors that are rapidly changing in the Anthropocene (Smith and Zeder 2013).

If species cannot adapt to climate change rapidly enough, it may be necessary to manage populations as climate changes. One widely discussed approach is to move organisms with the band of climate to which they are adapted. This movement is often referred to as "assisted migration" (AM) (McLachlan et al. 2007). In concept, AM has been the subject of controversy and confusion in the published literature, sometimes meaning translocation outside of the current range and sometimes within the current range. In the context of our case study, we use the term "forestry-AM" (Pedlar et al. 2012) that generally involves common, widespread species and strives to sustain ecosystem productivity through the within-range movement of populations. Although academics have debated the relative risks and benefits of this climate mitigation approach (Hoegh-Guldberg et al. 2008, McLachlan et al. 2007, Pedlar et al. 2012, Richardson et al. 2009, Williams and Dumroese 2013), some restoration ecologists and forest managers are forging ahead and implementing AM because the impacts of climate change, such as the decline and loss of canopy tree species, is already evident. Given that AM is a bold and largely untested restoration concept, it is critical that its success or failure is monitored over time.

For all these reasons, the field of restoration ecology would benefit from monitoring projects and other formal scientific studies that help improve our understanding of methods that underpin restoration success in general and provide opportunities for scientifically rigorous tests of alternative strategies, like AM. Here, we report on a unique partnership between a conservation organization (The Nature Conservancy [TNC]) and a regional university (University of Minnesota Duluth [UMD]) that achieved dual objectives through collaboration. From a conservation perspective, the goal was to conduct AM in the declining boreal forests of northeastern Minnesota. From a research perspective, the goal was to formally study the efficacy of AM. Here, we discuss our project, "Adaptation in the Great North Woods." We emphasize the value added by joining resources and expertise in this collaborative project. We also provide suggestions on how to establish similar fruitful relationships between restoration practitioners, academics, and their students.

Case Study

Background

Our study was conducted within the southern boreal-north temperate forest transition zone in Minnesota with the boreal forest to the north, temperate hardwood-dominated forests to the south, and the prairie-forest ecotone to the west. At present, this region is dominated by boreal species at the southern edge of their ranges with relatively low abundance of temperate species close to their northern range limits. Here, climate has warmed substantially in recent decades but especially in northeastern Minnesota (+1.0 to 1.9 °C [+1.8 to 3.4 °F]), where it continues to warm more rapidly than other parts of the State (figure 1a). Already, boreal species are declining (Muilenburg and Herms 2012), and this trend is expected to continue in the future along with increases in temperate species, including oaks (*Quercus* spp.) and northern hardwood species (figure 2) (Duveneck et al. 2014). Temperate species are recruiting into these boreal forests, but few species, especially red maple (*Acer rubrum* L.) and sugar maple (*Acer saccharum* Marshall), dominate this expansion (Fisichelli et al. 2014, Ravenscroft et al. 2010). Forestry-AM may be especially valuable as a mechanism to enhance forest diversity in this context, especially during transitional periods when the effects of climate change on community composition already occur.

