THE ACADIAN FOREST ECOSYSTEM RESEARCH PROGRAM: AN EXAMPLE OF NATURAL DISTURBANCE-BASED SILVICULTURE IN THE NORTHEAST

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Abstract.—The Acadian Forest Ecosystem Research Program (AFERP) began in 1994 as one of the nation's first trials of natural disturbance-based silviculture. The study tests the ecological impacts of two versions of expanding-gap silvicultural systems that are designed to emulate the spatial extent and frequency of natural disturbances in northeastern North America. The AFERP is now well into its second decade of monitoring. Inventory systems for overstory trees, saplings, herbaceous plants, tree regeneration, coarse woody debris, forest floor depth, and canopy light interception are described in this paper.

INTRODUCTION

Over the past 20 years, there has been a strong shift away from production-oriented management on public lands in the United States and Canada towards silvicultural practices guided by principles of disturbance ecology to increase ecosystem resilience and conserve biodiversity (Long 2009, Seymour et al. 2006). Inherently, these new practices are conceptually and practically much more complex, often requiring extensive dendrochronological reconstructions of stand and landscape age structures to effectively emulate natural disturbance patterns for forest types in each region (D'Amato and Orwig 2008, North and Keeton 2008). However, both voluntary and regulated implementation of these systems has proceeded even without extensive research on economic or ecological sustainability of the practices (Gamborg and Larsen 2003, Long 2009). Earlier experiments by the U.S. Department of Agriculture, Forest Service and Canadian Forest Service were limited in focus, treatment types, or experimental design, and did not fully inform policy makers of repercussions of the shift in emphasis (Seymour et al. 2006).

The resulting paucity of pertinent research spawned numerous innovative large-scale management experiments by the U.S. and Canadian Forest Services, universities, and other organizations starting in the early 1990s (Puettmann 2005, Seymour et al. 2006). In northeastern North America, there are two notable experiments: the Vermont Forest Ecosystem Management Demonstration Project (FEMDP) (Keeton 2006, North and Keeton 2008) and the Acadian Forest Ecosystem Research Program (AFERP) (Saunders and Wagner 2005, Seymour et al. 2006). These stand-level experiments use silvicultural systems that are designed to emulate wind disturbance, senescence, and other tree- to gap-level disturbances that historically affected 1-5 percent yr^{-1} of forest lands throughout the region (D'Amato and Orwig 2008, Lorimer and White 2003, Runkle 1982, Seymour et al. 2002).

The AFERP is the older experiment of the two with initial harvests occurring during winter 1995-96. Rather than using size-based structural control (e.g., a diameter distribution), the AFERP uses area control; all harvests are located within expanding gaps that are based loosely on the German "Femelschlag" system (Troup 1928). These treatments lead to distinctly irregular age and size structures, and may serve as a technique in a wide array of forest types to convert single-cohort stands to multi-aged stands more capable of sustaining selection-based forestry. Specifically, the

AFERP has three primary goals (Saunders and Wagner 2005): (1) develop alternative silvicultural techniques and systems based on regional disturbance ecology, (2) evaluate ecosystem-scale influences of forest management practices, and (3) enhance understanding about forest ecosystems in the Acadian ecoregion.

Saunders and Wagner (2005) reported on results from the first 10 years of the AFERP, giving a very brief overview of the experimental design and inventory systems of the study. Since that publication, the experimental gaps within the AFERP have been expanded. Planning for these harvests revealed that one of the treatments was conceptually flawed and would not test the expanding gap concept. Changes were made to the treatment design to rectify this oversight. Further, several modifications to inventory systems have been made to make each more efficient. This paper documents those changes in detail.

