Plenary Session

Science-Management Collaboration is Essential to Address Current and Future Forestry Challenges

Susan L. Stout, Andrea T. Hille, and Alejandro A. Royo[1]

Abstract.—Accelerating changes due to climate, invasive insects, plants, and diseases; and social values in northern hardwood forests make understanding and predicting impacts of natural and human variables ever more complex. Yet policy-makers are disinvesting in forestry research. We believe that science-management collaboration can help bridge the resulting gap. We give examples of advances in sustainable forestry from such collaboration and identify common elements of successful collaborations. Then we propose a new, three-tiered approach to science-management collaboration to reverse the trend away from forest science. Can such collaborations help us keep pace with forest change and develop management strategies to sustain forest values and benefits in the face of these changes?

INTRODUCTION

Northern hardwood forests are facing unprecedented changes at an accelerating pace while scientific capacity in forest ecology and forest management is diminishing. Can science-management collaboration help to address these changes? Integrating observations and insights from forest managers and results from deliberative adaptive management with traditional forestry research has the potential to bridge emerging scientific gaps. This cohesive approach facilitates prioritization of scarce research resources to the most essential problems. Our purpose in this paper is to illustrate the historical value and success of science-management collaboration and to outline models of collaborative adaptive management and traditional research suited to the present situation.

MANY CHANGES, ACCELERATING PACE

The stressors facing northern hardwood forests are many and interacting. Climate change is moving climate envelopes that favor individual species away from their current locations (Peters et al. 2020). The pace of these changes is anticipated to increase with increasing atmospheric carbon levels, and changes will persist even if we succeed in stabilizing or reducing emissions of greenhouse gasses. What were once called natural disturbances, such as windstorms and flooding, are more frequent and intense (Hayhoe et al. 2018). Yet eastern forests, particularly in the mid-Atlantic region, have insufficient advance regeneration to replace canopy trees in about 50 percent of areas surveyed (Miller and McGill 2019, Vickers et al. 2019). Atmospheric carbon has directly increased plant growth and fecundity (Norby et al. 2005). Resulting increases in maximum density shown in aspen may potentially render existing density management tools obsolete (Kubiske et al. 2019). Anthropogenic sources increased both nitrate and sulfate availability to forests in the twentieth century, resulting in nitrogen saturation in some forests (Aber 2002), but potentially benefitting species such as black cherry and tulip poplar elsewhere (Thomas et al. 2010, Canham and Murphy 2016). These inputs are now sharply declining and new changes are observed as

[1] Research Forester Emerita (SLS), Research Ecologist (AAR), USDA Forest Service, Northern Research Station, 335 National Forge Rd., Irvine, PA 16329; Ecosystem Management Team Leader (ATH), Allegheny National Forest, 4 Farm Colony Rd., Warren, PA 16365; SLS is corresponding author: to contact, call 814-688-4910 or email susan.stout@usda.gov.

ecosystems re-equilibrate (Royo et al. 2021). Invasive plants, insects, and diseases are other factors forcing change in forest ecosystem processes and values. Moreover, novel and changing climate conditions may affect invasive insect, disease and plant composition, density, competitive interactions, distribution, and management strategy effectiveness (Hellman et al. 2008). Interactions among these factors and with social changes such as changes in land use, increased recreation use, changing demand for species and types of wood products, changes in energy sources and infrastructure, and reduced hunting pressure will affect species and competitive interactions variably, further complicating the challenge of sustainable forest management in northern hardwood forests.

Keeping pace with these changes and managing these forests responsibly demands that all of us—scientists and managers alike— share and organize the observations regarding tree growth, health, seed production, seedling competitiveness and other factors to maximize shared insights and awareness.

In the Allegheny Plateau ecoregion, we have faced change with the help of close science-management collaboration for over 50 years (Stout and Brose 2014, Stout 2019). Our experience has shown that when scientists and managers interact on a regular basis in the context of careful observations of the forest, changes are detected and patterns emerge that help shape hypotheses about their causes and appropriate management strategies for addressing them.