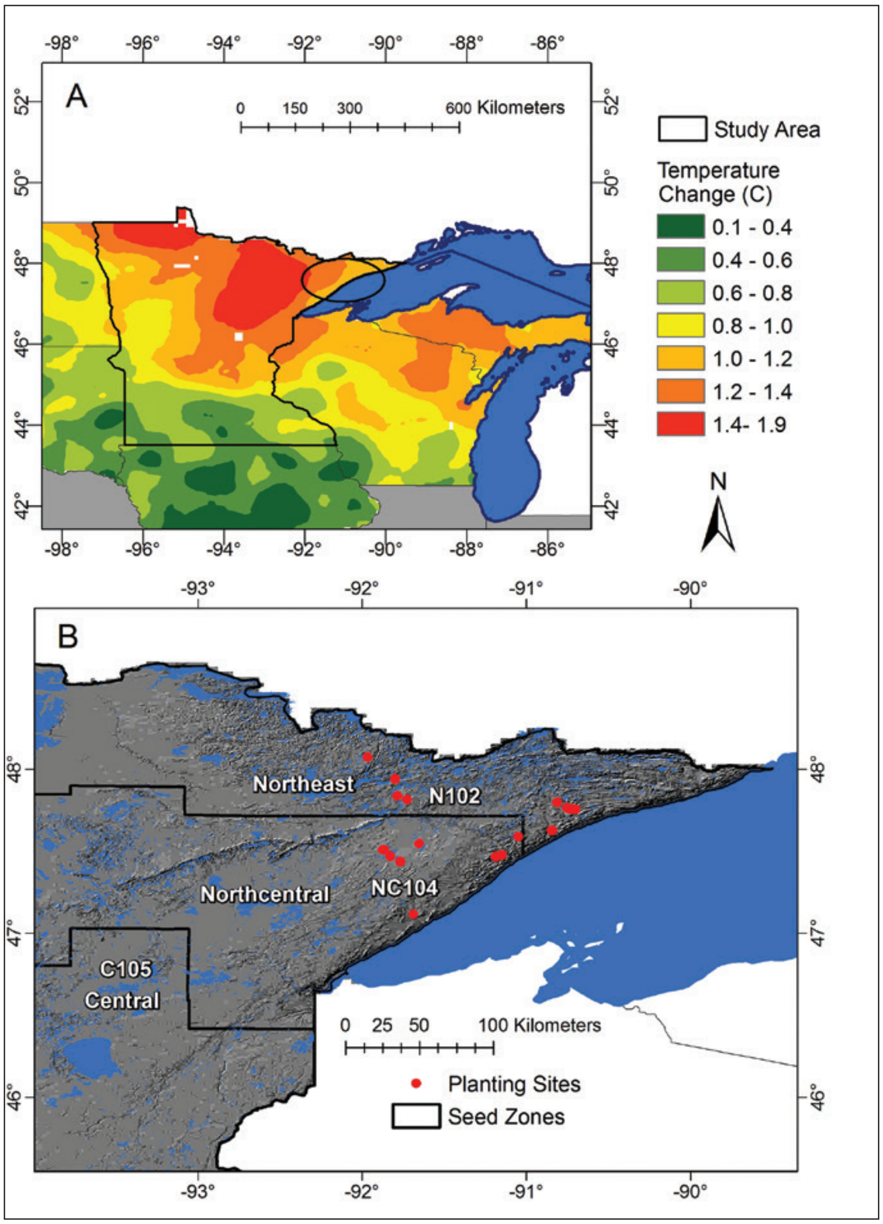

Figure 1. (a) Map of the upper Great Lakes region showing average temperature change (°C) for 1991 to 2012, relative to 1901 to 1960. (b) Seedlings of both species were obtained from the Minnesota Department of Natural Resources from two seed zones, central C105 and northcentral NC104. Seedlings in the research plots were planted with a randomized block design into 16 forest regeneration sites in northeastern Minnesota (red circles) in seed zones NC104 and N102.

Forests in northeastern Minnesota are entering this era of rapid climate change in a highly degraded state resulting from intensive logging and management for secondary growth (figure 3). Patch size is smaller and less variable than in the past (White and Host 2008). Intensive deer herbivory (White 2012) and invasions of exotic earthworms (Frelich et al. 2006, Hale et al. 2006) limit recruitment of tree seedlings. Homogenization and simplification of modern forests have led to associated declines in forest-dependent wildlife, most notably migratory songbirds (Sauer et al. 2017).

The cumulative loss of complexity has reduced the adaptive capacity of forests with the advent of emerging stressors, such as climate change (Duveneck et al. 2014). Today's forests are less resilient to disturbances, such as storm damage, and productivity is in decline, particularly on drier sites (Swanston et al. 2011). Northern forests, in particular, are especially vulnerable to climate change effects given the relatively narrow range of temperature and moisture conditions in which canopy tree species can persist. In this context, we conducted forestry-AM using deciduous species with more southern distributions and their populations from more southerly locations.

Project planning involved broad collaboration. In addition to the UMD and TNC, the project planning team included the Northern Institute of Applied Climate Science (U.S. Department of Agriculture, Forest Service), a national and regional leader in developing climate change vulnerability assessments and adaptation strategies for forests (Handler et al. 2014). We also worked with local land management agencies to locate appropriate planting sites and obtain needed permissions for implementing forestry-AM on their lands. These agencies include the Superior National Forest, Minnesota Department of Natural Resources (MNDNR), St. Louis County Land Department, and Lake County Land Department. Cooperation from these agencies was essential to successful implementation and subsequent research and monitoring.

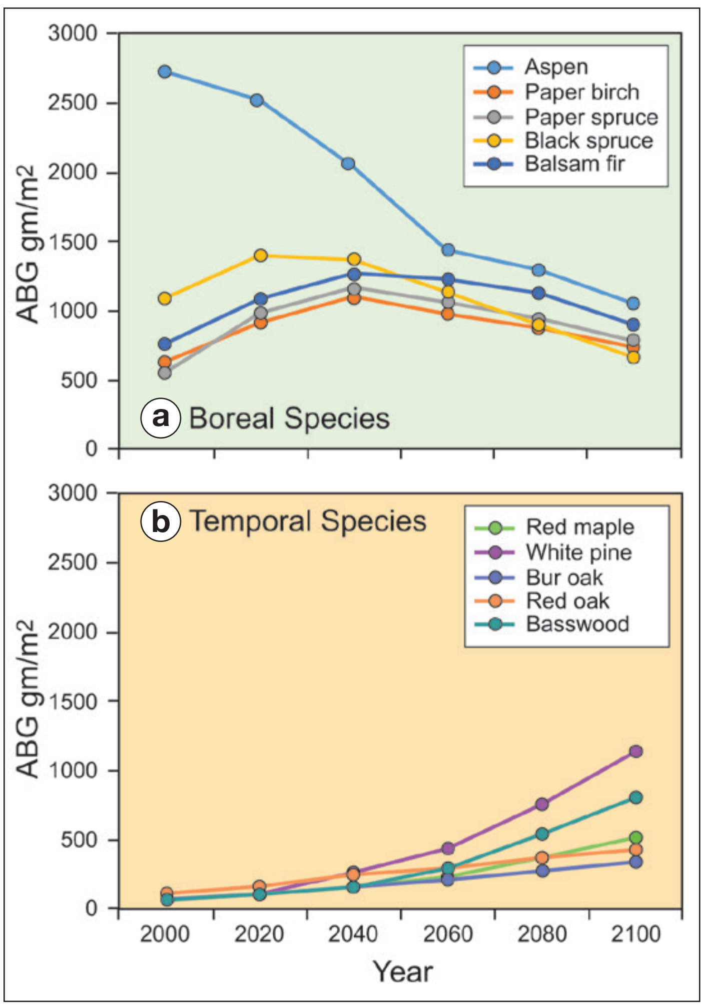

Figure 2. Landis II simulations showing changes in aboveground biomass for selected (a) boreal and (b) temperate species under a high emissions scenario (A1FI GFDL) expected by 2100. (Adapted from Duveneck et al. 2014)

Figure 3. A typical logged planting site in northern Minnesota. (Photo by J.R. Etterson, June 2013)

Plant Material

We chose to conduct this work using two oak species, bur oak (*Quercus macrocarpa* Michx.) and northern red oak (*Quercus rubra* L.). Although our study area occurs within the geographic ranges of both species, it is closer to each of their northern range limits. At present, bur oak and northern red oak are relatively minor components of the current forest composition in northeastern Minnesota. With climate change, however, both species are predicted to increase in abundance in the study area (Duveneck et al. 2014). Our rationale was that if seedlings were adapted to historical conditions, and this climate space has already shifted northerly with climate change, species with more southern distributions should thrive. Moreover, populations of these species from more southerly seed zones should also have higher survival and fitness when planted into a more northerly seed zone, where the climate more closely matches pre-industrial conditions.