METHODS

Study Area

The AFERP study is located on nine 9.4- to 11.3-ha sites within the Penobscot Experimental Forest (PEF) (see Kenefic and Brissette's "History" [this volume] for a description of the PEF). Although much of the PEF was originally heavily dominated by conifers, these sites have had a significant hardwood component for at least the past 50 years[1] and are generally of higher quality. Tree species with average, pretreatment basal areas greater than 1 m^2 ha^{-1} include (in decreasing order of dominance): eastern hemlock (*Tsuga canadensis* [L.] Carr.), red maple (*Acer rubrum* L.), eastern white pine (*Pinus strobus* L.), balsam fir (*Abies balsamea* [L.] Mill), northern white-cedar (*Thuja occidentalis* L.), paper birch (*Betula papyrifera* Marsh.), red spruce (*Picea rubens* Sarg.), and trembling aspen (*Populus tremuloides* Michx.). Sixteen other tree species are also present across the sites.

Topography in the AFERP sites is generally flat to rolling with slopes less than 20 percent. Soils are a fine-scaled mix of Spodosols and Histosols. Drainage is quite variable, ranging from moderately well drained to poorly drained. Based on stand growth projections, site qualities generally exceed 21 m for balsam fir (50 year base age) (Arsenault 2011).

Prior to initial harvests, sites did not differ significantly in basal area, density, or stand volume, although there were some minor compositional differences among the stands (Arsenault et al. 2011). Stand volume, basal area, and tree density averaged 283.6 m^3 ha^{-1}, 37.6 m^2 ha^{-1}, and 2,404 trees ha^{-1}, respectively (Arsenault et al. 2011).

Experimental Design

Treatments

Three treatments were implemented in three blocks using a randomized block design across the nine sites. Blocks are associated with initial harvest date, during the winter of either 1995-96, 1996-97, or 1997-98 (Table 1). Treatments were an unharvested, unmanaged experimental control and two expanding-gap silvicultural systems. Both use a common 10-year cutting cycle over a 100-year rotation.

The more intensive large-gap, or 20:10, treatment was described in detail by Saunders and Wagner (2005). Briefly, the 20:10 is an extended group shelterwood with reserves with 20 percent of the area harvested during each of the first five cutting cycles (i.e., a 10-year regeneration period) (Fig. 1). Initial gaps are approximately 0.2 ha in size. Study areas are scheduled to "rest" during the last five cutting cycles, although thinning and other intermediate treatments may occur if deemed necessary. The goal of this system is a mid-succession stand with a significant component of species that are intermediate in shade tolerance (i.e., white pine, paper birch, yellow birch [*Betula alleghaniensis* Britt.]).

[1] Seymour, R.S. [N.d.] FES 536: Forest stand dynamics (class files). On file with R.S. Seymour, University of Maine, School of Forest Resources, 5755 Nutting Hall, Orono, ME 04469-5755.

Table 1.—Schedule of completed AFERP measurements and harvests, 1995-2010, by year and block number. With a few exceptions as noted, inventories were completed by replicate block defined as follows: Block 1 = research areas 1-3, Block 2 = research areas 4-6, and Block 3 = research areas 7-9. Planned intervals between inventories for a block are also given.

	Inventory						
Year	Overstory & saplings	Coarse woody debris	Seedlings & herb. plants	Forest floor	Canopy light interception	Retention trees*	Harvest (winter)
1995	1,2	1,2§	1,2	1	1,2	1	
1996		2§		2			1
1997	3	3	3	3	3	2	2
1998		1	1		1	1,3	3
1999		2	2		2		
2000	1,3†	3	3		3	1	
2001	2					2	
2002	3					3	
2003							
2004							
2005	1	1	1			1	
2006	2	2	2			2	1
2007	3	3	3			3	2
2008							3
2009							
2010	1,2‡						
Planned Interval (yr)	5	10	5	20	5	5	

* Before 2005, retention trees were only measured in 20:10 replicates.
§ Inventory started in 1995, but only the control replicate was finished. Inventory on other replicates was completed in 1996.
† Inventory only included 20:10 replicate in block 3.
‡ Inventory only included 20:10 and control replicates in block 2.

