Research and Management Partnerships for Resolving Regeneration and Recruitment Challenges in Hardwood–Softwood Mixtures in Eastern North America

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ABSTRACT.—Naturally occurring mixtures of hardwoods and softwoods are found throughout the eastern United States and Canada. They are compositionally diverse and appear to have originated from a complex array of natural disturbances or past harvesting. Contemporary mixedwood stands can be difficult to regenerate and manage because individual species of these mixtures have differing shade tolerances, growth rates, longevities, phenology, and crown and root structure. Consequently, they often cannot be sustained without deliberate silvicultural efforts to regenerate and recruit desirable species. Despite the difficulties, foresters are interested in managing hardwood–softwood mixtures because of the many benefits that they confer including increased resistance to pests and diseases, improved habitat diversity, enhanced climate change resilience and adaptability, and increased diversity of forest products. The interest in and the challenges related to managing these mixtures have led to the development of many research-management partnerships across the eastern United States and Canada to resolve regeneration and recruitment problems. Here we discuss the regeneration and recruitment challenges for a variety of hardwood–softwood mixtures across the eastern United States, identify the research-management partnerships that have developed to address them, and describe how these partnerships are leading to solutions.

INTRODUCTION

Mixedwoods are stands that include mixtures of hardwoods and softwoods, with neither component comprising more than approximately 75 to 80 percent of the composition (Helms 1998). There are many different naturally occurring mixedwood types presently recognized throughout eastern North America including hemlock–yellow birch, white pine–northern red oak–red maple, shortleaf pine–oak, and loblolly pine–hardwood (see Table 2 for scientific names of tree species). However, data from the USDA Forest Service's Forest Inventory and Analysis (FIA) program indicate extensive acreages of hardwood–softwood mixtures, even for forest types that nominally include only hardwoods or softwoods (Table 1). Mixedwoods can occur as isolated stands within hardwood- or softwood-dominated landscapes or they can cover a large proportion of a forest landscape.

There is growing interest in managing mixed-species forests worldwide (Bravo-Oviedo et al. 2018, Waldrop 1989), and in eastern North America there is a particular interest in mixtures of

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Table 1.—Estimates of forest land area by forest-type across for 24 northeastern U.S. states[a], according to Forest Service Forest Inventory and Analysis Program data. Data from USDA Forest Service 2019.

Forest type	Hardwood	Softwood	Mixedwood	Area with no trees ≥5 in. d.b.h.	Total
			acres		
Aspen/birch	8,008,668	709,436	5,782,817	1,165,786	15,666,706
Douglas-fir		3,785	3,546		7,330
Elm/ash/cottonwood	11,720,566	151,667	2,068,484	390,278	14,330,995
Exotic hardwoods	301,784	6,803	17,957	5,854	332,399
Exotic softwoods	8,965	342,164	251,753	19,617	622,499
Fir/spruce/mt. hemlock		10,707		1,924	12,632
Loblolly/shortleaf pine	18,649	831,189	895,953	29,823	1,775,613
Maple/beech/birch	29,596,562	309,479	14,885,989	449,198	45,241,228
Nonstocked	612,345	279,316	75,439	632,599	1,599,700
Oak/gum/cypress	695,445	31,078	99,482	2,957	828,961
Oak/hickory	57,036,881	226,789	7,367,792	925,432	65,556,894
Oak/pine	140,323	257,907	5,496,269	118,519	6,013,018
Other eastern softwoods	44,763	541,042	369,110	56,506	1,011,422
Other hardwoods	1,239,787	200,656	471,935	271,451	2,183,829
Other softwoods			971		971
Pinyon/juniper		156,156	42,581	463	199,200
Ponderosa pine		1,217,560	76,040	14,244	1,307,845
Spruce/fir	55,278	10,738,601	4,433,130	1,060,993	16,288,001
White/red/jack pine	71,643	4,389,780	4,650,373	292,540	9,404,336
Total	109,551,660	20,404,116	46,989,618	5,438,184	182,383,578