Project Site and Study Design

In this project, we defined both applied and research goals (see Etterson et al. [n.d.] for a more complete description of the methods and results). Our applied goal was to conduct forestry-AM of two oak species using two seed sources. The planting sites are within two MNDNR seed zones adjacent to Lake Superior in north-central and extreme northern Minnesota (NC104 and N102, respectively; figure 1b). The sites are arrayed across approximately 1-degree latitude (47.12 to 48.07 units) and longitude (-91.97 to 90.70 units). A north-south temperature gradient spans the study area (average annual 2.98 to 3.92 °C [37.4 to 39.1 °F]) and an east-west precipitation gradient (average annual 722 to 841 mm [28.4 to 33.1 in]) (Gibson et al. 2002). Bur oak and northern red oak seedlings were obtained from the MNDNR Badoura State Forest Nursery (Akeley, MN) and originated from two seed zones—the north-central zone and a central zone (NC104 and C105, respectively; figure 1b).

In spring 2013, we planted approximately 72,000 2-year-old bur oak and 1-year-old northern red oak bareroot seedlings into 35 sites totaling about 810 ha (2000 ac) (figures 4 and 5). Trees were planted into plots that contained the same species and seed source and were protected from deer herbivory using mesh cages per individual tree (figure 6). The experimental design to evaluate the efficacy of forestry-AM was nested in the larger planting design and included 16 sites in a randomized complete block design (16 sites x 2 blocks per site x 2 species x 2 seed sources x 20 plants = 2,560 seedlings). Brush saw release treatments were implemented annually to reduce competition from understory vegetation.

Figure 5. Oak seedlings at the study sites were individually marked so they could be tracked over time. (Photo by J.R. Etterson, June 2013)

Figure 4. Chris Dunham (The Nature Conservancy) and Anna Reoh (Reoh Forestry) planting bareroot oak seedlings in a study to evaluate assisted migration. (Photo by J.R. Etterson, June 2013)

TNC staff and technicians and UMD students measured seedling survival, height, and diameter for 3 years, specific leaf area (SLA; ~leaf thickness) in 1 year, and spring and fall phenology in 2 years (figures 7 and 8). Our hypotheses were that, compared with northern source material, seedlings obtained from more southern seed zones would have more rapid height growth that can ultimately confer reproductive advantages (Gamache and Payette 2004), wider radial expansion associated with water balance (Daudet et al. 2004), lower SLA that promotes water conservation (Aranda et al. 2007), and

Figure 6. Mark White (The Nature Conservancy) installing a mesh cage to prevent deer browsing on oak seedlings at one of the study sties. (Photo by J.R. Etterson, June 2013)

Figure 8. Kristen Campbell (The Nature Conservancy) records spring leaf phenology on oak seedlings at a study site to evaluate assisted migration. (Photo by M. A. White, May 2015)

Figure 7. Research assistants, Ben Cogger (The Nature Conservancy [TNC]) and Ryan Sullivan (TNC), measure oak seedling traits in a study to evaluate assisted migration. (Photo by M.A. White, September 2014)

extended leaf phenology that permits seedlings to photosynthesize throughout longer growing seasons expected with climate change (Gunderson et al. 2012). In sum, this study was designed to provide essential information about adaptation and natural selection that can be used to inform climate-forward, seed-sourcing policy.

Preliminary Results

In brief, after 4 years of exposure to natural selection in these revegetation plots, both oak species had 93 percent survival on average. The high survival of these species provides a preliminary indication that within-range forestry-AM of trees with more southerly distributions could be an effective climate mitigation strategy. Moreover, even at this early time point, seedlings from the southern seed zone had higher survival than those from the northern seed zone, although this difference was not significant for bur oak (figure 9a). Overall, trees from the two source populations differed significantly for nearly all the traits described previously, and these differences were largely congruent with climate adaptation hypotheses. Specifically, northern red oak seedlings from the southern oak source had faster height (figure 9b) and diameter growth (figure 9c), lower SLA (figure 9d), and an extended leaf phenology that would permit