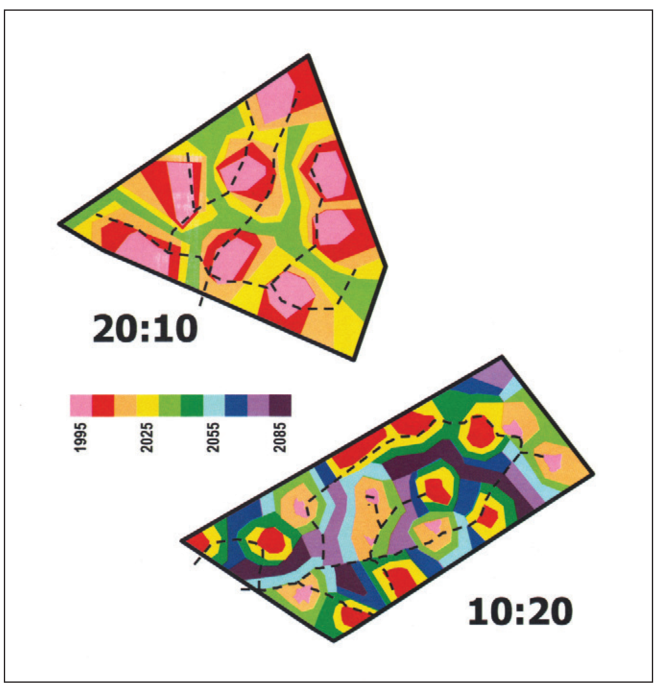

Figure 1.—Conceptual gap expansion diagrams for the two harvest treatments in the AFERP, color coordinated by year of entry. Initial entries into the 20:10 treatment (above) are in light red and expansion proceeds outward to the multi-colored strips. Initial entries into the 10:20 treatment (below) are the light and dark red areas, in 1995 and 2005, respectively. Successive expansions of these initial gaps occur every 20 years, alternating by gap cohort (i.e., 1995 gaps or 2005 gaps). In both treatments, gaps are coalesced to avoid narrow strips and patches that could be inoperable in a future cycle. Expansions release regeneration whenever possible and use natural or anthropogenic breaks in a stand (i.e., streams, wet areas, skid trails) to define their boundary. Skid trails are shown as black dashed lines.

The small-gap, or 10:20, treatment was refined during the 2005-2007 harvests to better reflect the original intent of the project. The 10:20 is an "expanding" group selection with 10 percent of the area harvested each cycle (Fig. 1). Initial gaps average 0.1 ha in size, and are expanded on alternative cutting cycles (i.e., a 20-year regeneration period); therefore two "cohorts" of gaps exist in each study area. This system encourages regeneration of shade-tolerant species, namely eastern hemlock, red spruce, sugar maple (*Acer saccharum* Marsh.), and balsam fir, and should accelerate the study area to a late-successional status.

Gap retention targets

Both systems use a permanent retention target of 10 percent of the experiment-wide, pretreatment basal area, or roughly 3.75 m^2 ha^{-1}. During gap creation and expansion, there are two possible retention scenarios depending on the amount of regeneration present (Fig. 2). If the gap or expansion has a sufficient stocking of large (at or above breast height or 1.37 m) and well-distributed seedlings and saplings—indicative of the understory reinitiation stage of stand development (Oliver and Larson 1996)—the gap or expansion is treated with a one-stage removal of the overstory (Fig. 2, top row), thereby lowering the residual basal area to the permanent 10 percent target. If the gap or expansion has an insufficient amount of regeneration (i.e., "nonregenerated"), the overstory removal will proceed in two stages to provide seed source and adequate shade for regeneration development (Fig. 2, bottom row). Initially, basal area will be reduced to a target of 30 percent, or 11.25 m^2 ha^{-1}. In the following gap expansion, 10 or 20 years for the 20:10 and 10:20 treatments, respectively, the basal area is then reduced to the final 10 percent target.

