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Accelerating the Development of Old-growth Characteristics in Second-growth Northern Hardwoods

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Abstract

Active management techniques that emulate natural forest disturbance and stand development processes have the potential to enhance species diversity, structural complexity, and spatial heterogeneity in managed forests, helping to meet goals related to biodiversity, ecosystem health, and forest resilience in the face of uncertain future conditions. There are a number of steps to complete before, during, and after deciding to use active management for this purpose. These steps include specifying objectives and identifying initial targets, recognizing and addressing contemporary stressors that may hinder the ability to meet those objectives and targets, conducting a pretreatment evaluation, developing and implementing treatments, and evaluating treatments for success of implementation and for effectiveness after application. In this report we discuss these steps as they may be applied to second-growth northern hardwood forests in the northern Lake States region, using our experience with the ongoing managed old-growth silvicultural study (MOSS) as an example. We provide additional examples from other applicable studies across the region.

Quality Assurance

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Cover Photos

Left: Standing dead wood in mesic forest, photo by Michele Woodford, Wisconsin DNR, used with permission. Right, top: Canopy gap, photo by Joshua Waukau, Wisconsin DNR, used with permission. Right, middle: large white pine in northern hardwoods, photo by J. Paul White, Wisconsin DNR, used with permission. Right, bottom: forest products from initial structural complexity harvest, photo by Karin Fassnacht, Wisconsin DNR, used with permission.

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INTRODUCTION

Maintaining compositional **diversity**[1], **structural complexity**, and **spatial heterogeneity** in forests is increasingly being recognized as necessary for sustaining forest ecosystem health and resilience (Addis et al. 1995, Kern et al. 2013, Mladenoff and Pastor 1993), particularly in the face of increased stresses from invasive species and climate change (Brang et al. 2014, Drever et al. 2006, O'Hara and Ramage 2013, Rhemtulla et al. 2009). In the northern Lake States (Minnesota, Wisconsin, Michigan), forest complexity, heterogeneity, and compositional diversity were reduced as a result of extensive forest cutting and burning at the turn of the 19th century. These events largely eliminated formerly dominant conifer species such as eastern white pine (*Pinus strobus*) and eastern hemlock (*Tsuga canadensis*), increased the amount of aspen (*Populus* spp.) and maple (*Acer* spp.) (Mladenoff and Pastor 1993, Schulte et al. 2007), and significantly reduced the percentage of trees in medium and large size classes (i.e., >25 cm **diameter at breast height** [d.b.h.]) (Rhemtulla et al. 2009). Although much of the region has reforested, the composition and **structure** of these second-growth systems are quite different from the old-growth forests that once predominated (Schulte et al. 2007).

In **northern hardwood forests** of the region, traditional forest management has contributed to maintaining systems that are less diverse in species composition (Crow et al. 2002) and less complex and heterogeneous in structure (Crow et al. 2002, Goodburn and Lorimer 1998) compared to the mature and old-growth forests (i.e., primary forest ≥120 yr old) which previously comprised almost 90 percent of the northern hardwoods in this region (Frelich 1995) (Table 1). In particular, a common management approach for these forests has been single-tree selection, with emphasis on removing defective, dead, and dying trees, as well as "less desirable" tree species (Arbogast 1957). As a result of these practices, structural components such as large standing dead wood (i.e., snags >45 cm d.b.h.) and large downed dead wood (>40 cm diameter) have been found to be significantly less abundant in managed **uneven-aged** and unmanaged **even-aged** northern hardwood forests in northern Wisconsin and the Upper Peninsula of Michigan compared to old growth (Goodburn and Lorimer 1998). Studying similar forest types in the same region, Scheller and Mladenoff (2002) found that understory species richness in old growth was less than in the other two forest types, but that the variability of species composition in patches of understory vegetation (i.e., spatial heterogeneity) was greater, and the average size of those patches was smaller in the older forests. At the stand scale, the average size of understory vegetation patches is strongly correlated with both **coarse woody debris** (CWD) and variability in understory light availability (Scheller and Mladenoff 2002). In a related study, bird species richness and abundance were found to be similar in old-growth and managed uneven-aged stands, and no species was strictly limited to old growth, but the extensive old-growth forests did have some distinct assemblages of bird species (Howe and Mossman 1995).

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[1] Words in bold are defined in the glossary that begins on page 32.

Table 1.—Comparison of selected characteristics of northern Lake States northern hardwoods among old-growth forests (OG), second-growth forests that are not managed (NM), second-growth forests under uneven-age management (UM), and second-growth forests under even-age management (EM)

Feature	EM	NM	UM	OG	Example	Reference
Large trees [percent of stems]	less	–	less	more	50 cm class UM = 3.2 OG = 7.9 ≥60 cm class UM = 3.2 OG = 5.7 (Hale)	Hale et al. (1999) – values derived from bar chart
					≥39.1 cm EM = 6.9 UM = 13.4 OG = 23.5 ≥49.1 cm EM = 1.2 UM = 4.1 OG = 11.3 (Angers)	Angers et al. (2005)
Standing dead wood – large d.b.h. [>45 cm G&L; ≥49.1 cm Angers]	–	less	less	more	NM = 2/ha, UM = 4/ha, OG = 17/ha (G&L)	Goodburn and Lorimer (1998)
	intermed* (but not signif)	–	less* (but not signif)	more (but not signif)	EM = 4.9/ha UM = 1.4/ha OG = 7.6/ha (Angers)	Angers et al. (2005) – *Year of last harvest for EM stand cut was ~20 yr longer ago vs for UM stand
Downed dead wood – large [>40 cm]	–	less	intermediate	more	NM ~ 2 m^3/ha UM ~ 15 m^3/ha OG ~ 37 m^3/ha	Goodburn and Lorimer (1998) – from graph
Gaps – sizes [m^2]	–	smaller (but not signif)	intermediate (but not signif)	larger (but not signif)	NM = 9-11 OG = 37-49 (Dahir)	Dahir and Lorimer (1996)
					NM = 19.3 UM = 41.1 OG = 64.6 (Gdbrn)	Goodburn (1996)
Gaps – diversity of sizes [range in m^2]	–	less	intermediate	more	NM = <10 to 30 OG = <10 to 130 (Dahir)	Dahir and Lorimer (1996)
					NM = 6 to 48 UM = 6 to 299 OG = 11 to 404 (Goodburn)	Goodburn (1996)
Gaps – number [No./ha]	–	less (but not signif)	more (but not signif)	intermediate (but not signif)	NM = 5.0 UM = 30.0 OG = 16.7	Goodburn (1996)
Diversity of tree sizes [range of d.b.h. classes]	–	less	less	more	NM = 4 to 60 cm UM = 4 to 68 cm OG = 4 to 84 cm	Goodburn (1996)

continued

Table 1.—continued

Feature	EM	NM	UM	OG	Example	Reference
Snags with loose bark plates	–	no diff	no diff	no diff	No./ha NM = 3.3 UM = 5.3 OG = 3.3 percent of snags NM = 3.7 UM = 13.9 OG = 8.5	Goodburn and Lorimer (1998)
Tip-up mounds [percent area covered by recent pit + mound]	–	no diff	no diff	no diff	NM = 0.1 UM = 0.8 OG = 0.6	Goodburn and Lorimer (1998)
Vertical complexity [variance of canopy tree ht & depth of main canopy layer]	–	less	intermediate	more	pooled variance NM = 7.1 UM = 19.9 OG = 44.8 depth of layer NM = 10.3 UM = 12.4 OG = 15.3	Goodburn (1996)
Horizontal complexity [avg coefficient of variation for total crown area of understory (<6 m) for 100 m^2 patch sizes]	–	no diff	no diff	no diff	NM = 97 percent UM = 68 percent OG = 62 percent	Goodburn (1996)
Spp richness – overstory [No. spp]	no diff	no diff	no diff	no diff	EM = 13 NM = 16 UM = 11 OG = 16 (Crow)	Crow et al. (2002) – avg 2 yr post-trt
					NM = 5.8 UM = 5.7 OG = 5.2 (Gdbrn)	Goodburn (1996) – avg 7 yr post-trt
Spp richness – understory [shrub and small tree]	no diff	no diff	no diff	no diff	EM = 14 NM = 14 UM = 10 OG = 10	Crow et al. (2002) – avg 2 yr post-trt
Diversity of light environments [avg variance in avail. seasonal solar radiation at 0.5 ha scale]	–	–	less	more	UM = 13 percent OG* = 132 percent	Hanson and Lorimer (2007) – *comparing mature and OG wind-disturbed vs UM

Restoring or conserving old-growth northern hardwood forests could contribute to enhancing the **biodiversity** of the northern Lakes States region. At the landscape scale, old-growth forest would contribute to the mosaic of forest ages and types, increasing the representation of a formerly abundant ecological condition. At the stand scale, the increased compositional diversity, structural complexity, and spatial heterogeneity of composition and structure naturally found in older forests would provide variability and habitat **niches** not found, or found to a lesser extent, in younger managed forests (Gilbert et al. 1997, Howe and Mossman 1995, Lindner et al. 2006, Werner and Raffa 2000, Will-Wolf and Nelsen 2008) (Table 1). Particularly important in older forests are age-related structural features such as large dead wood (Fig. 1), large canopy gaps, **supercanopy** trees, cavity trees, and **tip-up mounds** (Mladenoff and Pastor 1993, Schaetzl et al. 1989).