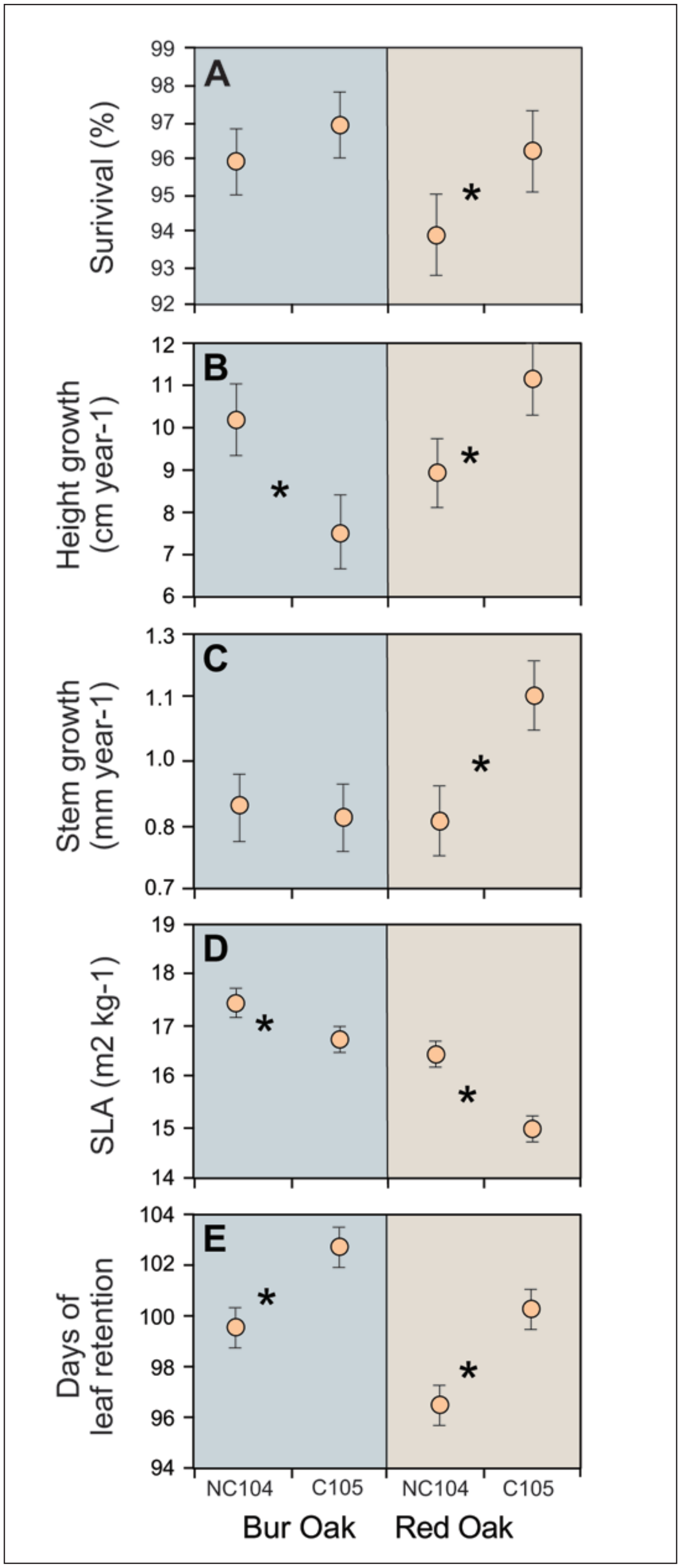

Figure 9. Estimated means (2 standard errors) for traits measured on bur oak and northern red oak seedlings that were sourced from 2 northern Minnesota seed zones, C105 and NC104, and planted into 16 forest regeneration sites in northeastern MN. Stars show significant differences between plants sampled in the different seed zones.

photosynthesis to occur for more days during the growing season (figure 9e) compared with those from the northern source.

The bur oak data also suggest climate adaptation but, on the whole, are somewhat weaker. The southern source of bur oak had significantly lower SLA (figure 9d) and a longer period of leaf retention during the growing season (figure 9e) compared with the northern source. At first glance, the bur oak growth results may seem counterintuitive; seedlings from the southern source had substantially lower growth rates than those from the northern source, the opposite of expectation (figure 9b). However, given bur oak's tendency to allocate a greater proportion of biomass to belowground growth during the early juvenile stages (Danner and Knapp 2001), this pattern could still be adaptive. To confirm this hypothesis, it will be necessary to sacrifice a subset of seedlings and measure relative allocation to aboveground and belowground biomass. Overall, given these initial results, we anticipate that trees sourced from the southern seed zone for both oak species will continue to thrive in the more northern sites where they were planted. If this outcome holds true, forestry-AM is a valid approach to restoration in the study area.

Value Added by Applied-Academic Partnerships

Increased Impact

Our case study is an example of "translational ecology" and illustrates how we can accomplish restoration objectives while also collecting rigorous data that can be used to evaluate methods and specific hypotheses. By joining resources and expertise, more comprehensive data can be collected, serving the goals of both applied and academic partners. Ultimately, these collaborations raise the impact and value of the project as a whole.

Advantages to Practitioners

Academic partners bring resources to the project that might not otherwise be available. Universities often have funding available to faculty for new research projects that can contribute to the overall project budget to pay for the additional time necessary to collect publishable data. Research faculty also have modern laboratories and field equipment that might not be accessible to practitioners, such as data loggers, soil moisture and light sensors, drying ovens, balances, computers and software for image analysis, among many other types of specialized equipment. In addition, most research universities have greenhouse facilities where additional experimentation can be conducted to follow up on hypotheses based on field observations. Many universities also have the capacity to do molecular studies for detailed genetic investigations. Collectively, these resources can be applied to obtain the greatest amount of information from restoration projects.

Advantages to Academics

Participation in on-the-ground projects and partnership with restoration practitioners has important benefits to academic partners as well. Academics learn from practitioners who are likely to have a greater familiarity with the natural history of an area and a deep practical knowledge that can be obtained only from extensive field experience. In addition, most researchers feel compelled to do work that has practical relevance. Partnerships permit academic researchers to conduct translational projects that have direct relevance and benefits to applied organizations. Moreover, community engagement is a common university goal that reflects well on faculty and is important for building relationships beyond campus. Finally, Federal granting agencies require broader impact statements that are deemed most valuable if they are based on bona fide partnerships, which lend credence to scientific objectives and create real opportunities for academic outreach.

Advantages to Both Partners

Perhaps most importantly, university faculty have access to undergraduate and graduate students, which provides opportunities to collect a broader and more diverse dataset. Because students are often supported by independent means, there is less burden on restoration managers in terms of time or money to meet research objectives. Graduate and undergraduate research students can often take full responsibility for the research components of a restoration project, including analysis and publication, under the supervision of their academic advisors. This advisory relationship is also beneficial to academic partners for whom student research mentoring is a fundamental job expectation. Collaboration between faculty and community organizations can be used to generate hypothesis-based research experiences.