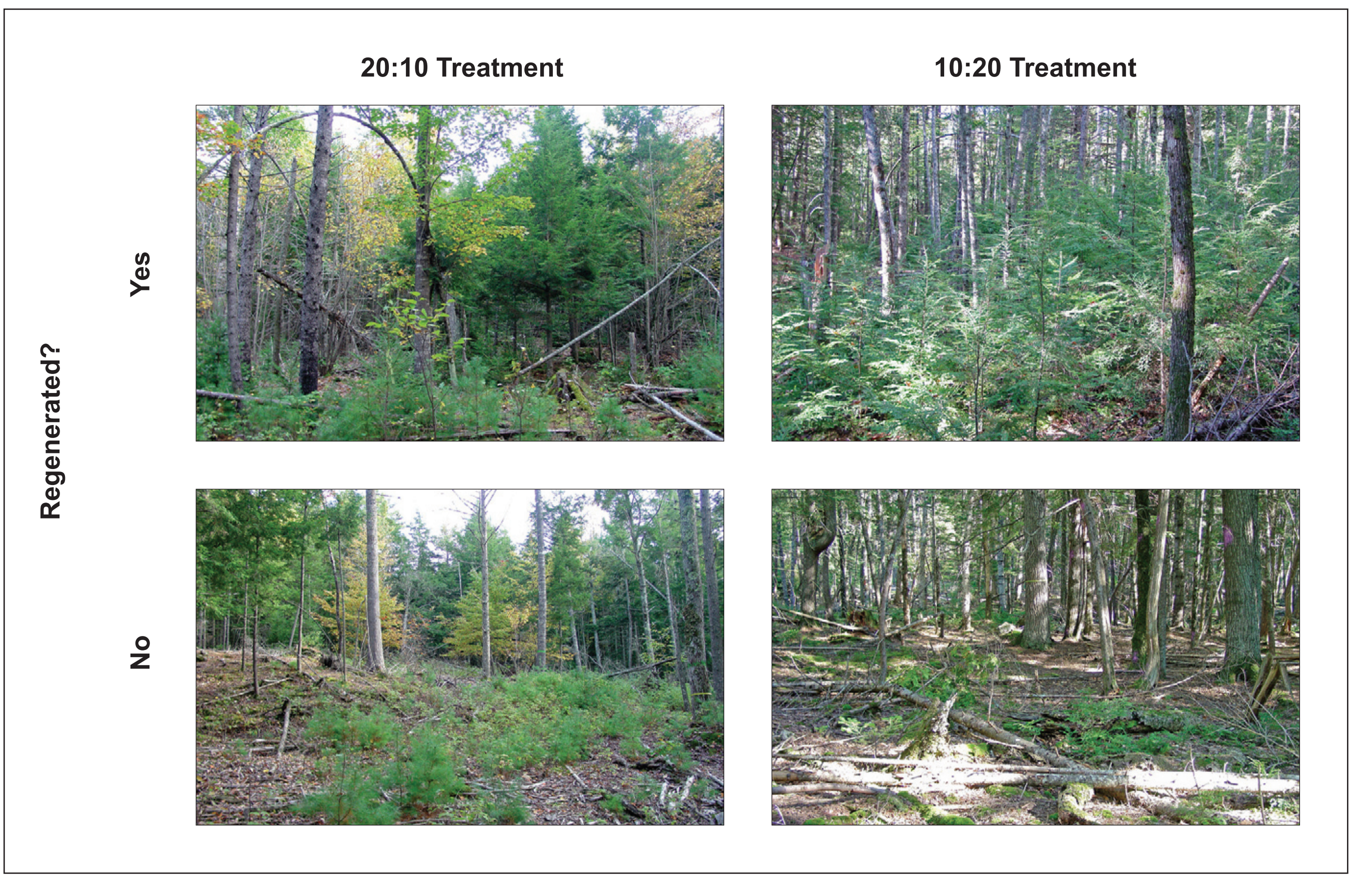

Figure 2.—Examples of regenerated gaps (top) and nonregenerated gaps (bottom) for both the 20:10 treatment (left) and 10:20 treatment (right). The 20:10 pictures are taken 10 years post-harvest; the 10:20 pictures were taken preharvest. Photos courtesy of Mike Saunders, Purdue University.