SOCIAL INVESTMENT IN FOREST SCIENCE IS AT AN ALL TIME LOW AND DECREASING

Nearly 20 years ago, the National Research Council conducted a review of U.S. forestry research capacity and found that “Forestry research capacity is at a crossroads, if not a precipice” (National Research Council 2002). Wheeler et al. (2015) reported that late twentieth century changes in forest landownership from forest industry to timber investment management organizations (TIMOs) and real estate investment trusts (REITs) were associated with reduced financial and in-kind investment in forestry research. From 2016–2020, the Forest Inventory and Analysis (FIA) budget within USDA Forest Service Research and Development (R&D) held steady; thus, the 12 percent decrease in overall R&D funding resulted in a 16 percent decrease in non-FIA R&D funding (USDA Forest Service 2020). D’Amato et al. (2018) reported declining McEntire-Stennis and USDA Forest Service investment in university research, along with loss of forestry-specific faculty positions through disciplinary consolidation.

McGinley et al. (2019) compared 2016 data about university and agency investment in forest science to the data collected by the National Research Council in 2002. They found a 12 percent decline in the number of forest scientists over that 14-year period. Inflation during the same period neutralized the small absolute dollar increase in investment in forest science. The authors summarized their results: “The data indicated that the nation’s forest research capacity continues to erode, leading to declines in research development and innovation, and putting at increasing risk the future health and productivity of America’s forests.” In short, as the rapid pace of ecological changes creates management uncertainties, forest research capacity has diminished. We argue that science-management cooperation has enhanced the science basis for forest management in the past and can be an important way to support sustainable forest management now and in the future. Active collaboration that encourages managers to help set priorities, implement adaptive trials on their own properties, choose which questions merit investment in designed studies, and share observations of change on a regular basis may also inspire increased investment in the designed research process. First, we look at two long-established examples of science-management cooperation highlighting specific advances in science that fed back into improved management.

SCIENCE-MANAGEMENT COLLABORATION CAN HELP

Michigan Partnership in Ecosystems Research and Management (PERM)

Walters et al. (2020) describe a science-management collaboration in Michigan: The Partnership for Ecosystem Research and Management (PERM). The primary partners are Michigan State University (MSU) and the Michigan Department of Natural Resources (MDNR). After about 20 years of successful collaboration, scientists and managers alike were concerned that, “the historically dominant silvicultural system, single-tree/small group selection (i.e., selection silviculture), is not producing well stocked, species-diverse tree sapling recruits.” Together, they hypothesized that the interaction of selection silviculture with browsing by white-tailed deer (*Odocoileus virginianus*) could be among the most important factors contributing to this result. Solving the problem would require balancing economic, recreational, and ecological factors to “ensure sustainable, resilient forests alongside socially acceptable deer populations.” They thought that the problem was too urgent for traditional small-scale studies that did not account for geographic variation in site conditions, deer browsing pressure and other factors across which the results would have to be applied. They believed that local adaptation of results would be facilitated by this approach as managers throughout the state would have examples of alternative silviculture in their back yard.

At MSU forestry scientists and wildlife biologists conducted a comprehensive literature review of northern hardwood forest responses to alternative silvicultural treatments and interactions with deer. This created a common language and framework as scientists and managers designed practical alternatives to be tested on the scale that partners believed necessary. Ultimately, they chose four silvicultural systems and two understory treatments to test on a network of study sites distributed across three different Michigan ecoregions, on public and industry land. The overstory treatments were single-tree/small-group selection (the current dominant system), large-group/patch cutting, shelterwood, and seed tree. The understory treatments were herbicide-scarification and leaving tops to deter deer browsing. This study has now been installed on 140 sites, supported by substantial financial and in-kind support from MDNR and other interested partners.

Regular communication with partners at all levels has been and continues to be imperative. Meetings rotate around the state and allow for the exchange of observations with personnel at every administrative level, increasing the power of the experiment by drawing scientists’ attention to details and associations that field personnel will be the first to notice.

Pennsylvania’s SILVAH Community of Practice

The SILVAH[2] community of practice that originated in northwestern Pennsylvania in the late 1960s is another example (Stout 2019). Science-management collaboration among USDA Forest Service scientists and managers from state and federal agencies, forest industry, consultants, and nongovernmental organizations has been sustained by regular training sessions, field trips with manager and scientist input, and frequent research reviews. These interactions ensure a common language and framework for describing forest conditions. Research based on this collaboration informs management on hundreds of thousands of forested acres in Pennsylvania and beyond. SILVAH’s history includes many examples of important scientific breakthroughs that demonstrably benefited from manager input, such as the three offered here.

[2] Originally an acronym for Silviculture of Allegheny Hardwoods, SILVAH is a systematic approach to silvicultural prescription development based on inventory and analysis of stand data.