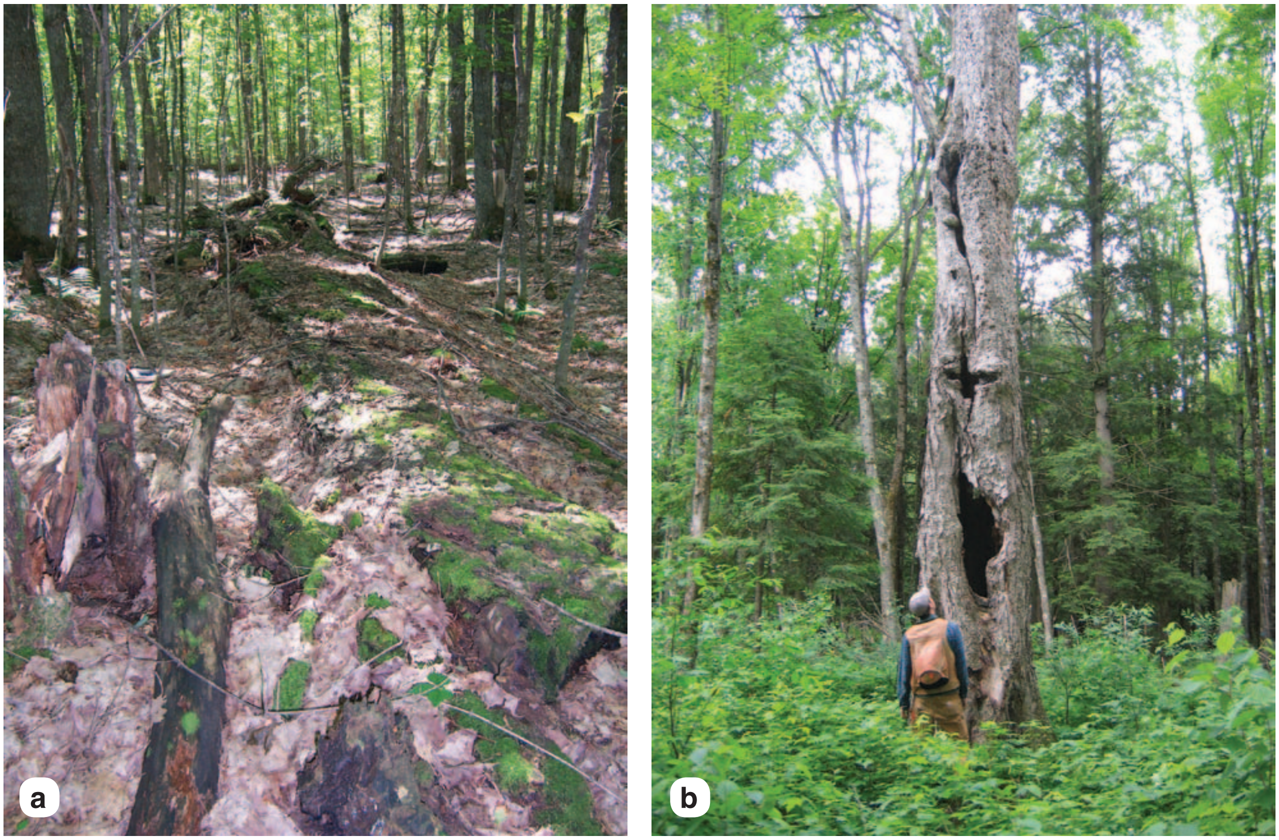

Figure 1.—Large (a) downed wood and (b) standing dead wood in mesic, nutrient-rich northern hardwood forests in northern Wisconsin. Photo (a) by J. Paul White, WDNR; photo (b) by Michele Woodford, WDNR; both used with permission.

Restoring old-growth conditions through **passive management** (i.e., permanently protecting areas from harvest) is desirable for some portion of the landscape (Bauhus et al. 2009, Mladenoff and Pastor 1993). However, this technique alone will not provide significant increases in acreage with old-forest conditions. Reasons include the long time period needed to attain old-growth characteristics in this forest type in the absence of management (Lorimer and Frelich 1994) and the continued demand for forest products and a finite forest land area with which to produce them. As a result, goals of forest biodiversity, health, and resilience will not be met through passive management alone (Bauhus et al. 2009, Mladenoff and Pastor 1993).

Active management techniques may offer an alternative. Recently, there has been increased discussion advocating the use of **silvicultural techniques** that better emulate natural forest disturbance and stand development to enhance biodiversity and structural characteristics in managed forests (Aplet and Keeton 1999, Crow and Perera 2002, Franklin et al. 2007, Palik et al. 2002, Zasada et al. 2004). While true old-growth forest cannot be restored through active management due to the extractive nature of such management, there is evidence that it is the structural features associated with old-growth forests, rather than the age of the forest itself, that is linked to the occurrence of many old-growth-associated species (Bauhus et al. 2009). Consequently, it may be possible to increase the benefits of old-forest characteristics in the broader forest landscape by accelerating the development of old-growth characteristics through active management if techniques can be found that do not substantially compromise other benefits derived from the forest.

In this report, we discuss issues to be considered when contemplating the use of active management to accelerate the development old-growth characteristics in second-growth northern hardwoods, as well as steps to be taken in the process of developing, implementing, and evaluating treatments. We use our experience with the ongoing managed old-growth silvicultural study (MOSS) (Fassnacht et al. 2013) as an example, and provide additional examples from other applicable studies across the region.

Table 2.—Criteria adding details to the general old-growth definition of "relatively old and relatively undisturbed by humans" (Hunter 1989). Adapted from Wisconsin Department of Natural Resources (2010).

Composition/succession variables

- presence of plant and animal species that prefer, or are possibly dependent upon, old-growth forest, such as fungi and lichens
- successional stage and the representation of late-successional tree species that establish in the understory and reach the canopy in tree-fall gaps

Structural development

- an abundance of large, old trees
- wide variation in tree sizes and spacing that reflect years of small natural disturbances
- diverse vertical structure that includes multiple layers, each reflecting a broad spectrum of ages
- large volumes of coarse woody debris (standing and down) representing a wide variety of decay classes
- tree-fall gaps of various sizes and ages
- randomly scattered pits and mounds

Functional variables

- species presence influenced by natural disturbance
- nutrient cycles influenced by long-term steady state
- undisturbed soils
- little evidence of human disturbance

Landscape/disturbance variables

- non-static; disturbance affects these stands
- shifting mosaic steady state

Minimum criteria for initial designation for northern hardwoods

- Even-aged/two-aged: ≥20 percent stand basal area in trees ≥170 yr old
- Uneven-aged: ≥18.4 m^2/ha of basal area in trees ≥12.7 cm d.b.h.; ≥50 percent of stand basal area in trees ≥45.7 cm d.b.h.; and 2.5 trees/ha >61.0 cm d.b.h.

Background

Defining Old Growth

To successfully describe desired management goals in terms of structure and composition, it is necessary to have a definition for old-growth forest. Arguments have been made for definitions based on maintaining or restoring process rather than structure, while at the same time recognizing the need for criteria that can be identified in the field (Frelich and Reich 2003). Here we adopt the multilevel definition for old-growth northern hardwood forests provided by the Wisconsin Department of Natural Resources (WDNR) (Wisconsin Department of Natural Resources 2010). At the most general level, old-growth forests are defined as forests that are relatively old and relatively undisturbed by humans (Hunter 1989). More specifically, these forests have diverse horizontal and vertical structure, including multiple canopy layers and canopy gaps in various stages of recovery. Plant and animal species are present that prefer, or are possibly dependent upon, old growth. These forests include a broad spectrum of canopy tree ages and have nutrient cycles and other processes potentially influenced by a **shifting mosaic steady state** at larger scales (Wisconsin Department of Natural Resources 2010). Additional mid- and fine-level characteristics are described in Table 2.

For larger forest tracts, typically under public management, it may be desirable to consider the economic, social, and political questions regarding how much of the landscape should be in old growth (or managed primarily for old-growth structural attributes), and which areas are best suited to this management. Such discussions might take place as part of the old-growth definition process (e.g., Rusterholz 1996) or they might occur separately.

Disturbance

Use of silvicultural systems that emulate natural disturbance requires an understanding of the particular regime associated with the forest type to be managed. Work by Frelich and Lorimer (1991) has shown that disturbance regimes in northern Lakes States northern hardwoods are complex. Frequent low-severity disturbances (10.0 to 19.9 percent stand-level canopy removal; 70-80 yr stand-scale **natural rotation period**) combine with intermediate-frequency moderate-severity disturbances and rare catastrophic disturbances (≥60 percent canopy removal; ~1800 yr natural rotation period) to create stands that are uneven-aged, with an average of more than 10 age classes present. Background mortality and small disturbances are commonly related to the singular and interactive effects of insects, disease, senescence, drought, ice, and wind (Frelich 2002, Lorimer et al. 2001, Parshall 1995). Moderate-severity events are generally due to ice storms and wind (Hanson and Lorimer 2007), and catastrophic events are primarily due to wind. While some catastrophic wind disturbance is caused by tornadoes, these intense disturbances are more commonly caused by downbursts associated with thunderstorms (Canham and Loucks 1984). The frequency of surface fires in the period prior to European settlement is not well known, but point recurrence intervals for stand-replacing fires were generally very long (Frelich and Lorimer 1991, Lorimer and Frelich 1994, Schulte and Mladenoff 2005).

Despite their less-frequent occurrence, moderate-severity disturbances have important impacts on stand structure and composition. Frelich and Lorimer (1991) found more than a quarter of the combined plot area studied was occupied by trees recruited in decades with disturbance events removing ≥30 percent of the canopy. Given the increased amount of light reaching the forest floor after such events, and the diversity of light environments and microhabitats (Hanson and Lorimer 2007), moderate-intensity disturbances could be expected to allow **mid-tolerant species**, such as yellow birch (*Betula alleghaniensis*), to persist in stands (Dahir and Lorimer 1996, Webster and Lorimer 2002, Webster and Lorimer 2005), and also contribute to a diversity of habitat niches. Given the natural rotation period of 300 to 400 yr for disturbances removing 30 to 49 percent of the canopy (Frelich and Lorimer 1991), most stands would be expected to be affected by moderate-severity disturbance during the maximum lifespan of the dominant tree species (300 to 500 yr) (Lorimer et al. 2001).

Examples of Active Approaches

In the northern Lakes States, several modeling efforts have explored opportunities and limitations of alternative silvicultural systems for developing old-growth features in northern hardwoods. Choi et al. (2007) found through simulation that moderately-heavy thinning in a mature even-aged stand could reduce the time required to develop minimum desired characteristics (e.g., >80 percent of **basal area** in trees ≥26 cm d.b.h., and >50 percent of basal area in trees ≥46 cm d.b.h.) from 79 to 36 yr. Similar treatment in an older uneven-aged stand, however, slowed development of desired characteristics due to the combined effects of natural mortality and the removal of medium-sized trees during harvest. Hanson et al. (2012) noted that the best balance between ecological and timber product objectives in simulated harvests was obtained using any cutting methods that retained eastern hemlock and yellow birch, had a **maximum residual d.b.h.** of 80 cm, or both. This was in comparison to other alternatives that considered various combinations of permanent **legacy trees**, CWD retention, and variable gap sizes (Hanson and Lorimer 2007).

In addition to modeling studies, there are ongoing field trials in northern hardwood forests testing hypotheses related to accelerating the development of old-growth characteristics through active management. A number of studies focus on gaps, including the impacts of retaining yellow birch seed trees in group selection openings (Klingsporn et al. 2012; Shields and Webster 2007; Shields et al. 2007a, b; 2008); the impacts of gap size on forest composition and structure (Kern et al. 2013); and the impact of gap size on sapling and stump-sprout growth (Dyer et al. 2009). Moderate- to broad-scale studies include the work of Keeton (2006) in Vermont and the Nature Conservancy in Michigan's Upper Peninsula (Strand 2012). The Vermont study compares modified single-tree and group-selection methods with a "structural complexity enhancement" treatment (SCE) (Keeton 2006) in 2-ha experimental units. The SCE treatment increased dead wood, used a "rotated sigmoid" diameter distribution to guide marking, and had a 90 cm maximum residual d.b.h. (Keeton 2006). The Nature Conservancy work created gaps of various sizes and retained dead wood as part of a commercial timber sale on a portion of ~9300 ha of Conservancy property (Strand 2012).