Fostering the Next Generation of Leaders in Our Disciplines

Most significantly, however, these experiences benefit students. Exposure to collaborative environments cultivates nontechnical skills in students that are valuable in the workplace, such as effective communication, teamwork, critical thinking, problem solving, and professionalism (Ferrini-Mundy 2013). Even for students with ambition and talent, successful pathways into scientific careers depend on the quality of their experiences beyond the classroom (Thiry et al. 2011), which is particularly true for underrepresented groups in science (McPherson 2014). Research experiences, especially in the early undergraduate years, can increase student interest in scientific careers (Adedokun et al. 2012, Bauer and Bennett 2003, Hathaway et al. 2002, Webb 2014) and help students develop a professional identity and confidence about their potential success (Maltese et al. 2014). Specifically, bachelor's students in science, technology, engineering, and math who have obtained research experience have a documented advantage in graduate school and in the workforce (Fairweather 2008, Graham et al. 2013, Hunter et al. 2007, Villarejo et al. 2008). Experiential learning is valuable for students, because it stimulates curiosity while creating opportunities to practice higher level thinking skills in search of evidence to help solve real-world problems. Such experiences translate into professional success, and by including students in restoration and research, we are training students who will be the professionals of the future. In other words, undergraduate and graduate student involvement recruits people into our respective fields (figure 10). Even if students chose a different career path, they will approach their career and life with knowledge and an experience that will make them part of the informed citizenry, which benefits us all.

Figure 10. Master of Science students Laura Kavajecz (University of Minnesota Duluth [UMD]) and Ada Tse (UMD) measure vegetation characteristics on research plots. (Photo by M.A. White, August 2013)

Recommendations

Build Relationships Proactively

A fundamental step in establishing translational research partnerships is developing professional relationships. Even to identify projects that would be mutually beneficial, it is necessary for people to communicate across professional boundaries. The greatest benefits of restoration-academic partnerships can be achieved if a synergy exists between the research that would benefit practitioners and an awareness of these needs in academic circles. Opportunities to foster these relationships are present in both arenas but take intentional action. Academics can reach out to practitioners by inviting them to seminars, lab group meetings, and student clubs on campus. Practitioners can reach out to academics by inviting them to professional meetings and workshops in their discipline. If these relationships are established preemptively, the groundwork is laid to take advantage of opportunities when they arise. Importantly, enhanced communication can bridge understanding between the realities of what needs to get done, the information gaps that need to be filled, and the resources that can be mobilized to achieve multiple but synergistic goals.

Keep It Local

Local entities are more likely to be interested in joint research ventures and have the nearby resources to get the work done compared with more distance potential partners. It is especially valuable to contact local universities where both faculty and students are more likely to be invested in community issues. In many cases, academic units, such as departments of biology, chemistry, and environmental science have graduate programs with students who are enthusiastic to focus on local problems for which they can more readily observe the impact of their work. In addition, many undergraduate students seek experiences in the local community to round out their education.

Engage Early

It is important that all partners be included in the early stages of potential joint projects, most critical of which is the planning stage. Engaging partners during the planning process fosters a sense of investment in the success of the project by all parties and assures that the design elements necessary to achieve both restoration and research goals are met. The quality of the experimental designs that are implemented for both restoration and research goals will determine the quality of the program outcomes. Careful early planning that meets both partners' needs will foster achievement of this goal.

Carve Out a Small Piece for Research

Typically, restoration projects occur on a scale that exceeds that which is necessary for statistically robust results. By carving out a smaller project embedded within a larger one, it is more feasible to garner human and financial resources to accomplish research objectives. Recognition that research studies can be confined to a smaller component embedded in the overall project helps reinforce the feasibility of joint projects to all collaborators.

Aim for the Long Term

Some of the most valuable information obtained from forest regeneration (and many other aspects of science) has resulted from long-term studies. In forestry, provenance trials have yielded some of the best examples of long-term studies of stand productivity across species' ranges (Callaham 1963). These extraordinarily valuable long-term datasets have been reinterpreted in more recent years to help understand the impacts of climate change and guide appropriate management responses (Alberto et al. 2013, Matyas 1996, O'Neill et al. 2008, Rehfeldt et al. 1999, Schmidtling 1994, Thomson and Parker 2008). Beyond forestry, long-term monitoring of diverse ecosystems has yielded insights into biotic response to climate change that could not otherwise have been obtained (e.g., Bertrand et al. 2011, Fitter and Fitter 2002, Gordo and Sanz 2005, Kelly and Goulden 2008, Lenoir et al. 2008). Similar long-term studies of restoration outcomes are not widely available. Long-term studies are important because they could provide critical information to guide habitat restoration in an age where, out of necessity, reconstruction efforts are increasingly common.

Future Work

Here, we described one set of information derived from this collaborative project. In addition to the results described in this article, another UMD graduate student collaborated with TNC to conduct similar work on eastern white pine (*Pinus strobus* L.). Teams of people characterized the soils on these plots and processed samples in the laboratory at UMD. In 2 successive years, students participating in the Biology Undergraduate Research Program in Science and Technology conducted invasive earthworm surveys in our revegetation plots. Other faculty and students have been engaged in processing field samples to better understand bud and leaf attributes in laboratories at both UMD and North Dakota State University. Crews of young professionals, which TNC hires seasonally, collected baseline data on herbaceous forest species within our plots. A more recent UMD graduate student is following up on that work and has begun to study genetic differentiation and the value of forestry-AM in this understudied component of forest ecosystems. Finally, TNC joined forces with aquatic ecologists to compare the degree of freshwater and terrestrial resilience in some of the Lake Superior coastal watersheds where our plots were located. Forthcoming publications on these rich and diverse initiatives will enhance our ability to mitigate the negative effects of climate change and other stressors in these forests that are already transitioning.