[a] In addition to the 20-state region defined in footnote 2 (page 131), forest land from an additional four states are included in these estimates: North Dakota, South Dakota, Nebraska, and Kansas. Mixedwood stands are defined on page 129.

hardwoods and softwoods growing together in the same stand (Kabrick et al. 2017). Mixtures are of interest because they provide compositionally and structurally diverse habitats (Comeau 1996, Girard et al. 2004, Jung et al. 1999) and because, compared to pure stands, they are more resistant or resilient to contemporary insect outbreaks and diseases (Campbell et al. 2008, Su et al. 1996). They produce a diverse revenue stream that is more economically resilient to changes in timber markets. They have the potential to produce more biomass, store more carbon, and produce more timber due to their structural complexity and vertical stratification that occurs because of differences in the growing space requirements of the component species. There is some evidence supporting the hypothesis that mixedwoods are equally or better adapted to forecasted changes in climate than their pure hardwood or softwood analog (Kabrick et al. 2017).

However, despite occurring naturally throughout eastern North America, mixedwoods are often a challenge to manage due to differing shade tolerances, growth rates, longevities, phenology, and crown and root structure of the component species (Kelty et al. 1992, Pretzsch 2014, Prévost 2008). In addition, historical land use in some regions often selectively removed conifer species from mixedwoods, limiting current availability of on-site seed sources (Kelty and D'Amato 2006). Species within mixedwoods often employ differing regeneration and growth strategies. Consequently, regenerating and recruiting mixtures can be challenging. Without carefully timed disturbances, mixedwoods transition into softwood or hardwood stands.

THE MIXEDWOOD INITIATIVE

The interest in restoring or managing mixedwoods and the long-standing challenges associated with their regeneration and tree recruitment in the eastern United States and Canada led to the development of many local partnerships between scientists and managers (Table 2). Partnerships often developed as isolated collaborations in response to local mixedwood management challenges. Many of these partnerships in the United States were between USDA Forest Service Research and Development scientists and National Forest managers or with state land managers. Many of these studies also included university partners. Although some of the studies focused on examining whether an increasing hardwood or softwood component in pure stands increased resistance or resilience to contemporary or emerging pest problems, most focused on resolving regeneration and recruitment problems in mixedwoods.

In April 2014, leadership within the Forest Service, Northern Research Station (hereafter referred to as Station), recognized that there were a number of research-management partnerships across the Station and beyond the 20-state Station boundary[2], each addressing information needs for managing hardwood–softwood mixtures. Station management proposed that a larger partnership would foster broader thinking about mixedwood ecology and silviculture and serve as a means for linking opposite corners of the Station and their partner land management agencies and universities around a common problem. By working together across the Station and beyond its borders, the scope of this research-management effort would expand, providing a more integrated and broadly cohesive problem identification and knowledge from a larger network of scientists and managers to more effectively identify and resolve some of the silvicultural issues. Funding was identified to help initiate this effort to be used for developing special sessions or symposia and work sessions organized by the scientific team members of the partnership. This effort become known among its members as the "Mixedwood Initiative."The founding scientific team members of the Mixedwood Initiative included Northern Research Station scientists and a number of their associates from other government agencies and universities (Table 3) including members from several U.S. states and Canadian. This group's approach was to pursue a research program working with management partners addressing the following themes and questions:

1. Resilience/resistance

- Are mixedwoods more resistant/resilient to contemporary or emerging pests and pathogens, or to changing climates, compared to their hardwood or softwood counterpart alone?
- Can resistance or resilience of mixedwoods be enhanced by management?

2. Function and services

- Do mixedwoods yield more merchantable biomass or store more carbon than their hardwood or softwood counterparts alone?
- Do mixedwoods contain a more diverse community of flora or provide more diverse habitats than their hardwood or softwood counterparts alone?