Northern Wisconsin Example

For the discussion that follows, we use MOSS (Fassnacht et al. 2013) as the primary example, with the simulation work and field trials described above providing additional examples. The MOSS is an ongoing, long-term study that compares the ability of six active treatments to accelerate the development of old-growth characteristics in second-growth northern hardwoods while still allowing sustainable timber harvests. The study is structured as an augmented split-plot design (Piepho et al. 2006) (Fig. 2) with three replicates (i.e., study sites) across northern Wisconsin (Fig. 3, Table 3). Active treatments combine harvest (i.e., canopy) treatments with coarse woody debris treatments. Canopy manipulation (whole plots; ~49 ha) includes a *small gaps* treatment (10.7-m diameter gaps plus thinning of the matrix), a *large gaps* treatment (18.3- and 24.4-m diameter gaps plus thinning; Fig. 4), and a novel *irregular multi-cohort* treatment (0.40-ha and 1.2-ha modified shelterwoods plus light-thin and heavy-thin zones; Fig. 5) based on the work of Hanson and Lorimer (2007). Each stand is split in half (split plot; ~24 ha) and receives two CWD treatments: low (no supplemental dead wood created) and high (supplemental dead wood created; Fig. 6). *Control* stands receive neither canopy treatment nor CWD treatment. All treatments are replicated at each study site. See Fassnacht et al. (2013) for more detail regarding the study sites, treatments, and treatment implementation.

SILVICULTURAL APPROACH

There are a number of steps to complete before, during, and after deciding to use active management to enhance the compositional diversity and structure of second-growth northern hardwoods in the northern Lake States region. These include specifying objectives and identifying initial targets, identifying and addressing contemporary stressors that may hinder the ability to meet those objectives and targets, conducting a pretreatment evaluation, developing and implementing treatments, and evaluating treatments for success of implementation and effectiveness after application. These and additional topics will be discussed.

Specifying Objectives and Identifying Initial Targets

The overall objective under discussion in this report is enhancing the compositional diversity, structural complexity, and spatial heterogeneity of second-growth northern hardwood forests through active management to accelerate the development of old-growth characteristics. To fully specify objectives for a particular stand, however, there are other factors to consider. For example: What should be used as a reference condition? To what degree should those reference conditions be met? What factors need to be manipulated to achieve desired targets? What are the tradeoffs (e.g., with timber production) of manipulating those factors? There are biological, economic, and social issues to contemplate when addressing these questions. Once objectives are specified, initial targets can be identified.

Reference Conditions

Within any given forest type, large differences can be expected among stands examined, reflecting a natural range of variability in structure and composition (Franklin et al. 2007). Examples from the scientific literature can be used to help gauge the range of structural and compositional characteristics that might be found in potential reference conditions. Information from the literature can be general or quite specific. Bauhus et al. (2009), for example, include "Large amount/mass of downed CWD" and "High spatial [variability] of tree distribution/irregular size and distribution of gaps" in a table of general old-growth structural attributes associated with different forest types. In contrast, Tyrrell and Crow (1994) include "dead wood >120-150 m^3/ha, with logs >80 m^3/ha" and "canopy gaps occupying >10 percent of the stand, with

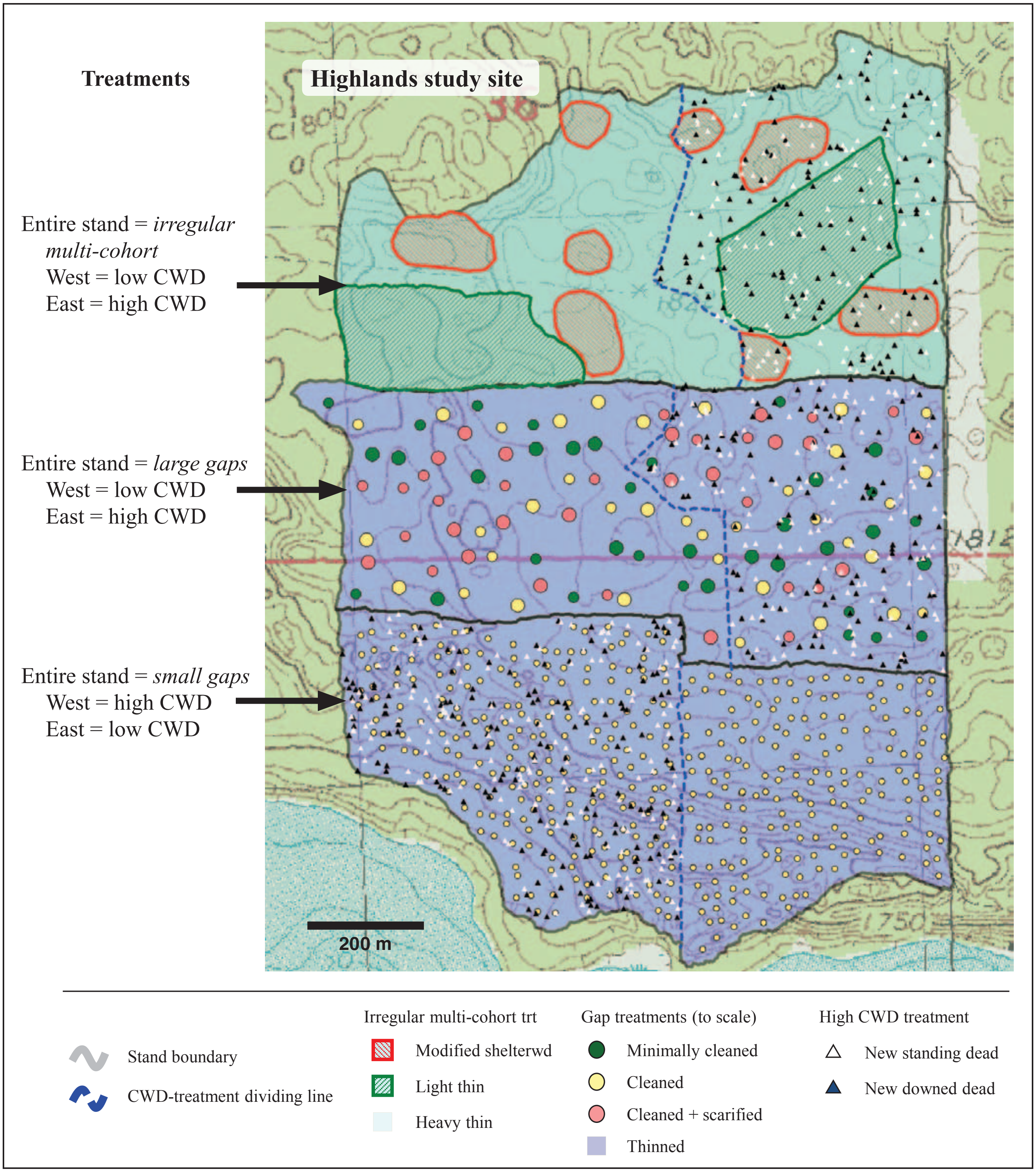

Figure 2.—The six active treatments investigated in the managed old-growth silvicultural study (MOSS) as applied at the Highlands study site. Canopy treatments were applied to ~48.6 ha stands; coarse woody debris (CWD) treatments were applied to half of each stand. The ~48.6 ha *control* stand (not shown) received no canopy or CWD treatment. Canopy and CWD treatments are defined on page 7. Figure and most text from Fassnacht et al. (2013), used with permission.

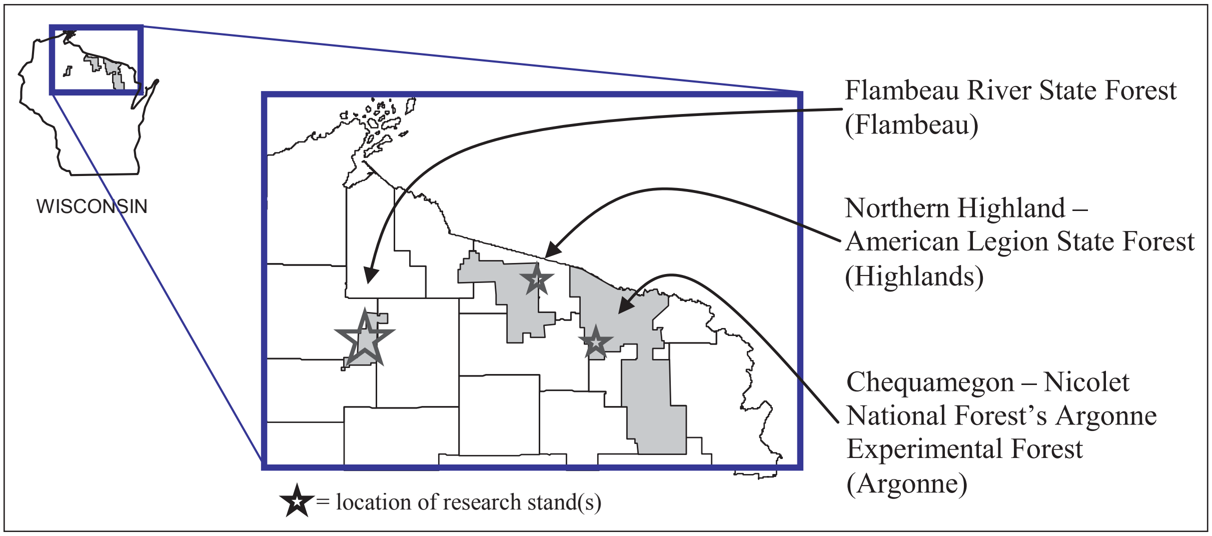

Figure 3.—Study sites of the managed old-growth silvicultural study (MOSS). Full site names are provided with the working site names shown below in parentheses. Working site names are used throughout the report. Figure from Fassnacht et al. (2013), used with permission.

Table 3.—Unweighted[a] pretreatment characteristics of the twelve study stands of the managed old-growth silvicultural study (MOSS). Data reported at the stand level. Standard errors provided in parentheses. Table and text modified from Fassnacht et al. (2013); used with permission.