Retention targets are meant to act as a flexible guide. Retention in individual openings may vary among replicates, but on average will be approximately 10 percent and 30 percent for regenerated and nonregenerated areas, respectively.

Special areas

Within several of the replicates, there are temporary and perennial streams, vernal pools, seeps, and other wetland features. These features are protected by a "special area" designation that extends 10 m away from the resource. Harvesting these areas is included within the 10 or 20 percent area control for a treated replicate, but retention guidelines are much higher, 60 percent of pretreatment basal area or 22.50 m^2 ha^{-1}. Further, for special areas protecting a stream, both sides of the stream cannot be harvested in the same entry. Mature canopy cover is thereby kept above the stream and the need for new stream crossings is minimized.

Inventory Systems

There are several types of inventories conducted across the AFERP research areas, including overstory and sapling plots, coarse woody debris transects, seedling and herbaceous plant quadrats, forest floor sampling, canopy light interception readings, retention tree measurements, and a census of harvested stems. Most inventories are spatially linked to a 50 m by 50 m grid that overlays each research area (Fig. 3a). All inventories had preharvest measurements in 1995-97, with most post-harvest measurements in 1998-2002 (Table 1). Planned resampling cycles are from 5-20 years, depending on inventory (Table 1). Data from nearly all inventories are contained within a geo-referenced database maintained by the School of Forest Resources and at the University of Maine.

Overstory and saplings

The purpose of this inventory is to monitor the growth and structural development in each of the replicates. Overstory and sapling plots are installed on 20 randomly selected grid points. Overstory trees are defined as woody vegetation ≥9.5 cm in diameter at breast height (d.b.h.) and measured on circular 0.05-ha plots. Saplings are defined as woody vegetation between 1.5 and 9.5 cm d.b.h. and measured on circular, nested 0.01-ha subplots (Fig. 3c). All overstory trees and saplings are spatially located within these plots and permanently tagged. Species, d.b.h., tree condition (e.g., live, dead, cull, broken top), canopy stratum, and light field (*sensu* Bechtold 2003) are recorded for both trees and saplings. For saplings, origin (i.e., seedling on mineral soil or forest floor, seedling on nurse log, or stump sprout), and overhead character (i.e., beneath contiguous overstory or within canopy gap) are also recorded.

Coarse woody debris

The purpose of this inventory is to monitor the biomass, volume, and spatial distribution of coarse woody debris by type and decay class within each replicate. Because individual pieces are tracked, decay rates and transitions between types may be estimated as well. In 2005, this inventory replaced a more costly and less efficient area-based sampling design; see Fraver et al. (2002) for a description of the prior system.

Coarse woody debris is defined within the AFERP as all standing snags and down wood >4.5 cm in diameter. Both snags and down wood are surveyed on 50-m or 100-m transects randomly oriented upon nearly every grid point in each research area (Fig. 3a). Transects are centered on the grid point and allowed to intersect one another. Transects that would otherwise extend beyond research area boundaries are either terminated or reflected back into the research area. Between 2,398 and 3,516 m of transects are installed per research area.

Transects are considered nested because coarse woody debris is measured in different size classes at different points along the transect (Fig. 3b). For 100-m transects, both snags and down wood ≥4.5-cm in diameter are sampled from 0-5 m, 45-55 m, and 95-100 m along the transect. Everywhere