[2] Northern Research Station boundaries consist approximately of the area between Maine, west to Minnesota, south to Missouri, and east to West Virginia.

Table 2.—Examples of local partnerships for examining the benefits and addressing the silvicultural issues associated with managing mixedwood stands

Forest type	Partnerships	Project themes	Persistent issues
Shortleaf pine–oak (*Pinus echinata* Mill., *Quercus* spp.)	Mark Twain National Forest, research group NRS-11[a], Univ. of Missouri, Univ. of Tennessee	Regenerating and recruiting shortleaf pine to restore mixed pine–oak forests and woodlands	Information is needed for managing intense hardwood competition during shortleaf pine recruitment; interest in the role and timing of fire, herbicides, stock types (bareroot vs. container) for successful shortleaf pine regeneration and recruitment
Shortleaf pine–white pine–oak (*Pinus echinata* Mill., *Pinus strobus* L., *Quercus* spp. L.)	Pisgah National Forest, research group SRS-4157[a], Virginia Tech Univ.	Examining effects of planting stock (bareroot vs. container) on survival, growth, and competition with naturally regenerated hardwood and softwood species (e.g., eastern white pine) Quantifying effects of top-kill (clipping vs. burning) during different seasons (dormant/fall vs. spring/growing) on resprouting potential and subsequent growth of shortleaf pine.	Information is needed for managing intense hardwood competition during recruitment phase; lingering questions about the role and timing of prescribed fire, herbicides, and stock types (bareroot vs. container) for successful establishment and recruitment
Loblolly pine–oak (*Pinus taeda* L., *Quercus* spp. L.)	Bankhead National Forest, research group SRS-4157[a]	Regenerating oaks in former loblolly pine plantations; using mixedwoods as an intermediary to restoring hardwood forests	Information is needed about the establishment of oak under partially harvested loblolly pine stands and how to transition loblolly pine plantations into diverse, oak-dominated hardwood forests
Pitch pine–oak (*Pinus rigida* Mill., *Quercus* spp. L.)	New Jersey Forest Fire Service, New Jersey Env. Protection, research group NRS-6[a], Dartmouth College, Rutgers Univ.	Quantifying resistance and resilience of oak – pine mixtures to gypsy moth and southern pine beetle	Information is needed about how climate is affecting the ecological processes and successional changes in this region
Hemlock–hardwoods (*Tsuga Canadensis* [L.] Carr., mixed hardwoods)	Research groups NRS-7 and NRS-11[a], Clarion Univ., State of Wisconsin Board of Commissioners of Public Lands	Developing and evaluating silvicultural methods for regenerating and recruiting eastern hemlock and yellow birch (*Betula alleghaniensis* Britton) along with other hardwoods and softwoods	Information is needed about how to produce a suitable seedbed for light-seeded species such as eastern hemlock and yellow birch that require exposed mineral soil and woody debris in addition to canopy gaps created through single-tree or group selection for regeneration and recruitment