Site	Canopy treatment[b]	Area[c] [ha]	Habitat type[d]	Mean live d.b.h. [cm]	Mean snag d.b.h. [cm]	Mean live stems/ha	Mean live BA[e] [m^2/ha]	Mean snag BA [m^2/ha]
Flambeau	*control*	45.93	low AH (w)	24.6 (0.3)	20.7 (1.5)	493 (21)	28.0 (1.0)	1.4 (0.3)
	small gaps	52.16	AH (w)	23.4 (0.3)	18.4 (0.9)	599 (22)	29.2 (0.8)	0.97 (0.1)
	large gaps	50.22	ATD/ATM - ATD/AH (wm, w)	26.6 (0.6)	26.3 (1.4)	448 (18)	30.7 (0.8)	2.0 (0.2)
	irregular multi-cohort	51.88	ATD (wm); ATAtOn (incl).	23.0 (0.3)	17.3 (0.6)	633 (17)	30.3 (0.5)	2.1 (0.3)
Highlands	*control*	48.28	ATD	29.0 (0.6)	27.3 (1.5)	415 (13)	34.0 (0.7)	2.2 (0.3)
	small gaps	47.83	ATD	25.2 (0.7)	25.1 (1.1)	464 (26)	29.1 (0.8)	1.8 (0.3)
	large gaps	49.33	ATD	26.9 (0.7)	26.4 (1.3)	417 (21)	29.3 (0.8)	2.0 (0.3)
	irregular multi-cohort	51.44	ATD	27.8 (0.6)	22.6 (1.1)	399 (16)	29.9 (1.0)	1.3 (0.2)
Argonne	*control*	47.31	ATD	30.6 (0.6)	27.6 (1.1)	417 (17)	36.4 (0.8)	3.3 (0.3)
	small gaps	49.17	AOCa (w)	29.7 (0.7)	28.5 (1.1)	352 (17)	29.7 (0.7)	3.6 (0.4)
	large gaps	55.24	AOCa	29.9 (0.6)	24.9 (1.3)	398 (17)	33.1 (0.8)	3.8 (0.4)
	irregular multi-cohort	46.34	AOCa (w)	31.7 (0.8)	27.7 (1.4)	351 (14)	32.6 (1.2)	4.3 (0.5)

[a] Values in this table are appropriate for characterizing the pretreatment conditions only and should not be used for comparison with post-treatment values (found in Fassnacht et al. 2013).
[b] Canopy treatments are defined on page 7.
[c] 1 ha = 2.47104393 ac
[d] Kotar et al. (2002); w = patches of wet, wm = patches of wet-mesic, incl = inclusions
[e] BA = basal area; 1 m^2/ha = 4.356017426 ft^2/ac

Figure 4.—A 24.4-m diameter gap in the fourth growing season after it was created at the Argonne site of the managed old-growth silvicultural study. Photo by Joshua Waukau, WDNR, used with permission.

Figure 5.—A 0.40-ha modified shelterwood in the second growing season after the establishment cut at the Highlands site of the managed old-growth silvicultural study. Photo by Brian Werner, WDNR, used with permission.

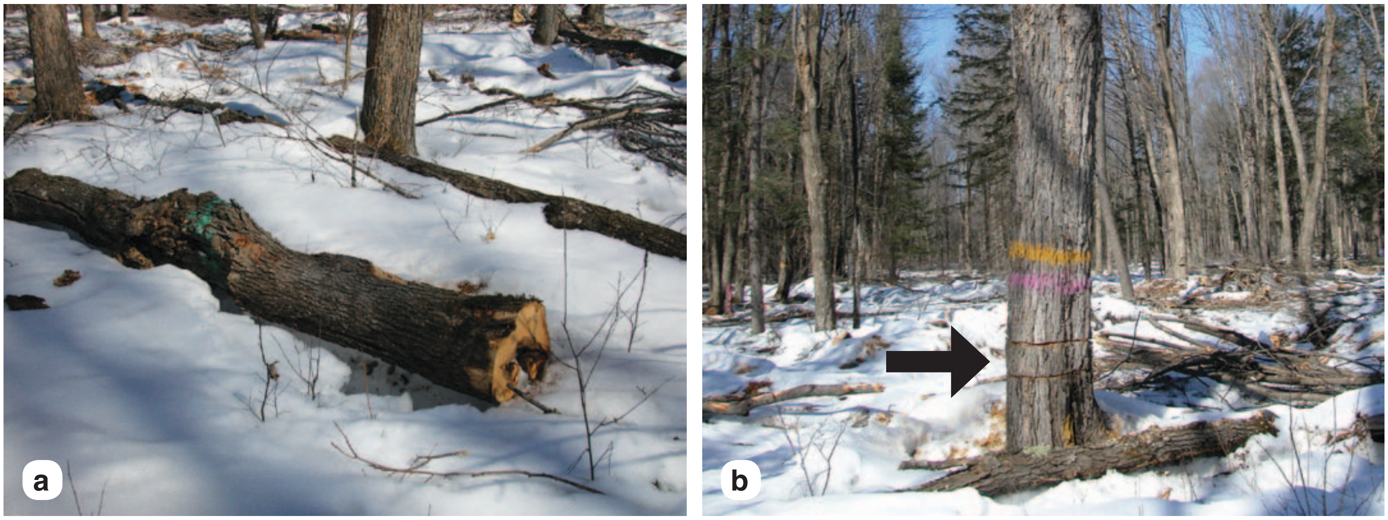

Figure 6.—Newly created (a) downed wood and (b) girdled tree at the Argonne site of the managed old-growth silvicultural study. The arrow in (b) points to the double girdle. Photos by Dean van Doren, WDNR, used with permisison.

average gap size >50 m^2…" among a list of characteristics shared by most of the older old-growth hemlock-hardwood stands they studied. Values such as those presented in the latter example can be used in developing specific targets once details of project objectives are finalized.

Deciding which reference to use within the range of variability observed, and the degree to which management should seek to achieve those reference conditions, is more of a social and economic decision than a biological one. Zasada et al. (2004) provide a framework for considering this question (see their Figure 19.3). Factors shown to impact the degree to which a given stand approaches reference conditions include time since disturbance (determined by factors such as rotation length, frequency of entries, and natural disturbance events), degree of structural complexity sought, and management objectives (on a scale from production forestry to reserve). Questions to consider in deciding how closely to mimic a reference condition include:

- What are the primary management objectives?
- What is the operability of the harvest being considered? Is there a minimum yield needed?
- What are the short-term and long-term costs as well as benefits of various options?
- What is the social tolerance for disturbance frequency, the methods being used (e.g., amount of dead wood left), or both?
- What resources are available to undertake the management?
- What wildlife and plant species would likely be favored or hindered by old-growth characteristics in the stand(s)?
- What interactions might there be between the proposed management and wildlife populations in the adjacent land cover types?
- What is the desired plant species composition?
- Are there exotic/invasive species or browsing pressure that may hinder or constrain restoration goals?
- What timeline is available to achieve the desired goals?

Factors to be Manipulated to Achieve Targets and the Potential Tradeoffs

Some of the questions from the list above can be answered by considering the factors to be manipulated to achieve potential targets of interest. For example, increasing the amount of large standing and downed dead wood typically involves leaving some trees on site that would otherwise be harvested. Trees can be left as designated permanent legacy trees (Bauhus et al. 2009) or as new dead wood created through girdling (Fassnacht et al. 2013) or mechanically tipping over (Keeton 2006) trees. Steele and others[2] are currently evaluating the opportunity costs associated with foregoing revenue associated with new dead-wood trees. For the amount of CWD being created in MOSS (Fassnacht et al. 2013), the opportunity costs appear to be minimal (~3 percent of volume, ~1 percent of value).[3]

In addition to dead wood, other common factors manipulated to enhance compositional diversity and structure include quantity, size, and spatial arrangement of overstory trees to be removed (or retained). Leaving larger trees, some permanent legacy trees, or both, harvesting trees in groups or small shelterwoods, and removing less volume may all impact the economics of a harvest. Simulation and field-based trials have evaluated the impacts of combined aspects of natural-disturbance-based silviculture in northern hardwoods. For example in a simulation study, Hanson et al. (2012) found that prescriptions incorporating varying aspects of structural complexity enhancement reduced timber volume produced compared to standard single-tree selection by highly variable amounts (9 to 55 percent) depending on the techniques included in the prescriptions. In a field trial, Keeton and Troy (2006) reported that treatments focused on structural complexity enhancement had the potential to be profitable on high-quality sites and with good market conditions, though they were less profitable compared to modified single-tree and group-selection alternatives.

Example

In MOSS, objectives were determined through a combination of public input and state-level policy priorities. The study is part of the second phase of old-growth research initiated by the WDNR in cooperation with other regional partners (e.g., University of Wisconsin–Madison, U.S. Forest Service Northern Research Station, University of Minnesota–Twin Cities, and University of Wisconsin–Green Bay) in response to public concerns that forest management practices were not maintaining biodiversity.[4] Public concern,

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[2] Manuscript in preparation: Steele, T. W.; Knoot, T. G.; Fassnacht, K. S.; Martin, K. J. The opportunity cost of enhancing structural complexity and species diversity in second-growth, even-aged northern hardwoods.

[3] T. Knoot, Wisconsin Department of Natural Resources, personal communication.

[4] Introduction to a report titled "A comparison of old-growth and managed forests in the Great Lake states." Introduction by G. A. Bartelt. Report on file with Nicholas Anich at Wisconsin Department of Natural Resources, 2501 Golf Course Road, Ashland WI 54806.

and Wisconsin's commitment to sustainable forest management, resulted in the development of a long-term old-growth research program. The first phase of this research compared old-growth with managed and unmanaged second-growth northern hardwood and hemlock-hardwood forests (e.g., Goodburn and Lorimer 1998, Howe and Mossman 1995, Lindner et al. 2006, Miller et al. 2002, Werner and Raffa 2000, Will-Wolf and Nelsen 2008). The second-phase research is seeking to determine what modifications in silvicultural practices have the potential to promote biodiversity while still allowing for timber production.

Specific forest harvest targets for MOSS were set based on state guidelines and references from the scientific literature. For the canopy treatments, the gap size (i.e., 10.7-m diameter) and density of gaps for the *small gaps* treatment were based on values recommended for conversion from even-age to uneven-age management in northern hardwoods (Wisconsin Department of Natural Resources 2006). For the *large gaps* treatment, the size and density of the 18.3-m diameter gaps was based on recommendations in the same document for conversion to uneven-age management while promoting mid-tolerant species. The size of the 24.4-m diameter gaps in this treatment was based on work by Strong et al. (1998) which identified gaps of intermediate size as providing the optimum balance between slowing gap closure rates and minimizing gap capture by *Rubus* species. Finally, structural targets for the *irregular multi-cohort* treatment were based on the values for wind-disturbed stands as reported by Hanson and Lorimer (2007).

For the CWD treatments, the target value was initially chosen to be 70 percent of the larger, less decayed dead wood volume (or stem density for snags) calculated for Sylvania Wilderness Area in the Upper Peninsula of Michigan, based on data collected for the WDNR phase I old-growth research[5] (Goodburn and Lorimer 1998 for snags). A target less than 100 percent was chosen to help maintain economic viability of the treatments in recognition that some opportunity costs would be incurred by leaving wood on site. In addition, the target was chosen to be greater than 60 percent, the approximate proportion of dead wood found in northern hardwoods managed using the selection system in the WDNR phase I old-growth studies. Further modifications of the 70 percent target were needed once treatment development and implementation were undertaken, as will be described in the sections "**Treatment Development"** and "**Treatment Implementation"** (see pages 16 and 19).