In the 1960s, managers and multiple case studies identified overabundant deer as a principal cause of widespread regeneration failures in the ecoregion. The U.S. Department of Agriculture (USDA) Forest Service team worked with managers on a study to test the effect of deer density on forest regeneration establishment, diversity, and growth (Horsley et al. 2003, Tilghman 1989). Study plots were multiple managed forest enclosures with each enclosure stocked with one to four live deer to achieve a range of white-tailed deer densities spanning the region's historic populations. Each enclosure started with the same proportion of its area in forage-producing conditions (10 percent early successional habitat). Investigators expected regeneration failures in the high deer density treatments (e.g., ≥40 deer per square mile) given the observed failures in managed forests on the landscape at those densities. After 5 years, regeneration was more abundant, albeit with low diversity, at the highest deer densities not anticipated. Conversation among scientists and forest and wildlife/game managers led to the hypothesis that forage in the study areas was greater than that available on the surrounding managed forests. There, managers intentionally withheld harvests until they could establish adequate advance regeneration resulting in approximately four percent of the landscape in clearcut, early successional habitat. Moreover, even when harvested, these areas were often fenced to mitigate overbrowsing, thereby eliminating them as a source of forage for deer. The results of these operational practices were lower proportions of good habitat, less accessible forage, and intensified deer impacts in the area's managed forests. This hypothesis was confirmed by a landscape-scale study made possible only by extensive management partner in-kind services (Royo et al. 2017).

In the late 1980s, managers and scientists became concerned about extensive dieback, mortality, and lack of regeneration in sugar maple (*Acer saccharum* Marshall). USDA Forest Service scientists organized a field trip to study the variation in condition of sugar maple trees and seedlings on the landscape, with sites suggested by managers. Managers showed that plateau-top positions in the unglaciated portion of the ecoregion were the sites with the most severe dieback and mortality, and that some of the healthiest trees occurred in glaciated areas. These observations became the basis of a northeast-wide study that confirmed the observations of the managers and tied the differences to soil calcium and magnesium levels (Horsley et al. 1999, Horsley et al. 2002, Long et al. 2009).

More recently, managers and scientists became aware of diminished establishment, growth, and survival of black cherry (*Prunus serotina* Ehrh.) seedlings. USDA Forest Service scientists reviewed the literature and contrasted results from current studies with those conducted decades earlier. They documented changes in precipitation patterns, reductions in nitrogen and sulfur deposition, apparent changes in virulence of fungal pathogens, increases in proportion of standing dead black cherry on several networks of forest health plots, decline of black cherry seed production, and more. Managers reported more abundant, healthier, and more persistent black cherry regeneration on sites with low proportions of cherry in the overstory compared with those with higher percentages of cherry, pointing to possible interactions with soil pathogens (Reinhart et al. 2005), and some suggested possible interactions between reduced nitrate and sulfate deposition and pathogens. Royo et al. (2021) summarize the status of this work, highlighting results that emerge from science-management collaboration. "Our review of the existing evidence suggests that altered nitrogen deposition dynamics and strengthened negative soil microbial feedback loops…, particularly given a warmer and wetter climate, represent promising avenues for future research."

In each of these cases, and others, results from research based on manager observations led to management change. More extensive use of fencing and more thoughtful planning about landscape forage availability have been used to increase diversity and success of regeneration harvests. Silviculture to favor sugar maple on the unglaciated Allegheny Plateau is focused on lower landscape positions that have higher levels of calcium and magnesium. Managers are actively adapting their regeneration expectations and silviculture to favor other species on sites with high proportions of black cherry in the current overstory.

Recently, managers and scientists in the Allegheny Plateau region have taken a step towards more formal organization. The Allegheny Forest Health Collaborative (AFHC) was formed in 2017 with more than 40 member organizations, and its working groups are developing strategies to address forest health problems like invasive insects, diseases, and plants with early detection and rapid response, and to develop adaptive management guidelines across ownership boundaries for stands affected by the very factors we listed here (Hanson et al. 2020). The AFHC Research Working Group is engaged in conversations about a potential research cooperative.

In addition to SILVAH and PERM, for which we are able to point to specific scientific advances that come as a result of science-management cooperation, we point to three other examples of recent or existing science-management collaborations to inspire new and future collaborations.