continued

Table 2.—Continued

Forest type	Partnerships	Project themes	Persistent issues
Eastern white pine–northern red oak (*Pinus strobus* L., *Quercus rubra* L.)	Research group NRS-7 [a], Univ. of Maine, Paul Smith's College, Univ. of Vermont	Developing and evaluating silvicultural methods for the regeneration and recruitment of oak–pine mixtures	Information is needed about how to manage hardwood competition during softwood recruitment, particularly on rich sites; lack of appropriate light conditions for maintaining advance regeneration of species prior to overstory disturbance
Northern white-cedar–mixed hardwoods (*Thuja occidentalis* L., hardwoods)	Research group NRS-7 [a], Laval Univ., Univ. of Maine, Cooperative Forestry Research Unit, The Nature Conservancy, Wisconsin Dept. of Natural Resources, Canadian Forest Service, Quebec Ministry of Forests, Parks, and Wildlife	Developing methods for regenerating and recruiting northern white-cedar along with other hardwoods and softwoods	Information is needed for resolving a region-wide problem with regeneration and recruitment of northern white-cedar, particularly where browsing by white-tailed deer (*Odocoileus virginianus)* is high and where harvesting practices favor competing species
Spruce–fir–hardwoods (*Picea rubens* Sarg., *Abies balsamea* (L.) Mill., hardwoods)	Research group NRS-7 [a], Univ. of Maine, Laval Univ., Canadian Forest Service, Quebec Ministry of Forests, Parks, and Wildlife, Univ. of Vermont.	Developing and evaluating silvicultural systems for maintaining mixed species composition and the structural attributes and functions needed for sustainable production and resiliency to climate change	Information is needed about the regeneration and recruitment of red spruce, balsam fir, yellow birch (*Betula alleghaniensis* Britton) along with sugar maple and other hardwoods
Fir–hardwoods (*Abies balsamea* [L.] Mill., hardwoods)	Univ. of New Brunswick, Natural Resources Canada	Quantifying the resistance and resilience of fir–hardwood mixtures to spruce budworm defoliation	Information is needed about how increasing the hardwood component in fir–hardwood mixtures reduces balsam fir defoliation by spruce budworm (*Choristoneura fumiferana* Clem.)

[a] Research groups refer to administrative designations within the USDA Forest Service Research and Development program. NRS designates groups that are part of the Northern Research Station; SRS designates groups that are part of the Southern Research Station.

Table 3.—Founding science partners of the Northern Research Station's "Mixedwood Initiative"

Name	Affiliation	Mixedwood forest type
John M. Kabrick	USDA Forest Service, Northern Research Station, Columbia, MO	Shortleaf pine–oak
Kenneth L. Clark	USDA Forest Service, Northern Research Station, New Lisbon, NJ	Pitch pine–oak
Anthony W. D'Amato	University of Vermont	White pine–northern red oak Spruce–fir–hardwoods
Daniel C. Dey	USDA Forest Service, Northern Research Station, Columbia, MO	Shortleaf pine oak
Laura S. Kenefic	USDA Forest Service, Northern Research Station, Bradley, ME	Spruce–fir–hardwoods
Christel C. Kern	USDA Forest Service, Northern Research Station, Rhinelander, WI	Hemlock–hardwoods
Benjamin O. Knapp	University of Missouri	Shortleaf pine–oak
David. A. MacLean	University of New Brunswick	Fir–hardwoods
Patricia Raymond	Ministère des Forêts, de la Faune et des Parcs du Québec	Spruce–fir–yellow birch
Justin D. Waskiewicz	Paul Smith's College	White pine–northern red oak

3. Ecology and silviculture

- Are mixedwoods stable forest types or transitional states?
- How are trees arranged spatially and vertically in mixedwoods?
- How are mixedwoods regenerated where they contain species with widely differing regeneration mechanisms, shade tolerances, and growth strategies?
- How are mixedwoods thinned or tended where they contain species with widely differing growth rates, longevities, and tolerances?
- What are the historical and contemporary recruitment dynamics for mixedwoods across broad spatial scales?

The Mixedwood Initiative is not limited exclusively to its founding members. Other scientist-manager partners working on mixedwoods are joining the effort and are participating in mixedwood meeting sessions and publishing papers along with the founding members.

PARTNERSHIP ACCOMPLISHMENTS

The Mixedwood Initiative goal is to produce three major types of accomplishments. The first was to maintain local scientist-manager partnerships to develop practical information and publications needed for evaluating the benefits of managing for various mixtures occurring in the eastern United States and Canada. The second was to develop synthesis publications addressing the benefits and silvicultural challenges of eastern mixtures and to identify common issues, processes, and problems occurring in mixedwoods in different ecoregions. The third was to engage with managers and fellow scientists in a variety of conference sessions and field workshops to share local and broader-scale findings related to the benefits and silviculture of mixedwood types. Examples of accomplishments are listed in Table 4 and include publications describing findings from local experiments, a synthesis publication, and sessions in conferences and workshops organized by the Mixedwood Initiative team members.