Contemporary Stressors

In developing management goals, it is important to identify and attempt to factor in contemporary stressors that may impact the ability of planned harvests to meet long-term objectives related to restoring old-growth compositional and structural conditions. For northern hardwood forests of the Lake States, such stressors include herbivores—especially white-tailed deer (*Odocoileus virginianus*)—invasive species, and climate change.

Deer

The ability of land managers to achieve structural targets in their managed stands can be made more difficult when a site is experiencing, or has experienced, moderate to high browsing pressure (Horsley et al. 2003, Kern et al. 2012, Reuling 2014). Negative impacts of deer browsing on the stem density and growth of tree regeneration have been noted for preferred browse species (e.g., eastern hemlock, yellow birch) compared to species that are not preferred (e.g., ironwood [*Ostraya virginiana*]) or which better tolerate browsing pressure (e.g., sugar maple [*Acer saccharum*]) (Dahlberg and Guettinger 1956, Frelich and Lorimer 1985, Horsley et al. 2003, Webb et al. 1956). Preferred species, which include many of the historically more abundant species in Lakes States northern hardwood forests, are less able to take advantage of purposely created canopy gaps (Horsley et al. 2003, Kern et al. 2012) due to the lack, or decreased vigor, of advanced regeneration resulting from recent browsing (Reuling 2014, Salk et al. 2011, Stoeckeler et al. 1957) (Fig. 7). There also may be a lack of seed source for these species as a result of historical browsing or land-use practices (Horsley et al. 2003, Mladenoff

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[5] For downed woody debris—unpublished data from R. Howe and M. Mossman. On file with Michael Mossman, Wisconsin Department of Natural Resources, 2801 Progress Road, Madison, WI 53716.

Figure 7.—Regeneration within a deer exclosure located within a gap at the Highlands site of the managed old-growth silvicultural study in the fourth growing season after the gap was created. The white bracket denotes the area of the exclosure. Notice the lack of advanced regeneration in the gap outside of the exclosure. Photo by WDNR staff, used with permission.

and Stearns 1993, Tanentzap et al. 2011). Suitable microsites for germination (e.g., well-decayed downed wood for hemlock and yellow birch) are also rendered less important if overbrowsing prevents seedling growth on these features (Frelich and Lorimer 1985, Witt and Webster 2010).

The best approach to addressing deer impacts is unclear given the complex relationship between deer population density and forest vegetation (e.g., Horsley et al. 2003) and the many other factors contributing to establishment and growth of various species (Kern et al. 2012, Mladenoff and Stearns 1993). Approaches might include activities that directly impact deer numbers, such as increased levels of deer hunting (Alverson et al. 1988, Tanentzap et al. 2011, Witt and Webster 2010), as well as activities designed to protect plants from browsing (Alverson et al. 1988, Tanentzap et al. 2011, White 2012, Witt and Webster 2010) and to increase the likelihood of successful establishment (White 2012, Witt and Webster 2010), including the use of fencing or tree shelters. If these activities are affordable, they may help reduce impacts of browsing over time and in selected locations. Nonetheless, other factors contributing to species decline at a landscape or regional scale (e.g., land-use history, climate, life-history requirements; Mlandenoff and Stearns 1993) may prevent successful re-establishment of historically important species even if browsing impacts can be reduced (Mlandenoff and Stearns 1993).

Invasive Species

The effectiveness of management strategies to enhance species diversity may be seriously compromised by invasive species. For example, composition and successional trajectories can be impacted through changes in forest floor thickness (Hale et al. 2005); mycorrhizal communities (Frelich et al. 2006, Rodgers et al. 2008); and nutrient dynamics associated with earthworms (Bohlen et al. 2004, Suárez et al. 2003), herbaceous plants (Rodgers et al. 2008) or exotic plant-eating insects (Gandhi and Herms 2010). In addition, canopy gaps installed to increase representation of mid-tolerant species (e.g., white ash; *Fraxinus americana*) may be rendered

Figure 8.—European swamp thistle (*Cirsium palustre*) and *Rubus* in a gap at the Highlands site of the managed old-growth silvicultural study in the fourth growing season after the gap was created. Photo by WDNR staff, used with permission.

ineffective if desired species are no longer providing seed sources or successful regeneration after having been severely reduced or eliminated from a stand (Frelich et al. 2006, Gandhi and Herms 2010, Holdsworth et al. 2007). Other barriers to gap colonization by desired species can include soil conditions altered by invasive species (Frelich et al. 2006, Rodgers et al. 2008) and competition from more aggressive native or exotic species such as Pennsylvania sedge (*Carex pensylvanica*), or garlic mustard (*Alliaria petiolata*) (Holdsworth et al. 2007, Rodgers et al. 2008) (e.g., Fig. 8). Invasive shrubs may also potentially impact which species, if any, are able to succeed in the created gaps (Fagan and Peart 2004, Gorchov and Trisel 2003).

Structural features of a stand can also be impacted by invasive species (Castello et al. 1995, Dukes et al. 2009). Small scattered gaps can be created throughout the stand due to mortality associated with exotic insect infestation (Gandhi and Herms 2010) or disease (Dahir and Lorimer 1996). While these deaths may increase variability of horizontal stand structure, the gap dynamics associated with insect- or disease-created gaps differ from those created by windthrow or tree senescence in that pest-associated gaps may result from the death of only a single tree species, and resulting snags may remain standing longer than trees killed by wind or senescence (Dahir and Lorimer 1996, Gandhi and Herms 2010). Insect infestations can also alter dead wood dynamics by increasing the amount and species composition of standing and down dead wood as trees are killed by the invaders (Gandhi and Herms 2010).

The approach to managing invasive species is complex. Early detection and removal is critical in many cases (Webster et al. 2006). Consequently, invasive species should be evaluated as part of every site assessment to help identify problems early. In addition, collaborative efforts across ownerships are often necessary due to the landscape-scale nature of the problem (Webster et al. 2006). Once invasive species are established, eradication can be expensive and difficult (Webster et al. 2006), if it is even possible, and impacts may take a very long time to overcome (Frelich et al. 2006).

Climate Change

Climate change has the potential to create challenges with respect to meeting many types of management objectives, including increasing plant diversity and forest complexity/heterogeneity. For example, forest community composition may be altered by climate change (Iverson et al. 2011, Webb 1992) because individual tree species may be affected by, and react differently to, changing conditions (Scheller and Mladenoff 2008). As a result, successional trajectories may become difficult to predict (Swanston et al. 2011), thereby increasing the uncertainty in the outcomes of silvicultural activities[6]. Impacts will likely be greatest on species currently at the edge of their range (Davis and Shaw 2001, Swanston et al. 2011). Regeneration may also become more difficult[6] and require active measures in areas where natural regeneration was previously sufficient. Furthermore, large older trees may be more susceptible to increased frequency and magnitude of wind disturbance due to their larger size (Hanson and Lorimer 2007), complicating efforts to increase large-tree representation within a stand.

Uncertainty regarding future climate conditions provides a substantial challenge in determining the best approach to incorporating potential impacts into management plans. Choosing prescriptions that incorporate flexibility and robustness are generally recommended (D'Amato et al. 2011, Dukes et al. 2009, Janowiak and Swanston 2012, U.S. Forest Service 2011). Swanston and Janowiak (2012) provide a clear framework for this decisionmaking process, with a menu of potential strategies and approaches and a workbook to help land managers incorporate potential climate change impacts into existing policies and plans. They emphasize the need to consider that, under climate change, management objectives may need to be changed or adjusted if challenges to meeting current objectives significantly reduce the feasibility of meeting those objectives. Peterson et al. (2011) suggest that instead of focusing on outcomes with a particular composition and structure, plans incorporating adaptation to climate change focus more on ecosystem services and ecological processes.

Example

Incorporation of climate change into forest management plans is being undertaken with several demonstration projects in northern Wisconsin in collaboration with the Shared Landscapes Initiative.[7] In upland hardwood areas of demonstration projects of the Bayfield Regional Land Conservancy[8] and The Nature Conservancy[9], possible adaptation actions include creating refugia for eastern hemlock by maintaining high quality patches of the species where they occur, increasing species and age diversity using larger gap sizes in areas with active management, favoring eastern white pine and other better-adapted species where they occur either by releasing advanced regeneration or planting, and using shelterwoods or large group cuts to increase northern red oak (*Quercus rubra*) representation where there is already regeneration. These approaches are generally compatible with management strategies aimed at increasing compositional and structural complexity/heterogeneity, and a blending of these objectives (i.e., adaptation and complexity enhancement) may be necessary to address future uncertainties.

Pretreatment Evaluation

After determining the forest management goals for a stand, the next step in the process involves gaining information about the stand of interest. Inventories of forest stands have long been performed by foresters to gain information helpful for management. Timber cruises are an obvious example. When contemplating using active management to enhance structural complexity and compositional diversity, many of the forest characteristics measured are the same as in a traditional cruise; however, there are additional characteristics that

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[6] Wisconsin initiative on climate change impacts, forestry working group report. Unpublished report. Available at http://www.wicci.wisc.edu/report/Forestry.pdf (accessed March 19, 2014).

[7] http://www.sharedlandscapes.org/adaptation-projects.html (accessed March 10, 2014)

[8] http://forestadaptation.org/node/224 (accessed March 10, 2014)

[9] http://climateframework.org/node/193 (accessed March 10, 2014)

may be of interest. Volume, size, and species of dead wood, number and sizes of newer pre-existing gaps (i.e., younger gaps that might appear/function similarly to any gaps created through management), and diversity of light environments are some examples. The exact variables to measure depend on specific objectives for the stand, what information may be available for comparison from reference stands (as discussed above), and amount of time available. Characteristics noted in Table 1 provide some examples for consideration. In addition, if there are specific wildlife objectives, such as increasing habitat for northern flying squirrels (*Glaucomys sabrinus*), then surveys of particular habitat features—such as the number of cavity trees, presence of mast species (such as northern red oak), or percentage of basal area in conifers (Wisconsin Department of Natural Resources 2013)—may be desired.

Characteristics measured in the pretreatment inventory will provide information from which initial treatments can be developed, and which will help determine the feasibility of meeting desired objectives. In addition to collecting information on features that are directly related to objectives, such as those listed above, collecting data related to deer browsing (e.g., Brose et al. 2008, Frelich and Lorimer 1985, Witt and Webster 2010), presence and prevalence of invasive species, and any special notes related to susceptibility or opportunities associated with climate change may also be advisable.

Example

In MOSS, the pretreatment evaluation included measurement of overstory vegetation, canopy characteristics, pre-existing gaps, site index, habitat type, understory characteristics, and downed woody debris.