Summary

As practitioners struggle with how to restore and manage populations that are threatened with climate change, applied-academic partnerships can achieve both restoration and research goals. Through translational collaboration, we can increase the impact of our work by combining our resources to get projects done while also studying their efficacy. Student engagement is an important component in this effort because it increases opportunities to collect more extensive and longer term data using different cohorts of students over time. However, the greatest benefit may be to stimulate interest in a diverse cadre of students to encourage them to continue on to professional careers in our disciplines and become a component of an informed citizenry.

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REFERENCES

Adedokun, O.A.; Zhang, D.; Parker, L.C.; Bessenbacher, A.; Childress, A.; Burgess, W.D.; Adedokun, B. 2012. Understanding how undergraduate research experiences influence student aspirations for research careers and graduate education. Journal of College Science Teaching. 42(1): 82–90.

Alberto, F.J.; Aitken, S.N.; Alía, R.; González-Martínez, S.C.; Hänninen, H.; Kremer, A.; Lefèvre, F.; Lenormand, T.; Yeaman, S.; Whetten, R. 2013. Potential for evolutionary responses to climate change–evidence from tree populations. Global Change Biology. 19(6): 1645–1661.

Aranda, I.; Pardos, M.; Puértolas, J.; Jiménez, M.D.; Pardos, J.A. 2007. Water-use efficiency in cork oak (*Quercus suber*) is modified by the interaction of water and light availabilities. Tree Physiology. 27(5): 671–677.

Bauer, K.W.; Bennett, J.S. 2003. Alumni perceptions used to assess undergraduate research experience. The Journal of Higher Education. 74(2): 210–230.

Bertrand, R.; Lenoir, J.; Piedallu, C.; Riofrío-Dillon, G.; De Ruffray, P.; Vidal, C.; Pierrat, J.-C.; Gégout, J.-C. 2011. Changes in plant community composition lag behind climate warming in lowland forests. Nature. 479(7374): 517–520.

Bottin, L.; Le Cadre, S.; Quilichini, A.; Bardin, P.; Moret, J.; Machon, N. 2007. Re-establishment trials in endangered plants: a review and the example of *Arenaria grandiflora*, a species on the brink of extinction in the Parisian region (France). Ecoscience. 14(4): 410–419.

Callaham, R.Z. 1963. Provenance research: investigation of genetic diversity associated with geography. Unasylva. 18(2–3): 2–12.

Danner, B.T.; Knapp, A.K. 2001. Growth dynamics of oak seedlings (*Quercus macrocarpa* Michx. and *Quercus muhlenbergii* Engelm.) from gallery forests: implications for forest expansion into grass-lands. Trees. 15(5): 271–277.

Daudet, F.-A.; Améglio, T.; Cochard, H.; Archilla, O.; Lacointe. A. 2004. Experimental analysis of the role of water and carbon in tree stem diameter variations. Journal of Experimental Botany. 56(409): 135–144.

Davis, M.B.; Shaw, R.G.; Etterson, J.R. 2005. Evolutionary responses to changing climate. Ecology. 86(7): 1704–1714.

Deredec, A.; Courchamp, F. 2007. Importance of the Allee effect for reintroductions. Ecoscience. 14(4): 440–451.

Duveneck, M.J.; Scheller, R.M.; White, M.A. 2014. Effects of alternative forest management on biomass and species diversity in the face of climate change in the northern Great Lakes region (USA). Canadian Journal of Forest Research. 44(999): 700–710.

Enquist, C.A.; Jackson, S.T.; Garfin, G.M.; Davis, F.W.; Gerber, L.R.; Littell, J.A.; Tank, J.L.; Terando, A.J.; Wall, T.U.; Halpern, B. 2017. Foundations of translational ecology. Frontiers in Ecology and the Environment. 15(10): 541–550.

Etterson, J.R.; White, M.A.; Cornett, M.W.; Kavajecz, L.C. [N.d.] Assisted migration in a boreal forest that is already transitioning under climate change. Manuscript in preparation.

Fairweather, J. 2008. Linking evidence and promising practices in science, technology, engineering, and mathematics (STEM) undergraduate education. Washington, DC: Board of Science Education; National Research Council; The National Academies of Sciences, Engineering, and Medicine. 31 p.

Fanelli, D. 2010. Do pressures to publish increase scientists' bias? An empirical support from US States Data. PLOS One. 5:e10271.

Ferrini-Mundy, J. 2013. Driven by diversity. Science. 340(6130): 278–278.

Field, C.B.; Barros, V.R.; Mach, K.; Mastrandrea, M. 2014. Climate change 2014: impacts, adaptation, and vulnerability. New York: Cambridge University Press. 1101 p.

Fisichelli, N.A.; Frelich, L.E.; Reich, P.B. 2014. Temperate tree expansion into adjacent boreal forest patches facilitated by warmer temperatures. Ecography. 37(2): 152–161.

Fitter, A.; Fitter, R. 2002. Rapid changes in flowering time in British plants. Science. 296 (5573): 1689–1691.

Frelich, L.E.; Hale, C.M.; Reich, P.B.; Holdsworth, A.R.; Scheu, S.; Heneghan, L.; Bohlen, P.J. 2006. Earthworm invasion into previously earthworm-free temperate and boreal forests. In: Hendrix, P.F, ed. Biological invasions belowground: earthworms as invasive species: 35–45. Chapter 4.

Gamache, I.; Payette, S. 2004. Height growth response of tree line black spruce to recent climate warming across the forest-tundra of eastern Canada. Journal of Ecology. 92(5): 835–845.