Canadian Industrial Chair Research Grants

Until recently, the Natural Resources and Engineering Research Council of Canada supported a program called Industrial Chair Research Grants. This competitive grant program supported collaborations between Canadian universities and private and/or public sector partners leading to economic, social, or environmental benefits for Canada. The industrial or eligible public-sector organization made a financial commitment to partner financially with a leading scientist to conduct an intensive, sustained research program, matched by the government for successful applicants. Recently, for example, Steeve Côté of Laval University held an Industrial Chair Research Grant for two 5-year terms to understand the impact of moose (*Alces alces*) and white-tailed deer on forests on Anticosti Island. The research results enhanced understanding of ungulate browser-forest interactions far beyond the forests where they were conducted (e.g., Beguin et al. 2009, Cardinal et al. 2012), and were guided throughout by input from the forest industry based on their sustainable forest management needs for the island and beyond.

Research Cooperatives

Research cooperatives engage private, public, and academic organizations to finance and address shared research priorities. As we noted earlier, support for cooperatives diminished as forest land ownership passed from forest industry to REITs and TIMOs in the latter part of the 20th Century. The 50-year-old Forest Productivity Cooperative (FPC), based in the United States at North Carolina State University and Virginia Technical University, is one of the best known and most successful forestry research cooperatives. The FPC has 40 members and an annual budget at millions of dollars; private landowner members pay dues in proportion to the number of planted acres they own, while public agencies and nonlandowning stakeholders pay flat fees. Participating universities support some permanent positions for the Cooperative's work, but mainly the permanent staff of 15 is paid by stakeholder and member dues. The remaining dues support designed research studies. The landowning members choose which working groups (such as genetics or fertilization) receive their dues, and the scientists and managers on the working groups set the research agenda for each. The FPC hosts regular meetings and field tours to share results and observe conditions on experimental sites. There are several other working examples of this kind of cooperative around the country, most of a smaller scale, such as the Maine Cooperative Forestry Unit (Anderson and Ferguson 2020), the Sierra Cascade Intensive Forest Management Research Coop, and the National Council for Air and Stream Improvement (NCASI).

Adaptive Management Cooperatives

The previous examples show science-management collaboration to support traditional, designed research. The best example we know of collaborative support for adaptive management is the partnership between The Nature Conservancy and the Washington-Jefferson National Forest to adaptively manage a large-scale prescribed fire program on their lands (Lorber et al. 2018). The most important difference between this model and the traditional cooperative model is that there are no designed studies. Rather, managers and scientists collaborated to define the desired future conditions to be achieved by a landscape-scale prescribed fire program, and the environmental and biotic factors that might influence achievement of the desired conditions. Then they designed a monitoring program to measure outcomes and influencing factors across a very broad landscape. Participating members collect data on assigned monitoring plots each year and financially support a staff that manages data collection, analysis, and storage. Communication among cooperative members is sustained through regular meetings and field visits. The staff also coordinates the data-based adaptive management cycle.

Common Attributes of these Science-Management Collaborations

There are compelling commonalities among these examples of productive science-management collaboration. Researchers and managers are critical to their success—researchers develop, implement, and tease out significant findings and implications for management strategies, while managers and field personnel are often the first to notice ecosystem changes or patterns that can be significant when viewed collaboratively through a broader lens. Both are needed to facilitate collaborative discussions and idea generation. In the face of disinvestment in forestry research, these collaborations offer a viable model for science-based collaboration to support adaptive management of northern hardwood forests.

MODELS OF INSTITUTIONAL SCIENCE-MANAGEMENT COLLABORATIVES

We believe that such collaboratives require several elements to succeed:

- Sustained institutional and financial commitment by management and science partners, their organizations, and their personnel, ensuring investment and ongoing participation
- Frequent two-way communication based on mutual respect, including site visits
- Development of a common framework and language for sharing observations tied to a strong, shared sense of place
- Purposeful inclusion of management priorities and informational needs when planning a research agenda

A Proposed Hybrid Model

The rapidly accelerating rate of change across regional scales in northern forests may require a hybrid of the Research Cooperative and Adaptive Management/Natural Experiment Cooperative models. Adaptive management or natural experiments[3] can add to regional forestry knowledge bases in a flexible, possibly quicker, and coarse-grained way. Shared engagement in defining

[3] A natural experiment is an empirical study in which individuals are exposed to the experimental and control conditions that are determined by nature or other factors outside the control of the investigators. The process governing the exposures arguably resembles random assignment (Wikipedia, accessed May 19, 2021).

problems and learning from the results of formal adaptive management or natural experiments can serve as a sieve through which the most critical hypotheses must pass to become the basis for the more robust and fine-grained results that come only from designed studies.