Measurements made of overstory vegetation included species, d.b.h., and suppression class (suppressed or not suppressed) of all live trees ≥10 cm d.b.h. In addition species, d.b.h., snag height class, and snag decay class were noted for all self-supporting dead trees that were at least breast height tall and ≥10 cm d.b.h. The presence of cavities and **hollows** were also recorded. From these variables, the following stand characteristics were determined: stand basal area, basal area of individual species, diameter distribution of the overstory, average d.b.h. of live trees, average d.b.h. of snags, live standing tree volume, and the stem density (i.e., trees/area) of live trees, snags, cavity trees, and trees with hollows.

Canopy characteristics measured included percentage of canopy closure and light transmission (direct, diffuse, and total). The size class and frequency of newer pre-existing gaps were also inventoried using line transects (Table 4). Site index was determined for sugar maple only, as it was the dominant tree species. Site index for other species was determined from sugar maple site index using conversion equations from Carmean (1979). Habitat type for each site was characterized according to Kotar et al. (2002). Understory measurements included number of stems per area by species in three size classes (0.10 to 0.49 m tall, 0.5 m tall to 1.9 cm d.b.h., and 2.0 to 9.9 cm d.b.h.) for woody vegetation. In addition, percentage of cover for all herbaceous understory vegetation together was measured, as was percentage of cover for six individual native and exotic invasive species of special interest. Measurements for large downed woody debris included volume of stumps and root flares, and volume of large downed woody debris other than stumps and root flares (Fig. 9).

Methods used, and summaries of values determined, from the MOSS pretreatment evaluation are reported in Fassnacht et al. (2013).

Treatment Development

Once targets are determined and an initial pretreatment survey has been completed, development of treatments can begin. A comparison of values measured in the inventory with targets from reference sites will highlight how far current stand conditions are from the desired goal. If current and future desired conditions are substantially different, the time to achieve goals may need to be extended, targets revised, or other alterations made to initial plans, such as number of entries required to achieve desired goals. Furthermore, data collected during the inventory can identify additional activities that may be necessary to improve chances of success, such as measures to control or remove invasive species or to reduce deer populations or impacts.

Table 4.—Number of pre-existing gaps[a] by stand and size class (modified from Fassnacht et al. 2013)

	Size[c] [m]		
Site/canopy treatment[b]	10.7 to 18.3	18.3 to 24.4	24.4+
Flambeau			
Control	3	0	0
Small gaps	3	1	0
Large gaps	1	0	0
Irregular multi-cohort	2	0	0
Highlands			
Control	0	0	2
Small gaps	4	0	0
Large gaps	2	1	1
Irregular multi-cohort	10	1	0
Argonne			
Control	16	1	0
Small gaps	34	3	2
Large gaps	17	3	1
Irregular multi-cohort	24	3	0

[a] For a gap to be included in the survey, woody regeneration in the gap was required to average ≤2 m tall.

[b] Canopy treatments are defined on page 7.

[c] Diameter ranges of round gaps (35 to 60 ft, 60 to 80 ft, and 80+ ft in original units). Diameters were allowed to have somewhat smaller minor axes in the case of elliptical gaps. Dimensions for elliptical gaps to qualify to be a "10.7-m diameter" gap were 9.14 x 12.5 m; 15.51 x 21.64 m for a "18.3-m" gap; and 21.03 x 28.35 m for a "24.4-m" gap.

Figure 9.—Measuring downed woody debris. Photo by Brian Werner, WDNR, used with permission.

Treatment development also includes a consideration of finer details associated with desired targets. For example, if ~10 percent of the stand area is to be converted to new gaps, what size gaps should be used and how should they be distributed across the stand? Given a desired residual basal area, how will this target be met? That is, what types of trees should be marked and in what size classes? If a certain volume of dead wood is an objective, what does that translate into with respect to numbers and sizes of trees?

Previous research efforts can help address some of these questions and provide insights into special considerations. For example, a number of studies have evaluated gap size with respect to effects on species diversity, some specifically examining impacts on mid-tolerant species such as yellow birch (Bolton and D'Amato 2011; Kern et al. 2013; Shields et al. 2007b; Webster and Lorimer 2002, 2005). These studies suggest that site quality and current species composition are important in determining the effectiveness of canopy gaps for increasing representation of mid-tolerant tree species. They also give guidance on the most appropriate size of gaps and the need for additional management to support objectives.

On moderately-rich, mesic sites, which are less likely to be sugar maple dominated, larger gaps appear to have the potential to increase representation of mid-tolerant species such as yellow birch. For example, working in a hemlock-hardwood forest, Webster and Lorimer (2002) found that gaps >400 m^2 (~23-m diameter if circular) favored yellow birch over eastern hemlock, with yellow birch generally making up more than 40 percent of dominant and codominant gap saplings for gaps 16 to 55 yr old (Webster and Lorimer 2005). Sugar maple was present in these gaps but contributed less to relative stem densities compared to yellow birch.

On richer sites, which are more likely to be sugar maple dominated and to have abundant sugar maple advanced regeneration, it is not clear that creating canopy gaps is effective in increasing representation of mid-tolerant species without supplemental management (Bolton and D'Amato 2011, Kern et al. 2013, Shields et al. 2007b). In one study, regeneration failure for all species was reported for larger gaps (i.e., >10-m diameter), where larger gaps were dominated by *Rubus* species 12 yr after gap establishment (Kern et al. 2013). Other studies have reported increased stem densities of yellow birch seedlings, saplings, or both, in gaps compared to closed-canopy forest, but yellow birch was substantially less abundant than sugar maple (Bolton and D'Amato 2011, Shields et al. 2007b). Yellow birch also did not necessarily differ in density among gap sizes (Shields et al. 2007b) and likely had insufficient densities to maintain its abundance in the overstory at historical levels (Shields et al. 2007b).

Factors found to be associated with yellow birch occurrence on these richer northern hardwood sites included microsite factors (e.g., exposed mineral soil and coarse woody debris, especially large, well-decayed conifer coarse woody debris; Bolton and D'Amato 2011, Shields et al. 2007b) and location within the gap (more birch at the edge; Shields et al. 2007b). Competition with advanced regeneration of shade-tolerant species also appeared to be an important barrier to increasing yellow-birch representation (Bolton and D'Amato 2011).

On these richer northern hardwoods sites, consequently, additional management activities may be necessary, beyond simply creating canopy gaps, to improve the likelihood of increasing representation of mid-tolerant species. Examples include creation of gaps around seed trees; scarification or pulling over of trees to expose mineral soil and create tip-up mounds; addition of conifer downed wood; periodic enlarging of gaps; removal of advanced regeneration from competing shade-tolerant species such as sugar maple; underplanting desired species in gaps; application of herbicides or physical removal of competing shrubs to release established regeneration; and erecting fencing to exclude deer (Bolton and D'Amato 2011, Kern et al. 2013, Shields et al. 2007b, Webster and Lorimer 2002).

Prior to finalizing treatments, land managers should consider modifications that may be necessary due to the contemporary stressors discussed previously. For example, for sites near the southern edge of the range of underrepresented species such as yellow birch, it may be prudent to adjust a management plan such that targeted mid-tolerant species include those better adapted to projected future climate conditions and stresses, such as northern red oak or black cherry (*Prunus serotina*) (Iverson et al. 2011).

Example

Information gained during the pretreatment evaluation phase of MOSS resulted in several adjustments to the initial targets for new CWD creation. As described above, the initial target for the MOSS CWD treatment was 70 percent of the larger, less-decayed standing and downed dead wood found in Sylvania Wilderness Area (the reference site used for dead wood). In addition, all trees to be girdled, or felled and left on site, initially were to be ≥40.6 cm d.b.h. Based on data from the pretreatment stand inventories, it became apparent that there were not enough large trees that could be marked to meet proposed CWD targets while still permitting the removal of sufficient volume to ensure economic viability of the harvest. Economic viability was an important aspect of the prescriptions being developed in order to increase the likelihood of broader adoption of the methods should desired ecological outcomes be achieved.

To accommodate the concerns raised by the pretreatment assessments, three modifications were made to the original targets. First, desired CWD targets were reduced from 70 to 65 percent of the larger, less decayed dead wood found in the Sylvania Wilderness Area reference site. Second, the size of trees to be felled and left, or girdled, was modified to include smaller trees. The assessment found that two sites had very few trees ≥40.6 cm d.b.h.; consequently the desired size class for CWD was reduced to ≥30.5 cm d.b.h. for those sites. In addition, required sizes of newly added CWD for all sites were spread over three size classes per site rather than just one (i.e., ≥40.6 cm d.b.h. or ≥30.5 cm d.b.h., depending on stand), with the new smallest size class being 25.4 to 30.2 cm d.b.h. for all sites. The third adjustment allowed girdled trees to be counted toward both standing dead wood quotas as well as downed dead wood quotas (since the newly created snags would eventually fall and become part of the downed wood pool). This adjustment had ecological, economic, and logistic advantages. Ecologically, counting girdled trees toward our downed wood total would allow us to effectively add downed wood over time, rather than in one large pulse. With this approach there would be a smaller initial pulse of downed wood added with the trees that were felled and left on site, and then additional wood would be added over time, in various states of decay, as the girdled trees fell. Economically, this adjustment reduced the total number of trees needed to meet added CWD targets, thus reducing the opportunity costs associated with this treatment. From a logistical perspective, it was more straightforward to have CWD-tree targets evenly split between standing and downed wood at each site, than to have very different requirements for downed and standing dead wood, potentially varying in relative proportion among sites. To facilitate marking in the field, desired downed wood volumes were converted to number of trees per area by applying a single volume-to-tree conversion factor to calculated volumes of downed wood needed to meet targets.

Information regarding the development and implementation of other MOSS treatments can be found in Fassnacht et al. (2013).

Treatment Implementation

There are many potential questions associated with treatment implementation. How will the location of gaps be determined in a stand? How will gaps be marked? How will “CWD trees” be distributed within a stand? How will CWD trees be selected? These questions may be best addressed using trials in a small portion of the stand to be managed. Different methods can be tried and compared to determine which best meets project needs and objectives. Initial implementation of treatments can also serve as a trial of sorts, potentially highlighting areas of the management plan still in need of modification. Over time, experience gained by a land manager or by others, with results reported in the literature, will reduce the need for trials and in-process modifications.

Example

Developing the CWD treatment in MOSS was an iterative process. After the adjustments described above had been made, one additional adjustment was required after marking had started. For two treatment areas, the total amount of new CWD to be created under the 65 percent-of-reference target was simply more than could be accommodated while maintaining an economically viable timber sale. These two sites had the lowest amount of pre-existing CWD, consequently they required the largest amount of wood to be added to reach target dead-wood quantities (Fassnacht et al. 2013). The last CWD-treatment adjustment, made for these two sites only, was to extend the time period over which the 65 percent-of-reference target was to be met to include more than one entry. As a result of this adjustment, amounts of new dead wood required for the two treatment areas was changed for this initial entry to be more similar to volumes required for the other study treatment areas (Fassnacht et al. 2013).