Table 4.—Accomplishments of the Mixedwood Initiative and partnerships since its inception in 2014

Accomplishment	Product Examples
Development of locally important, practical information and publications needed for evaluating the benefits of or managing for various mixedwoods occurring in the eastern US and Canada	Publications 1. Kenefic, L.S. [et al.]. 2014. Silvicultural rehabilitation of cutover mixedwood stands. *See full citation in Literature Cited section.* 2. Kabrick, J.M. [et al.]. 2015. Effect of initial seedling size, understory competition, and overstory density on the survival and growth of Pinus echinata seedlings underplanted in hardwood forests for restoration. *See full citation in Literature Cited section*. 3. Puhlick, J.J. [et al.]. 2016. Factors influencing organic-horizon carbon pools in mixed-species stands of central Maine, USA. *See full citation in Literature Cited section.* 4. Raymond, P. [et al.]. 2016. Patch cutting in temperate mixedwood stands: what happens in the between-patch matrix *See full citation in Literature Cited section.* 5. Raymond, P.; Bedard, S. 2017. The irregular shelterwood system as an alternative to clearcutting to achieve compositional and structural objectives in temperate mixedwood stands. *See full citation in Literature Cited section.* 6. Raymond, P. [et al.] 2018. Assessing the single-tree and small group selection cutting system as intermediate disturbance to promote regeneration and diversity in temperate mixedwood stands. *See full citation in Literature Cited section.* 7. Zhang, B. [et al.]. 2018. Effects of hardwood content on balsam fir defoliation during the building phase of a Spruce Budworm outbreak. *See full citation in Literature Cited section.* 8. Jin, W. [et al.]. 2018. How can prescribed burning and harvesting restore shortleaf pine-oak woodland at the landscape scale in central United States? Modeling joint effects of harvest and fire regimes. *See full citation in Literature Cited section.* 9. Kern, C. [et al.]. 2019. Mounds facilitate regeneration of light-seeded and browse-sensitive tree species after moderate-severity wind disturbance. *See full citation in Literature Cited section.* 10. Muñoz Delgado, B.L. [et al.]. 2019. Northern mixedwood composition and productivity 50 years after whole-tree and stem-only harvesting with and without post-harvest prescribed burning. *See full citation in Literature Cited section.* 11. Power, H. [et al.]. 2019. Basal area and diameter growth in high-graded eastern temperate mixedwood forests: the influence of acceptable growing stock, species, competition, and climate. *See full citation in Literature Cited section.* 12. Puhlick, J.P. [et al.] 2019. Crop tree growth response and quality after silvicultural rehabilitation of cutover stands. *See full citation in Literature Cited section.*
Development of synthesis publications and scientific products for assessing the benefits and silvicultural challenges of all eastern mixedwoods and to look for common issues	Publication 1. Kabrick, J.M. [et al.]. 2017. Managing hardwood-softwood mixtures for future forests in eastern North America: assessing suitability to projected climate change. *See full citation in Literature Cited section*.
Engagement with managers and fellow scientists in a variety of conference sessions and field workshops	Conferences and Workshops 1. New England Society of American Foresters (SAF) annual winter meeting (Fairlee, VT; March 2015) Three-talk session: Mixedwood Management. 2. National Silviculture Workshop (Baton Rouge, LA; October 2015) Presentation: Managing "Mixedwoods" for Future Forests in Eastern North America: Current State of Knowledge and Research Needs. 3. SAF national convention (Madison, WI; November 2016) Nine-paper session moderated by J.M. Kabrick and B.O. Knapp: The Benefits and Challenges Of Managing Hardwood – Softwood Mixtures In Eastern North America. 4. Eastern CANUSA (Burlington, VT; October 2016) Presentation: Managing Multi-aged Mixedwood Stands: Perspectives from the Penobscot Experimental Forest in Maine, USA. 5. Presentation: Northern mixedwood site productivity 50 years after whole-tree and stem-only harvesting, with and without prescribed burning. 6. Eastern CANUSA (Fredericton, NB; October 2018) Four-paper session moderated by D.A. MacLean: Mixedwood Management. 7. North American forest ecology workshop (Flagstaff, AZ; June 2019) Eight-paper session: Promoting Forest Resistance and Resilience Through Mixedwood Management.