We see this as a basis for new, self-interested public/private investment in forest ecological and management research. The vision we have is that public management agencies, forest industry, and forest managing NGOs will form cooperatives with scientists willing to commit to conducting research according to priorities identified with managers. Such cooperatives will identify landscape-scale changes that require relatively immediate management responses, such as the widespread black cherry decline observed in the Allegheny Plateau ecoregion. Together, as the members of the Nature Conservancy/Washington-Jefferson National Forest cooperative have done, they will identify specific desired outcomes and determine the metrics needed to determine whether adaptive strategies are yielding desired outcomes. Some cooperative contributions (in-kind and financial) will be expended to monitor outcomes at the landscape level and analyze their correlation with biotic, environmental, and management factors. In the Allegheny Plateau case, this might mean monitoring at the landscape (rather than stand) level the composition, diversity, and growth rate of regeneration in stands managed according to adaptive guidelines in cherry-decline impacted stands. At the same time, the cooperative would identify a subset of questions of management relevance that merit a more rigorous designed-study approach and provide support to scientists to conduct such studies. In the Allegheny Plateau case, this might include formal tests of fertilization or fungicide application to increase survival and growth of seedlings. When resources and need are sufficient, they might also support a suite of related, intensive studies, as was supported in Canada by the Industrial Chair Research Grants. On the Plateau, this might be a suite of studies focused on the interactions among temperature, precipitation, nutrition, and pathogen activity.

CONCLUSION

If we face the future without changing the way we do business, forestry and forestry research resources are inadequate to address the complex and rapidly changing factors that will influence the sustainability of northern hardwood forests. With inaction, we risk failing to recognize, understand or adapt to the changes that we know are coming. Yet within the northern hardwood region, differences in the makeup and capacity of the forest management sector abound. State agencies have different capacities to fund forest ecosystem and management research. Similar variations are found in the NGO and industrial sectors. The composition of the research community varies as well, based on the number and nature of universities in the region and on the orientation of the Forest Service research labs found there. The model proposed here is flexible enough to meet this variability with creative engagement of scientists and managers who want to work together.

Science-management cooperation offers a substantially more hopeful model for facing this future. When scientists collaborate with managers in a formal, adaptive management framework—including disciplined and sustained support to monitor the outcome of management strategies targeted at expected changes—and adapt accordingly, and when managers and scientists work together to identify and fund research to address the most pressing mechanistic hypotheses, the probability of managing sustainably in the face of these changes increases dramatically.

In fact, when we look realistically toward the future, science-management collaboration is not just an option—it's essential.

ACKNOWLEDGMENTS

We acknowledge the contributions of scientists and managers who have worked together, especially in the Allegheny Plateau region, and the contributions of generations of forestry technicians who made the research happen. We also acknowledge very helpful reviews from Robert Long, Barbara McGuinness, Mike Walters, Jan Wiedenbeck, and Elizabeth Larry, as well as Barbara McGuinness' contributions to the associated presentation.

LITERATURE CITED

Aber, J.D. 2002. **Nitrogen saturation in temperate forest ecosystems: current theory, remaining questions and recent advances.** In Horst, W.J.; Burkert, A.; Claasen, N. [et al.]. Progress in plant nutrition: plenary lectures of the XIV International Plant Nutrition Colloquium. Dordrecht, The Netherlands: Springer: 179–188. https://doi.org/10.1007/978-94-017-2789-1_13.

Anderson, S.M.; Fergusson, M., eds. 2020. **Cooperative forestry research unit: 2019 annual report.** Orono, ME: Center for Research on Sustainable Forestry. 108 p.

Beguin, J.; Prevost, M.; Pothier, D.; Côte, S.D. 2009. **Establishment of natural regeneration under severe browsing pressure from white-tailed deer after group seed-tree cutting with scarification on Anticosti Island.** Canadian Journal of Forest Research. 39(3): 596–605. https://doi.org/10.1139/x08-196.

Canham, C.D.; Murphy, L. 2016. **The demography of tree species response to climate: seedling recruitment and survival.** Ecosphere. 7(8): e01424. https://doi.org/10.1002/ecs2.1424.