Treatment Evaluation

Once treatments have been implemented, evaluation and monitoring are important steps to determine progress toward desired targets. Monitoring allows for an assessment of current management practices and has the potential to highlight the need for alterations in the management plan. Important questions to consider include: How does one define success? What kind of monitoring is necessary? What variables need to be monitored? What time frame should be considered for monitoring and reaching targets? Are there any unanticipated consequences of the active management?

Treatments can be evaluated for successful implementation as well as for effectiveness. Success in implementation refers to the degree to which targets are met for variables directly manipulated by management. For example, in the Vermont study of structural complexity enhancement (SCE) (Keeton 2006), post-treatment diameter distributions were compared to the target rotated sigmoid distribution and found to be statistically indistinguishable (Keeton 2005). Implementation of this aspect of the treatment, therefore, could be considered successful. Effectiveness, in contrast, refers to the degree to which targets are met for variables indirectly impacted by variables manipulated by management. For example, if manipulating forest structure as prescribed is intended to improve the habitat for high priority bird species or bird species that serve as indicators of old-growth forest, and increases in those bird species are observed, the prescribed management may be considered to be effective.

Implementation monitoring is valuable because if eventual outcomes do not meet expectations, it is possible to know whether the problem was that the treatment was not implemented as prescribed or was not effective as prescribed. Effectiveness monitoring is critical to improving management strategies when outcomes are not as expected. For example, Bolton and D'Amato (2011) found that that creating canopy gaps within the range of variability of those found in older northern hardwood systems was insufficient on its own to increase tree species diversity and promote mid-tolerant tree species such as yellow birch on nutrient-rich, sugar-maple-dominated sites in Minnesota. Effectiveness monitoring allowed the authors to provide suggestions for additional management activities that might improve the prescription, including the addition of large conifer downed wood, scarification, and removal of advanced regeneration of competing shade-tolerant species such as sugar maple.

Variables to monitor include those that were manipulated directly, as well as the indirect outcomes identified as objectives for the project. The time frame for monitoring will depend on the type of monitoring (implementation or effectiveness) and objectives. Implementation monitoring will be relatively short term, i.e., the same time frame as treatment implementation. Effectiveness monitoring may take place over years, decades, or potentially centuries, depending on objectives.

Effectiveness monitoring done soon after treatment implementation may be of interest but may not demonstrate the full effectiveness of the treatments since plant and animal populations can take much more time to respond. For example, field trials in New York evaluating regeneration responses to shelterwoods cuts using a chronosequence found yellow birch seedlings on less than a third of the plots measured in a stand 2 yr after treatment, and among none of the tallest saplings measured (Kelty and Nyland 1981). In contrast, in stands 6 and 10 yr after treatment, yellow birch was found on more than three quarters of the plots, and was the tallest on 40 percent of them.

If objectives are more economically focused, the effectiveness of some aspects of treatment can be evaluated on the scale of 10 to 15 yr. For example, Kern et al. (2013) considered the gap treatments installed on a nutrient-rich, sugar maple-dominated site to be regeneration failures after 12 yr due to the high levels of *Rubus* species and unacceptably low levels of tree saplings in the gaps. From a purely ecological perspective, in contrast, if sufficient numbers of trees were able to overtop the *Rubus* species after 20 or 30 yr and eventually capture the gap, the gaps could potentially still be considered effective.

Evaluation of treatments also includes monitoring changes taking place in forest structure to determine the timing of future treatment manipulations. For example, with MOSS the regeneration in modified shelterwood areas is being monitored to determine the appropriate time to remove a portion of the remaining overstory.

Example

For MOSS, an initial post-treatment cruise of areas receiving different cutting intensities was conducted to determine residual basal area. Comparing observed and target residuals, some substantial differences were noted (Table 5). Additional implementation monitoring found that, in most cases, error was incurred primarily in the marking phase of implementation rather than in the harvesting of marked trees.[10] Further analyses of data associated with the harvest is estimating logger error rates for trees receiving different prescriptions and is evaluating potential contributing factors to those errors.[10] In another implementation evaluation effort[11], treatments are being assessed with respect to their success

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[10] Manuscript in preparation: Steele, T.W.; Fassnacht, K.S. Comparison of prescribed versus observed outcomes of timber harvests in northern hardwood forests.

[11] Manuscript in preparation: Fassnacht, K.S.; Steele, T.W. Snag dynamics in northern hardwood forests under different management scenarios.

Table 5.—Comparison of managed old-growth silvicultural study (MOSS) target residual basal areas with values derived from an initial post-treatment cruise for different canopy treatments, cutting zones, or both, within canopy treatments

Canopy treatment/site	No. sample points	Observed basal area	Target basal area	Absolute difference	Percentage difference
		------------------------ m^2/ha	-----------------		
Small gaps					
Flambeau	38	18.8	19.5	-0.7	-4
Highlands	36	20.0	19.5	0.5	2
Argonne	41	22.0	20.0	2.1	10
Large gaps					
Flambeau	38	24.6	19.5	5.1	26
Highlands	34	21.6	19.5	2.1	11
Argonne	38	23.4	20.0	3.4	17
Irregular multi-cohort					
Light thin					
Flambeau	11	23.9	20.1	3.2	16
Highlands	14	25.3	22.3	3.0	13
Argonne	9	23.4	23.0	0.5	2
Heavy thin					
Flambeau	24	23.7	18.4	5.3	29
Highlands	13	21.1	20.2	0.9	5
Argonne	14	23.4	20.7	2.8	13
Shelterwood					
Flambeau	36	14.0	13.8	0.2	2
Highlands	37	10.6	13.8	-3.2	-23
Argonne	36	14.9	13.8	1.1	8

in enhancing standing dead wood, as well as determining potential factors related to snag longevity (for natural snags) and the transition between live and standing dead, and standing dead and down (for girdled trees only).

Early effectiveness monitoring has been initiated for MOSS as well. One study has compared tree regeneration and groundlayer abundance and diversity in the different treatment areas (Reuling 2014). Results from this study suggest that, from this early perspective, there may be some challenges in meeting study objectives, particularly with respect to species diversity. While stem densities in smaller size classes (<2.0 cm d.b.h.) increased in treatments compared to *controls*, the largest gains were in shade-tolerant species, providing little progress towards species diversity goals. The study also found that groundlayer vegetation was richer in small gaps due to contributions from forest interior species. In treatments creating more open canopies, however, enhanced diversity and richness was due to greater numbers of exotic invasives and disturbance-related species, both of which may have negative impacts on desired tree regeneration. In addition, comparison of fenced and unfenced areas found that while regeneration stem density generally was not impacted by deer browsing 3 to 4 yr after treatment, yellow birch did benefit from deer exclusion. This suggests that browsing may have the potential to hinder the ability of treatments to meet species diversity objectives for some species.

In a second study, habitat use and nesting patterns of southern flying squirrels (*Glaucomys volans*) were compared among treatments in the first 2 yr after harvest (Steinhoff 2010, Steinhoff et al. 2012). Results showed that all management strategies provided adequate squirrel habitat. There were some differences in nest use among treatments, however, with more nest switching in the *small gaps* treatment compared to the *irregular multi-cohort* treatments. Nest switching in the *irregular multi-cohort* treatment did not differ from that in the *control* stands, however. Moderate levels of nest switching are expected for southern flying squirrels to help reduce nest parasite loads and to access resources at other nest sites (Steinhoff et al. 2012). Low levels of switching can indicate low parasite loads, abundant resources at the nest site location, or a lack of suitable nest trees. The latter reason was suspected as a factor in the lower nest switching rate of the *irregular multi-cohort* treatment, with heavy cutting in some areas reducing number of available nest sites. Additional studies over time will need to evaluate habitat use and nesting patterns as the treated stands continue to develop.

Timeline

One of the considerations in the decision to use active forest management to accelerate the development of old-growth characteristics is the time available to achieve the desired conditions. How long will it take a given stand to achieve target conditions in the absence of management, and how does that compare to what could be achieved through active management? How far might the initial harvest move a stand toward project goals?

In a modeling study, Choi et al. (2007) found that a 77-yr-old even-aged northern hardwood stand receiving no management took an additional 79 yr (stand age 156 yr) to reach minimum old-growth criteria. Multiple entries of moderately-heavy thinning in this stand reduced the time to meet old-growth criteria to 36 yr (stand age 113 yr). In contrast, a second-growth northern hardwood stand that was already uneven-aged was projected to reach old-growth thresholds in only 12 yr in the absence of management. Moderately-heavy thinning increased the time to reach the old-growth threshold to 20 yr due to the need to remove larger trees to meet the thinning targets. Using moderate thinning instead of moderately-heavy thinning in this second example reduced the time to reach old-growth criteria compared to the no-treatment alternative by only 2 yr. These results suggest that the time to achieve structural goals will not necessarily be decreased with active management for all northern hardwood stands. Furthermore, they suggest that somewhat younger, even-aged stands may offer the best opportunity to shorten the time to meet goals through active management.

Example

The MOSS treatment stands were evaluated before and after treatment relative to basic minimum structural criteria required to attain old-growth characteristics as defined by Choi et al. (2007) (Table 6). Values were calculated individually for each treatment area (i.e., half stands for active treatments, whole stands for *controls*) to illustrate the degree to which results might vary depending on initial conditions. Results showed that none of the treatment areas would meet minimum thresholds before treatment, although several were close. After the initial harvest, 5 of the 21 treatment areas met minimum conditions. Additional analyses (not shown) suggest that for three of the five areas, artifacts of the sampling strategy may have increased calculated basal areas in large trees somewhat, contributing to perhaps a premature determination that the thresholds were reached. Furthermore, analyses using only slightly different thresholds (defined by Hanson et al. 2012; not shown) resulted in two stands meeting criteria before treatment and six treatment areas meeting criteria after treatment, highlighting the influence that differences in definitions of old-growth characteristics can have on outcomes. Nonetheless, using either set of criteria, the harvest treatments moved stands closer to meeting old-growth conditions, and in some cases helped stands meet basic minimum structural conditions after a single entry. With stands meeting basic minimum criteria identified, additional variables can be evaluated (e.g., volume of downed wood, measures of vertical structure), to determine whether these stands have attained a more complete suite of characteristics associated with old-growth forests.

Levels of Implementation

The concepts described in this report can be applied to forest stands under a variety of ownerships, both public and private, and with a range of primary management objectives, from ecological to economic. Because techniques to increase forest structural complexity include a number of different strategies, the degree to which they may be implemented can vary with landowner objectives

Table 6.—Comparison of stratum-weighted managed old-growth silvicultural study stand characteristics with minimum criteria for old-growth status as defined in Choi et al. (2007) before and after initial treatments. Highlighted cells have surpassed minimum criteria.