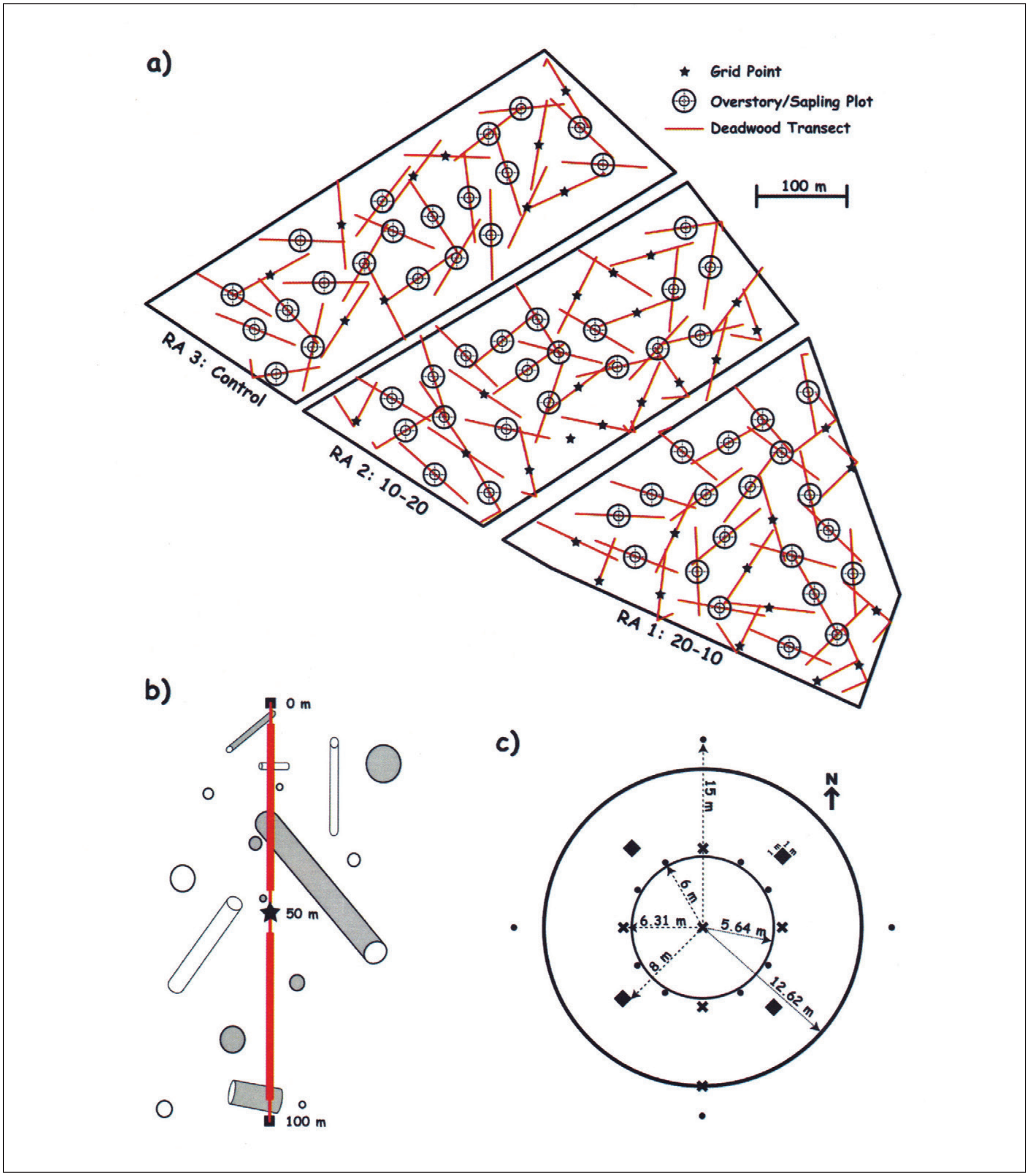

Figure 3.—Overview of the inventory systems for the AFERP. (a) Spatial layout of overstory plots and deadwood transects across the network of gridpoints in the first replicate block. (b) Schematic drawing of a 100-m-long nested, deadwood transect showing zones where sampling includes material ≥9.5 cm (thick red lines) and ≥4.5 cm (thin red lines). Items sampled include all down woody items crossing the transect line that are ≥0.3 m in length (gray cylinders) and standing snags that are measured “in” using a 4-m BAF variable radius prism centered on the transect perpendicular to the snag (gray circles). (c) Schematic drawing to scale of an 0.05-ha overstory plot, with a nested 0.01-ha sapling plot, four 1-m^2 herbaceous and seedling quadrats (black diamonds), 12 forest floor sampling points (black circles), and six canopy light interception points (X’s).

else, snags and down wood must measure ≥9.5 cm in diameter. To be sampled, down wood must intersect the transect and have a diameter exceeding the size threshold. Snags are sampled when their d.b.h. exceeds the size threshold for that part of the transect, and they can be counted as "in" from a 4-m basal area factor (BAF) prism held above a point on the transect perpendicular to the snag location (i.e., at the shortest point between the snag and the transect). Down wood with a diameter greater than its length and snags shorter than breast height are not sampled.