KEY FINDINGS

Our assessments related to resistance and resilience to pests and pathogens and future climate suitability suggests that mixedwoods provide many advantages compared to pure hardwood or softwood stands. For example, balsam fir (*Abies balsamea*) grown with hardwoods in the Great Lakes-St. Lawrence forest region in Quebec has proportionally less defoliation from spruce budworm (*Choristoneura fumiferana)* than pure fir stands or plantations (Zhang et al. 2018). Preliminary data from the mid-Atlantic region of the eastern United States suggest that pitch pine (*Pinus rigida*) mixed with oak (*Quercus* spp.) has lower mortality from southern pine beetle (*Dendroctonus frontalis*) attacks than high-density, pine-domiz nated stands. Oaks in these pitch pine–oak mixtures also appear to have less defoliation by gypsy moth (*Lymantria dispar)*. Data from the Forest Service's Climate Change Tree Atlas (Prasad et al. 2014) suggest that most mixtures occurring in the eastern United States are composed of tree species that were equally or better suited to climate change scenarios than are pure stands (Kabrick et al. 2017).

Regardless of mixedwood type, our assessment suggests that regenerating or recruiting the softwood component is a universal problem in eastern mixedwoods. In the absence of appropriate disturbances, many mixedwood forests transition into hardwood-dominated stands. Thus, maintaining mixedwoods requires conditions for the establishment, early growth, and recruitment of limiting species, such as eastern hemlock (*Tsuga canadensis*), red spruce (*Picea rubens*), or shortleaf pine (*Pinus echinata*), to be carefully managed. Considerations include maintaining the seed source and creating suitable seedbed for limiting species by exposing mineral soil through mechanical scarification for yellow birch (*Betula alleghaniensis*) or hemlock (Kern et al. 2017, 2019) or prescribed burning for pines (Clabo and Clatterbuck 2015), or by retaining highly decayed deadwood for spruce (Raymond and Bédard 2017) or hemlock (Kern et al. 2017). In the absence of conditions suitable for germination, underplanting pine (Kabrick et al. 2015) or spruce (Kenefic et al. 2014, Raymond et al. 2018) or other artificial methods may be required. Controlling the microclimate to meet the shade and light requirements of varying species can be accomplished with irregular shelterwoods or group selection in spruce–hardwoods (Raymond et al. 2018), shelterwoods in fir–hardwoods (Raymond and Bédard, 2017), or shelterwood and seed tree methods in shortleaf pine–oak (Kabrick et al. 2015). Competition control can be accomplished via mechanical or chemical treatments in northern temperate forests or prescribed fires in central and mid-Atlantic regions (Fig. 1).