Gibson, W.; Daly, C.; Kittel, T.; Nychka, D.; Johns, C.; Rosen-bloom, N.; McNab, A.; Taylor, G. 2002. Development of a 103-year high-resolution climate data set for the conterminous United States. Proceedings of the 13th AMS Conference on Applied Climatology. Portland, OR: American Meteorological Society: 13–16.

Godefroid, S.; Piazza, C.; Rossi, G.; Buord, S.; Stevens, A.-D.; Aguraiuja, R.; Cowell, C.; Weekley, C.W.; Vogg, G.; Iriondo, J.M. 2011. How successful are plant species reintroductions? Biological Conservation. 144(2): 672–682.

Gordo, O.; Sanz, J.J. 2005. Phenology and climate change: a long-term study in a Mediterranean locality. Oecologia. 146(3): 484–495.

Graham, M.J.; Frederick, J.; Byars-Winston, A.; Hunter, A.-B.; Handelsman, J. 2013. Increasing persistence of college students in STEM. Science. 341(6153): 1455–1456.

Guerrant, E.O., Jr.; Kaye, T.N. 2007. Reintroduction of rare and endangered plants: common factors, questions and approaches. Australian Journal of Botany. 55(3): 362–370.

Gunderson, C.A.; Edwards, N.T.; Walker, A.V.; O'hara, K.H.; Campion, C.M.; Hanson, P.J. 2012. Forest phenology and a warmer climate–growing season extension in relation to climatic provenance. Global Change Biology. 18(6): 2008–2025.

Hale, C.M.; Frelich, L.E.; Reich, P.B. 2006. Changes in hardwood forest understory plant communities in response to European earthworm invasions. Ecology. 87(7): 1637–1649.

Handler, S.; Duveneck, M.J.; Iverson, L; Peters, E.; Scheller, R.M.; Wythers, K.R.; Brandt, L.; Butler, P.; Janowiak, M.; Shannon, P.D.; Swanston, C.; Barrett, K.; Kolka, R.; McQuiston, C.; Palik, B.; Reich, P.B.; Turner, C.; White, M.; Adams, C.; D'Amato, A.; Hagell, S.; Johnson, P.; Johnson, R.; Larson, M.; Matthews, S.; Montgomery, R.; Olson, S.; Peters, M.; Prasad, A.; Rajala, J.; Daley, J.; Davenport, M.; Emery, M.R.; Fehringer, D.; Hoving, C.L.; Johnson, G.; Johnson, L.; Neitzel, D.; Rissman, A.; Rittenhouse, C.; Ziel, R. 2014. Minnesota forest ecosystem vulnerability assessment and synthesis: a report from the Northwoods Climate Change Response Framework project. Gen. Tech. Rep. NRS-133. Newtown Square, PA; U.S. Department of Agriculture, Forest Service, Northern Research Station. 228 p.

Hathaway, R.S.; Nagda, B.A.; Gregerman, S.R. 2002. The relationship of undergraduate research participation to graduate and professional education pursuit: an empirical study. Journal of College Student Development. 43(5): 614–631.

Heschel, M.S.; Paige, K.N. 1995. Inbreeding depression, environmental stress, and population size variation in scarlet gilia (*Ipomopsis aggregata*). Conservation Biology. 9(1): 126–133.

Hoegh-Guldberg, O.; Hughes, L.; McIntyre, S.; Lindenmayer, D.; Parmesan, C.; Possingham, H.P.; Thomas, C. 2008. Assisted colonization and rapid climate change. Science. 321(4679): 345–346.

Hunter, A.B.; Laursen, S.L.; Seymour, E. 2007. Becoming a scientist: the role of undergraduate research in students' cognitive, personal, and professional development. Science Education. 91(1): 36–74.

Kelly, A.E.; Goulden, M.L. 2008. Rapid shifts in plant distribution with recent climate change. Proceedings of the National Academy of Sciences. 105(33): 11823–11826.

Kremer, A.; Ronce, O.; Robledo-Arnuncio, J.J.; Guillaume, F.; Bohrer, G.; Nathan, R.; Bridle, J.R.; Gomulkiewicz, R.; Klein, E.K.; Ritland, K. 2012. Long-distance gene flow and adaptation of forest trees to rapid climate change. Ecology Letters. 15(4): 378–392.

Lenoir, J.; Gégout, J.-C.; Marquet, P.; De Ruffray, P.; Brisse, H. 2008. A significant upward shift in plant species optimum elevation during the 20th century. Science. 320(5884): 1768–1771.

Maltese, A.V.; Melki, C.S.; Wiebke, H.L. 2014. The nature of experiences responsible for the generation and maintenance of interest in STEM. Science Education. 98(6): 937–962.

Matyas, C. 1996. Climatic adaptation of trees: rediscovering provenance tests. Euphytica. 92(1–2): 45–54.

Maunder, M. 1992. Plant reintroduction: an overview. Biodiversity and Conservation. 1(1): 51–61.

McCarty, J.P. 2001. Ecological consequences of recent climate change. Conservation Biology. 15(2): 320–331.

McDonald, T.; Gann, G.; Jonson, J.; Dixon, K. 2016. International standards for the practice of ecological restoration–including principles and key concepts. Washington, DC: Society for Ecological Restoration. 47 p.

McLachlan, J.S.; Hellmann, J.J.; Schwartz, M.W. 2007. A framework for debate of assisted migration in an era of climate change. Conservation Biology. 21(2): 297–302.

McPherson, E. 2014. High-impact practices that retain underrepresented STEM students. Rochester, MI: Oakland University 2nd Annual Retention Conference. 22 p. http://www.oakland.edu/upload/docs/UGEducation/Retention_Conference/Retention_Preseations/2014_Ret_Conf_Presentations/52_HIP_That_Retain.pdf. (January 2015).