Cardinal, E.; Martin, J.L.; Côté, S.D. 2012. **Large herbivore effects on songbirds in boreal forests: lessons from deer introduction on Anticosti Island.** Ecoscience. 9(1): 38–47. https://doi.org/10.2980/19-1-3441.

D'Amato, A.W.; Jokela, E.J.; O'Hara, K.L; Long, J.L. 2018. **Silviculture in the United States: an amazing period of change over the past 30 years.** Journal of Forestry. 116(1): 55–67. https://doi.org/10.5849/JOF-2016-035.

Hanson, J.W.; Hille, A.T.; Stout, S.L.; McDonough, M.; Oldland, W. 2020. **Managing forest health through collaboration on the Allegheny High Unglaciated Plateau.** Journal of Forestry. 118(3): 324–336. https://doi.org/10.1093/jofore/fvaa010.

Hayhoe, K.; Wuebbles, D.J.; Easterling, D.R.; Fahey, D.W.; Doherty, S. 2018. **Our changing climate.** In: Reidmiller, D.R., Avery, D.R.; Easterling, K.E. [et al.], eds. Impacts, risks, and adaptation in the United States: fourth national climate assessment, volume II. Washington, DC: U.S. Global Change Research Program. 72–144 [chapter 2]. https://nca2018.globalchange.gov/chapter/climate (accessed Nov. 21, 2022).

Hellmann, J.J.; Byers, J.E.; Bierwagen, B.G.; Dukes, J.S. 2008. **Five potential consequences of climate change for invasive species.** Conservation Biology. 22(3): 534–543. https://doi.org/10.1111/j.1523-1739.2008.00951.x.

Horsley S.B.; Long, R.P.; Bailey, S.W.; Hallett, R.A.; Hall, T.J. 1999. **Factors contributing to sugar maple decline along topographic gradients on the glaciated and unglaciated Allegheny Plateau.** In: Horsley, S.B.; Long, R.P., eds. Sugar maple ecology and health: Proceedings of an International Symposium. Gen. Tech. Rep. NE-261. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station: 60–62.

Horsley S.B.; Long, R.P.; Bailey, S.W.; Hallett, R.A.; Wargo, P.M. 2002. **Health of eastern North American sugar maple forests and factors affecting decline.** Northern Journal of Applied Forestry. (19): 33–34. https://doi.org/10.1093/njaf/19.1.34.

Horsley, S.B.; Stout, S.L.; deCalesta, D.S. 2003. **White-tailed deer impact on the vegetation dynamics of a northern hardwood forest**. Ecological Applications. 13(1): 98–118. https://doi.org/10.1890/1051-0761(2003)013[0098:wtdiot]2.0.co;2.

Kubiske, M.E.; Woodall, C.W.; Kern, C.C. 2019. **Increasing atmospheric CO_2 concentration stand development in trembling aspen forests: are outdated density management guidelines in need of revision for all species?** Journal of Forestry.117(1): 38–45. https://doi.org/10.1093/jofore/fvy058.

Long, R.P.; Horsley, S.B.; Hallett, R.A.; Bailey, S.W. 2009. **Sugar maple growth in relation to nutrition and stress in the northeastern United States**. Ecological Applications. 19(6): 1454–1466. https://doi.org/10.1890/08-1535.1.

Lorber, J.; Thomas-Van Gundy, M.; Croy, S. 2018. **Characterizing effects of prescribed fire on forest canopy cover in the George Washington and Jefferson National Forests**. Res. Pap. NRS-31. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 30 p. https://doi.org/10.2737/nrs-rp-31.

McGinley, K.A.; Guldin, R.W.; Cubbage, F.W. 2019. **Forest sector research and development capacity.** Journal of Forestry. 117(5): 443–461. https://doi.org/10.1093/jofore/fvz030.

Miller, K.M.; McGill, B.J. 2019. **Compounding human stressors cause major regeneration debt in over half of eastern US forests.** Journal of Applied Ecology. 56: 1355–1366. https://doi.org/10.1111/1365-2664.13375.

National Research Council. 2002. **National capacity in forestry research.** Washington, DC: National Academy Press 135 p. https://doi.org/10.17226/10384.