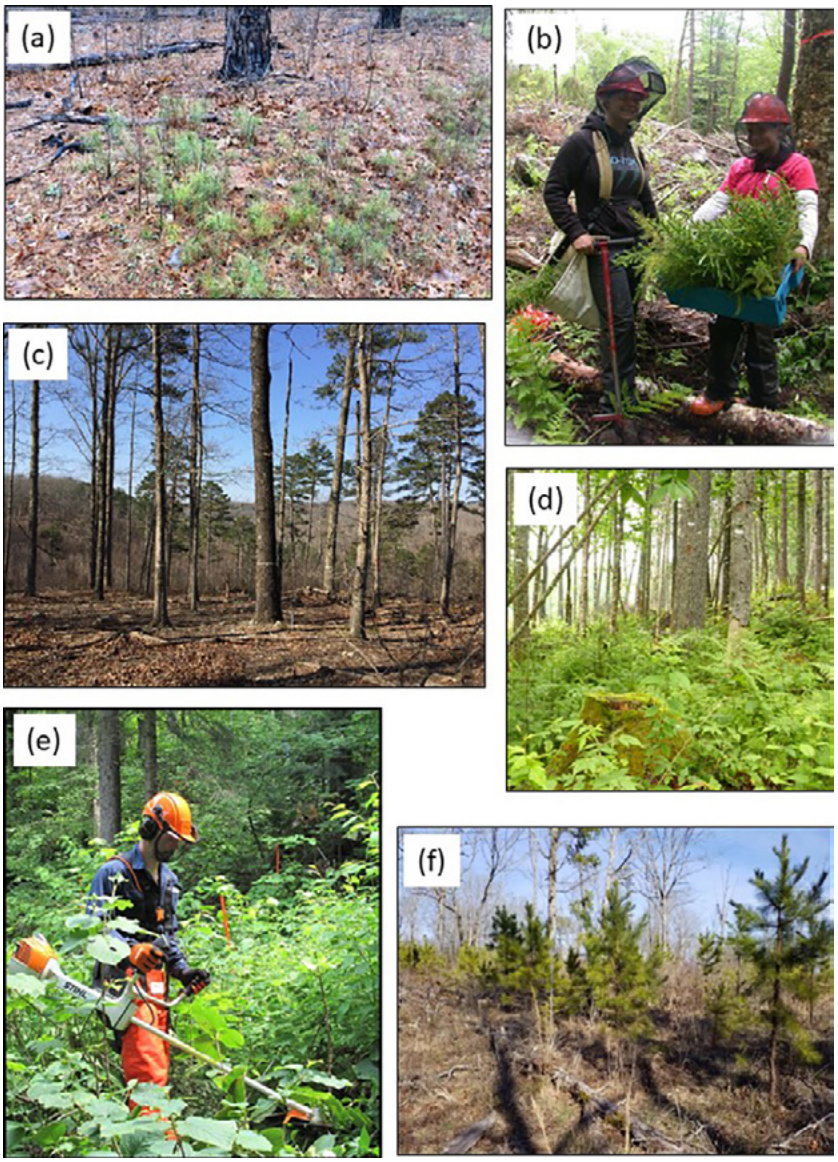

Figure 1.—Methods to facilitate regeneration and recruitment of mixedwoods including (a) maintaining a suitable seedbed such as with prescribed burning for shortleaf pine in pine–oak mixes, (b) underplanting species such as red spruce in spruce–fir–hardwood mixes, controlling the microclimate to meet the shade and light requirements of varying species accomplished through partial cutting such as with shelterwood and seed tree methods (c) or irregular shelterwoods (d); and controlling hardwood competition via mechanical (e, f) and chemical methods or prescribed fire. Photos a and f by the USDA Forest Service; photo c by Benjamin Knapp, used with permission; photos b, d, and e by Patricia Raymond, used with permission.

SUMMARY

Hardwood–softwood mixtures offer benefits but also many silvicultural challenges. The Mixedwoods Initiative was formed in northeastern North America to assess benefits and resolve management problems with sustaining these types. During the past 5 years, members of the Mixedwood Initiative have developed research and information products needed for managing for mixedwoods through scientist-manager partnerships. These partnerships facilitate local and regional collaboration among scientists and managers for producing practical information relevant to managers, and highly technical information of interest to a broader scientific audience for advancing knowledge about mixedwood ecology and silviculture. This initiative has created a powerful collaborative framework for guiding a long-term, regional research agenda focused on the silviculture and ecology of these critically important forest types.

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