Menges, E.S. 2008. Restoration demography and genetics of plants: when is a translocation successful? Australian Journal of Botany. 56(3): 187–196.

Miller, J.R.; Hobbs, R.J. 2007. Habitat restoration—Do we know what we're doing? Restoration Ecology. 15(3): 382–390.

Muilenburg, V.L.; Herms, D.A. 2012. A review of bronze birch borer (Coleoptera: Buprestidae) life history, ecology, and management. Environmental Entomology. 41(6): 1372–1385.

O'Neill, G.A.; Hamann, A.; Wang, T. 2008. Accounting for population variation improves estimates of the impact of climate change on species' growth and distribution. Journal of Applied Ecology. 45(4): 1040–1049.

Pachauri, R.K.; Allen, M.R.; Barros, V.R.; Broome, J.; Cramer, W.; Christ, R.; Church, J.A.; Clarke, L.; Dahe, Q.; Dasgupta, P. 2014. Climate change 2014 synthesis report: fifth assessment report. Geneva, Switzerland: Intergovernmental Panel on Climate Change. 151 p.

Pedlar, J.H.; McKenney, D.W.; Aubin, I.; Beardmore, T.; Beaulieu, J.; Iverson, L.; O'Neill, G.A.; Winder, R.S.; Ste-Marie, C. 2012. Placing forestry in the assisted migration debate. Bioscience. 62(9): 835–842.

Ravenscroft, C.; Scheller, R.M.; Mladenoff, D.J.; White, M.A. 2010. Forest restoration in a mixed-ownership landscape under climate change. Ecological Applications. 20(2): 327–346.

Rehfeldt, G.E.; Ying, C.C.; Spittlehouse, D.L.; Hamilton, D.A., Jr. 1999. Genetic responses to climate in *Pinus contorta*: niche breadth, climate change, and reforestation. Ecological Monographs. 69(3): 375–407.

Richardson, D.M.; Hellmann, J.J.; McLachlan, J.S.; Sax, D.F.; Schwartz, M.W.; Gonzalez, P.; Brennan, E.J.; Camacho, A.; Root, T.L.; Sala, O.E. 2009. Multidimensional evaluation of managed relocation. Proceedings of the National Academy of Sciences. 106(24): 9721–9724.

Ruiz-Jaen, M.C.; Mitchell Aide, T. 2005. Restoration success: how is it being measured? Restoration Ecology. 13(3): 569–577.

Sauer, J.R.; Pardieck, K.L.; Ziolkowski, D.J., Jr.; Smith, A.C.; Hudson, M.-A. R.; Rodriguez, V.; Berlanga, H.; Niven, D.K.; Link, W.A. 2017. The first 50 years of the North American breeding bird survey. The Condor. 119(3): 576–593.

Schmidtling, R. 1994. Use of provenance tests to predict response to climate change: loblolly pine and Norway spruce. Tree Physiology. 14(7–9): 805–817.

Smith, B.D.; Zeder, M.A. 2013. The onset of the anthropocene. Anthropocene. 4: 8–13.

Strauss, S.Y.; Lau, J.A.; Carroll, S.P. 2006. Evolutionary responses of natives to introduced species: what do introductions tell us about natural communities? Ecology Letters. 9(3): 357–374.

Swanston, C.; Janowiak, M.; Iverson, L.; Parker, L.; Mladenoff, D.; Brandt, L.; Butler, P.; Pierre, M.S.; Prasad, A.; Matthews, S. 2011. Ecosystem vulnerability assessment and synthesis: a report from the climate change response framework project in northern Wisconsin. Gen. Tech. Rep. NRS-136. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 247 p.

Swindell, W.R.; Bouzat, J.L. 2006. Gene flow and adaptive potential in *Drosophila melanogaster*. Conservation Genetics. 7(1): 79–89.

Temperton, V.M. 2004. Assembly rules and restoration ecology: bridging the gap between theory and practice. Washington, DC: Island Press. 465 p.

Thiry, H.; Laursen, S.L.; Hunter, A.-B. 2011. What experiences help students become scientists? A comparative study of research and other sources of personal and professional gains for STEM undergraduates. The Journal of Higher Education. 82(4): 357–388.

Thomson, A.M.; Parker; W.H. 2008. Boreal forest provenance tests used to predict optimal growth and response to climate change. 1. Jack pine. Canadian Journal of Forest Research. 38(1): 157–170.

Villarejo, M.; Barlow, A.E.; Kogan, D.; Veazey, B.D.; Sweeney, J.K. 2008. Encouraging minority undergraduates to choose science careers: career paths survey results. CBE—Life Sciences Education. 7(4): 394–409.

Webb, M. 2014. Early college expansion: propelling students to postsecondary success, at a school near you. Alameda, CA: Alameda Science and Technology Institute. 22 p. https://files.eric.ed.gov/fulltext/ED559689.pdf. (January 2015).

White, M.; Host, G. 2008. Forest disturbance frequency and patch structure from pre-European settlement to present in the Mixed Forest Province of Minnesota, USA. Canadian Journal of Forest Research. 38(8): 2212–2226.

White, M.A. 2012. Long-term effects of deer browsing: composition, structure and productivity in a northeastern Minnesota old-growth forest. Forest Ecology and Management. 269: 222–228.

Williams, M.I.; Dumroese, R.K. 2013. Preparing for climate change: forestry and assisted migration. Journal of Forestry. 111(4): 287–297.

Zachos, J.; Pagani, M.; Sloan, L.; Thomas, E.; Billups, K. 2001. Trends, rhythms, and aberrations in global climate 65 Ma to present. Science. 292(5517): 686–693.