	Pretreatment			Post-treatment		
Canopy treatment[a]/ site – CWD trt[a]	Total BA[b] [m^2/ha]	Percent BA in trees ≥26 cm d.b.h.	Percent BA in trees ≥46 cm d.b.h.	Total BA [m^2/ha]	Percent BA in trees ≥26 cm d.b.h.	Percent BA in trees ≥46 cm d.b.h.
Min. OG threshold[c]	>20	>80	>50	>20	>80	>50
Control						
Flambeau	30	67	20	32	71	22
Highlands	35	82	39	35	84	40
Argonne	37	85	35	37	86	38
Small gaps						
Flambeau - low	29	63	3	24	76	5
Flambeau - high	31	65	10	25	77	14
Highlands - low	32	76	31	25	83	42
Highlands - high	32	71	16	25	78	20
Argonne - low	30	85	49	24	89	56
Argonne - high	31	83	32	25	86	41
Large gaps						
Flambeau - low	33	80	42	28	86	53
Flambeau - high	34	83	46	29	88	55
Highlands - low	31	75	16	22	79	25
Highlands - high	32	83	45	24	87	54
Argonne - low	34	79	30	24	88	40
Argonne - high	34	88	33	23	94	46
Irregular multi-cohort						
Flambeau - low	32	63	8	25	77	12
Flambeau - high	31	58	8	24	71	10
Highlands - low	28	77	31	23	82	39
Highlands - high	33	79	35	25	86	45
Argonne - low	36	90	47	26	95	61
Argonne - high	31	82	27	24	89	41

[a] trt = treatment; CWD = coarse woody debris; canopy and CWD treatments are defined on page 7.
[b] BA = basal area
[c] Min. = minimum; OG = old-growth

and available resources. Even forests managed largely for timber production can incorporate some techniques (e.g., retaining some legacy trees) (Zasada et al. 2004) which can increase ecological complexity with relatively minor losses in timber production (Hanson et al. 2012).

Modeling studies, such as those by Hanson et al. (2012), can provide useful data for informing decisions regarding how to best balance ecological and economic objectives. In this study, modeled results from 22 different manifestations of ecological forestry techniques were compared to single-tree selection and to a no-treatment control. The ecological forestry techniques ranged from simple actions, such as increasing the maximum residual tree diameter, to more complex combinations of treatments, such as multi-cohort harvests in combination with retention of all yellow birch and eastern hemlock and an increased maximum residual tree diameter. Results showed varying degrees of impact on timber production, from a 9 percent long-term reduction in yield associated with permanently retaining 7 trees/ha, to a 55 percent reduction in yield associated with a combination of CWD creation (75 percent of old-growth levels), increased maximum residual diameter (to 80 cm d.b.h.), and group selection. Results also showed varying degrees of success with respect to achieving ecological goals. For example, none of the treatments provided similar volumes of CWD compared with old, unmanaged forests. The CWD retention treatments, however, did double CWD volume over single-tree selection, and treatments retaining all yellow birch and eastern hemlock performed similarly to CWD retention treatments after approximately 110 yr. Likewise, while most treatments, including group selection and multi-cohort management, performed poorly relative to species diversity goals, treatments including retention of all eastern hemlock and yellow birch significantly increased basal area representation of these species compared to alternatives.

With information regarding tradeoffs from modeling studies as described above, or from field trials, as described briefly earlier, discussions can be undertaken regarding the levels of implementation appropriate for a given property. For example, large blocks of forest on national forests may be the most suitable for implementing the full suite of techniques to enhance forest structure. Other public lands under state or county ownership might be well-suited to incorporating an intermediate level of implementation, allowing for a moderate level of ecological benefits while increasing revenue from forest products. On private ownerships focused on timber production, or for small parcels of land, incorporating a few, more modest, ecological forestry techniques may represent the best balance of considerations.

SUMMARY

Active management techniques that emulate natural forest disturbance and stand development processes have the potential to enhance species diversity and structural complexity in managed forests, helping to meet goals related to biodiversity, ecosystem health, and forest resilience in the face of uncertain future conditions. In considering the use of active management to enhance composition and structure in northern hardwood forests, it is important to clearly define what reference conditions are to be used, and the degree to which management will seek to meet those reference conditions. Specific initial targets can then be identified. Modification of these targets may be necessary to accommodate contemporary stressors including herbivory, invasive species, and climate change. A pretreatment evaluation of the stand(s) being considered for management will provide information from which initial treatments can be developed, and which will help determine the feasibility of meeting desired objectives. Additional adjustments to targets may be needed at this time. Pilot implementation of targets being considered can be useful in refining techniques and identifying additional adjustments to targets that may be necessary prior to full implementation of the prescription. Finally, evaluation and monitoring of the treatments, both for success of their implementation as well as for effectiveness, is critical for learning what works and what does not, allowing future treatments to be modified as part of an adaptive management process. It is our belief that the process described in this report can be used to determine which techniques, from the suite that are available to enhance forest structure, might be appropriate for a given forest and set of management objectives, thereby helping to increase the ecological complexity of managed northern hardwood forests.

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GLOSSARY

active management – management consisting of any purposeful activity in a stand or area

basal area – cross sectional area of an individual tree at breast height (tree basal area), or the cumulative cross sectional area at breast height of trees in a specified size range within an area of interest (plot basal area, stand basal area, etc.); stand basal area is commonly reported in ft^2/ac or m^2/ha; see **diameter at breast** height below for a definition of breast height

biodiversity – biological diversity (see definition for **diversity** below)

coarse woody debris [CWD] – large standing and downed woody debris

cohort – group of trees which became established more-or-less at the same time

diameter at breast height [d.b.h.]– the diameter of a tree measured 1.37 m (4.5 ft) above the point of germination; in Canada, breast height is 1.3 m above the point of germination

diversity – the condition of having or being comprised of differing elements[12]

even-aged – stand of trees composed of a single age class in which the range of ages is usually not more than 20 percent of the potential rotation age

hollow – as defined for the managed old-growth silvicultural study, a cavity that touches the ground, is due to rot, provides overhead protection from precipitation, and is ≥10 cm wide and ≥10 cm deep (Fassnacht et al. 2013)

legacy tree – a tree retained (permanently or for a long period) in a stand after harvest; these trees increase structural and age diversity of a stand harvest, can act as a seed source, and can act as a refuge from which plant or animal species can either repopulate a stand after harvest or maintain populations despite harvest (e.g., northern flying squirrel; Carey 1995) (Lindenmayer and Franklin 2002)

maximum residual d.b.h. – diameter at breast height of the largest tree(s) to be left in a stand after harvest; all trees larger than the maximum residual d.b.h. may be harvested

mid-tolerant tree species – tree species requiring intermediate levels of light for adequate survival and growth

natural rotation period – "Mean time needed to disturb an area equivalent to the study area (the study area is arbitrarily defined; some sites may be disturbed several times in this period and others not at all – thus 'study area' must be explicitly defined)".[13] Natural rotation period is most often <u>not</u> equivalent to "return interval," which refers to the average interval between consecutive events on the same site. Natural rotation period equals return interval only in the case where the magnitude of the event is catastrophic, such that it disturbs an area equivalent to the entire study area in a single event. In all other cases (i.e., where events disturb an area smaller than the equivalent of the entire study area), more than one event will be required in order to disturb an area equivalent to the study area, and therefore natural rotation period > return interval.

niche – a combination of biotic (such as plant species composition, and structure) and abiotic (such as temperature and moisture) factors making up the environment required by an organism

northern hardwood forest – forest dominated by a combination of sugar maple, American basswood (*Tilia americana*), yellow birch, white ash, and American beech (*Fagus grandifolia*); associated species may include red maple (*Acer rubrum*), eastern hemlock, balsam fir (*Abies balsamea*), northern red oak, and eastern white pine (Wisconsin Department of Natural Resources 2006)

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[12] www.merriam-webster.com/dictionary/diversity (accessed February 12, 2014)

[13] www.biol.ttu.edu/faculty/mncintyre/Landscape%20Ecology/disturb_defns_scales.pdf (Accessed February 12, 2014)

passive management – management consisting of purposeful inactivity in an area (i.e., leaving it alone)

shifting mosaic steady state – a condition of a forest stand or landscape is composed of a mosaic of **cohorts** of different ages, with each cohort occupying an approximately equal area; while each cohort changes over time, the mosaic itself is stable with respect to properties such as size distribution, species composition, and biomass (see definition for **steady state** below)

silvicultural techniques – forest management practices that manipulate the establishment, growth, composition, quality, and health of forest stands

spatial heterogeneity – in relation to species composition and structural elements, reflects their non-uniform spatial arrangement in a stand, creating a diversity of conditions and habitats that vary across space

steady state – a state, such as composition, structure, or biomass which does not change substantially over time

structural complexity – characterized by having many parts in an intricate arrangement[14]

structure – "the vertical and horizontal arrangement of plants, dead and alive"[15]; in reference to stand structure – pertaining to the array of elements directly or indirectly derived from trees that occur in a diversity of sizes (e.g., diameters, downed logs), conditions (e.g., cavities, tip-up mounds) and configurations (e.g., multiple age cohorts); best conceived relative to a simplified condition (e.g., narrowly even-age, lacking large deadwood, etc.).

supercanopy trees – trees extending above the main canopy of a stand; these trees are typically remnants of the stand that existed before the stand-replacing disturbance which initiated the current stand

tip-up mounds – mounds left by the decaying root wads of trees that have fallen over due to uprooting; associated with pits, next to the mounds, from where the root wads used to be

uneven-aged – a forest stand with at least three distinct age classes, either intimately mixed or in small groups

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[14] http://en.wikipedia.org/wiki/Complexity (accessed February 12, 2014)

[15] http://northernwoodlands.org/articles/article/what-is-forest-stand-structure-and-how-is-it-measured/ (accessed February 12, 2014)

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Active management techniques that emulate natural forest disturbance and stand development processes have the potential to enhance species diversity, structural complexity, and spatial heterogeneity in managed forests, helping to meet goals related to biodiversity, ecosystem health, and forest resilience in the face of uncertain future conditions. There are a number of steps to complete before, during, and after deciding to use active management for this purpose. These steps include specifying objectives and identifying initial targets, recognizing and addressing contemporary stressors that may hinder the ability to meet those objectives and targets, conducting a pretreatment evaluation, developing and implementing treatments, and evaluating treatments for success of implementation and for effectiveness after application. In this report we discuss these steps as they may be applied to second-growth northern hardwood forests in the northern Lake States region, using our experience with the ongoing managed old-growth silvicultural study (MOSS) as an example. We provide additional examples from other applicable studies across the region.

KEY WORDS: compositional diversity, structural complexity, spatial heterogeneity, Wisconsin, old-growth forest, active management, Lake States

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