For snags, species (if it can be determined), decay class (Cline et al. 1980), origin (i.e., windsnap, windthrow, logging), d.b.h., height, and spatial location are recorded. Attributes such as cavities and history (e.g., dead tree from overstory inventory) are also noted.

For down wood, species, decay class (Maser et al. 1979), origin, and transect intersection location are recorded. To estimate volume using line transect-based estimators (van Wagner 1968), diameter at transect intersection, diameter at large end, diameter at small end, horizontal (i.e., straight-line) length, curved length, number of pieces, and hollowness are measured. Lengths and diameters are taken only on that portion of a piece with a diameter greater than the 4.5- or 9.5-cm threshold. Finally, suspension class (i.e., proportion of length not contacting the mineral soil or duff), history, and other special features are noted.

Seedlings and herbaceous plants

The purpose of this inventory is to both monitor changes in the herbaceous plant community and quantify tree regeneration up to 1.5 cm in d.b.h. Measurements take place on four 1-m^2 quadrats systematically located within the 0.05-ha overstory plots (Fig. 3c, black diamonds).

In each quadrat, ferns, grasses, sedges, rushes, forbs, shrubs, and tree seedlings are identified to species whenever possible. Mosses and lichens are identified to genus only. In cases in which identification to species in the field is not possible, collections from outside of the quadrat are made if numerous other individuals of the species are present. For all plants, percentage cover is estimated to the nearest 0.1 percent for 0.1-5 percent cover, the nearest 1 percent for 5-10 percent cover, the nearest 5 percent for 10-25 percent cover, and the nearest 10 percent for greater than 25 percent cover. Number of stems is recorded for ferns, forbs, shrubs, and tree seedlings.

Forest floor

The purpose of this inventory is to quantify changes in forest floor organic horizons by stratum depth and mass. Forest floor depth measurements are taken at eight locations within the 0.05-ha overstory plots (Fig. 3c, inner small black circles). In addition, 15 cm by 15 cm removal subplots are taken at four locations surrounding each overstory plot (Fig. 3c, outer small black circles); organic matter layer depth is measured to the nearest 0.1 cm on each side of the removal subplot. Collected material from each subplot is oven-dried at 70 ºC for 48-72 hours and weighed to the nearest 0.01 g to determine mass. All samples are then archived for future use.

Canopy light interception

The purpose of these measurements is to estimate changes in leaf area index and gap fraction in response to treatments. Measurements are taken twice per summer, once in July and once in August, with a LiCOR LAI-2000 plant canopy analyzer (LiCOR, Inc. 1992) at six precise locations within each 0.05-ha overstory plot (Fig. 3c, X's). Readings are taken on completely overcast days or on completely cloudless days in either early morning or late afternoon hours when diffuse light conditions predominate. Canopy masks (180º) are used to block out the southern portion of the sky for all readings. After downloading, average leaf area index and gap fraction of each overstory plot are calculated using the central 43º cone (rings 1-3) (Puettmann and Reich 1995), although all mean contact frequency (CT#_) and gap fraction (GAP_) values are saved for recalculation of leaf area or gap fraction for any masking scheme.

Retention trees

The purpose of this inventory is to quantify the growth and fate of trees retained during harvest operations. This inventory is not associated with plots or a grid, focusing on individual trees instead. Further, this inventory is not fully implemented. Records exist since 1995-97 for trees that meet the 10 percent long-term target in the 20:10 treatment (n=535). Trees are being added from the 10:20 treatment areas and for meeting the 30 percent target for nonregenerated gaps. In total, 907 individuals are now being monitored.