Norby, R.J.; DeLucia, E.H.; Gielen, B.; Calfapietra, C.; Giardina, C.P. [et al.] 2005. **Forest response to elevated CO_2 is conserved across a broad range of productivity.** Proceedings of the National Academy of Sciences. 102(50): 18052–18056. https://doi.org/10.1073/pnas.0509478102.

Peters, M.P.; Prasad, A.M.; Matthews, S.N.; Iverson, L.R. 2020. **Climate change tree atlas, version 4.** Madison, WI: U.S. Forest Service, Northern Research Station; and Houghton, MI: Northern Institute of Applied Climate Science. https://doi.org/10.2737/climate-change-tree-atlas-v4.

Reinhart, K.O.; Royo A.A.; Van Der Putten, W.H.; Clay K. 2005**. Soil feedback and pathogen activity in *Prunus serotina* throughout its native range**. Journal of Ecology. 93: 890–898. https://doi.org/10.1111/j.1365-2745.2005.01028.x.

Royo, A.A.; Kramer, D.W.; Miller, K.V.; Nibbelink, N.P.; Stout, S.L. 2017. **Spatio-temporal variation in foodscapes modifies deer browsing impact on vegetation.** Landscape Ecology. 32(12): 2281–2295. https://doi.org/10.1007/s10980-017-0568-x.

Royo, A.; Vickers, L.; Long, R.; Ristau, T.; Stoleson, S.; Stout; S.L. 2021. **The forest of unintended consequences: anthropogenic actions trigger the rise and fall of black cherry.** BioScience. 71(7): 686–696. https://doi.org/10.1093/biosci/biab002.

Stout, S.L., ed. 2019. **SILVAH: 50 years of science-management cooperation**, Proceedings of the Allegheny Society of American Foresters training session; 2017 Sept. 20-22; Clarion, PA. Gen. Tech. Rep. NRS-P-186. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 146 p. https://doi.org/10.2737/nrs-gtr-p-186.

Stout, S.L.; Brose, P.H. 2014. **The SILVAH saga: 40+ years of collaborative hardwood research and management highlight silviculture**. Journal of Forestry. 112(5): 434–439. https://doi.org/10.5849/jof.13-099.

Thomas, R.Q.; Canham, C.D.; Weathers, K.C.; Goodale, C.L. 2010. **Increased tree carbon storage in response to nitrogen deposition in the US.** Nature Geoscience. 3(1): 13–17. https://doi.org/10.1038/ngeo721.

Tilghman, N.G. 1989. **Impacts of white-tailed deer on forest regeneration in northwestern Pennsylvania.** The Journal of Wildlife Management. 524–532. https://doi.org/10.2307/3809172.

USDA Forest Service. 2020. **2020 USDA Explanatory Notes – Forest Service.** Washington, DC: U.S. Department of Agriculture, Forest Service. https://www.fs.usda.gov/sites/default/files/media_wysiwyg/usfs-fy-2020-budget-justification.pdf (accessed May 8, 2021.)

Vickers, L.A.; McWilliams, W.H.; Knapp, B.O.; D'Amato, A.W.; Dey, D.C. [et al.] 2019. **Are current seedling demographics poised to regenerate northern US forests?** Journal of Forestry. 117(6): 592–612. https://doi.org/10.1093/jofore/fvz046.

Walters, M.B.; Roloff, G.J.; Henry, C.R.; Hartman, J.P.; Donovan, M.L. [et al.]. 2020. **Rethinking northern hardwood forest management paradigms with silvicultural systems research: research–management partnerships ensure relevance and application.** Journal of Forestry. 118(3): 260–274. https://doi.org/10.1093/jofore/fvz071.

Wheeler, N.C.; Steiner, K.C.; Schlarbaum, S.E.; Neale, D.B. 2015. **The evolution of forest genetics and tree improvement research in the United States.** Journal of Forestry. 113(5): 500–510. https://doi.org/10.5849/jof.14-120.

CITATION: Stout, Susan L.; Hille, Andrea T.; Royo, Alejandro A. 2023. **Science-Management Collaboration is Essential to Address Current and Future Forestry Challenges.** In: Kern, Christel C.; Dickinson, Yvette L., eds. Proceedings of the first biennial Northern Hardwood Conference 2021: Bridging science and management for the future. Gen. Tech. Rep. NRS-P-211. Madison, WI: U.S. Department of Agriculture, Forest Service, Northern Research Station: 15–24. https://doi.org/10.2737/NRS-GTR-P-211-paper5.