Each monitored tree is tagged and spatially located. Species, d.b.h., tree condition, height, lowest live crown (as defined by lowest whorl), canopy stratum, and light field are recorded. Presence of cavities, foliose lichen, and other special structural features are noted.

Harvested trees

The purpose of these measurements is to quantify the volume and quality of harvested material. This is a recent addition to the monitoring protocols as these data were not collected in the initial harvests in 1995-97. Before each harvest, the species and d.b.h. of marked stems are recorded within each gap. For trees greater than 20 cm in d.b.h., merchantable height to the nearest 1.22 m (15 cm minimum inside bark diameter) and number of clear faces in the 2.59-m (including trim) butt log are recorded to approximate the quality of sawtimber and veneer being removed.

Other inventories

Several other kinds of data have been collected since the experiment began, largely for short-term studies that documented various community responses to the initial gap harvests. Nearly all these data have been spatially referenced with Universal Transverse Mercator coordinates. Results and methodology of some of these studies have been published elsewhere (Miller et al. 2007, 2008; Thomas et al. 2009) although several exist only as unpublished theses. For example, Schofield (2003) collected herbaceous vegetation and tree regeneration data in 4-m^2 quadrats placed along north-south transects bisecting 45 harvest gaps, 23 recent (i.e., <25 years) natural gaps, and 23 closed-canopy areas across the experiment. Data collected were similar to the aforementioned inventory of seedlings and herbaceous plants, but also included spatial location in the gap, overstory basal area, canopy gap fraction, and increment cores and cross-sectional disks (i.e., tree cookies) from gap edge trees to determine gap age and origin. In a study of gap harvest impacts on the amphibian community, Strojny (2004) measured volume, decay class, and abundance of down wood ≥10 cm within 17 harvest gaps, 19 natural gaps, and 6 closed-canopy areas using 10-m line transects. Lastly, Olson (2009) superimposed 4-m^2 vegetation quadrats in a repeating pattern, cyclical sampling design (sensu Scheller and Mladenoff 2002) upon the coarse woody debris transects to investigate the spatial pattern of both herbaceous communities and tree regeneration in response to overstory basal area and canopy gap fraction.

Two other data sources are of note. For several of the research areas, stand histories have been reconstructed based on dendrochronological analysis of increment cores collected from trees in the overstory inventory.[2] Cores have been archived for future use. Second, airborne light detection and ranging data have been collected for five of the nine sites at a first return point density of >5 on a 1 m by 1 m grid. Raw and post-processed data are available from the lead author.

DISCUSSION

Puettmann et al. (2009) suggested that forests must be managed as complex adaptive systems in which silviculturists must produce forests with heterogeneous structures, composition, and functions in order to be resilient to changing biotic and abiotic conditions. Silvicultural research, they argued, thus must be designed to investigate aspects of scale and scaling

[2] Seymour, R.S. [N.d.] FES 536: Forest stand dynamics (class files). On file with R.S. Seymour, University of Maine, School of Forest Resources, 5755 Nutting Hall, Orono, ME 04469-5755.

to quantify nonlinear thresholds, local feedbacks, and other emergent properties (Puettmann et al. 2009).

The AFERP is a model example of this approach to forestry management and research. The AFERP uses silvicultural systems that can create quite heterogeneous stand structures and can be adapted to local conditions. Although inventory systems were initially designed to experimentally compare treatments with analysis of variance techniques (Seymour et al. 2006), redesigns over the past 5 years were done to explicitly investigate spatial patterns over multiple scales (e.g., Olson 2009). Retention tree inventories, for example, can be used to investigate tree growth in response to neighborhood competition; kriging can be used on the deadwood data to estimate relative salamander abundance.

Although the basic monitoring remains focused on vegetation, the AFERP continues to invite researchers interested in other biotic communities. This experiment, along with its more traditional PEF counterpart, the U.S. Forest Service Compartment Study (Brissette and Kenefic, this volume), will continue to be invaluable to both managers and researchers for years to come.

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