Revisiting the Northern Hardwood Silviculture Toolbox

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Outline

- Background
  - Early land-use
  - Species change
- Selection system silviculture
  - Stand structure
    - Species composition
    - Diameter distributions
- The silviculture toolbox
  - Examples

Early land use in the northern Great Lakes

- Historical land-use patterns of the Great Lakes was very similar to the northeastern US, including periods of:
  - heavy logging
  - land-clearing for agriculture and mining
  - farm abandonment
  - subsequent growth of secondary forests
- Most of the state of Michigan was logged between 1840 and 1900, with Michigan becoming the nation's leading lumber producer between 1869 and 1900
- The first sawmill in Michigan was built at the mouth of the Menominee River in the Upper Peninsula in 1832

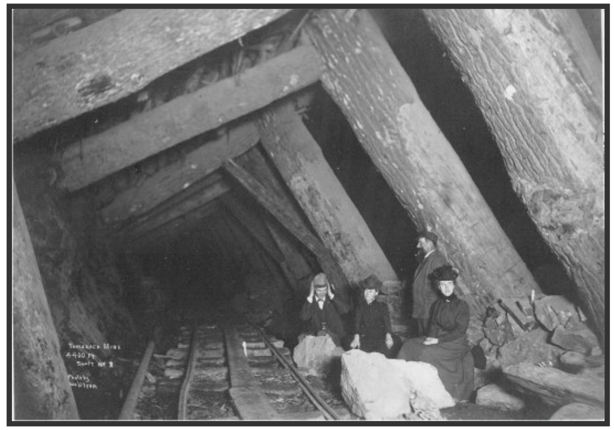
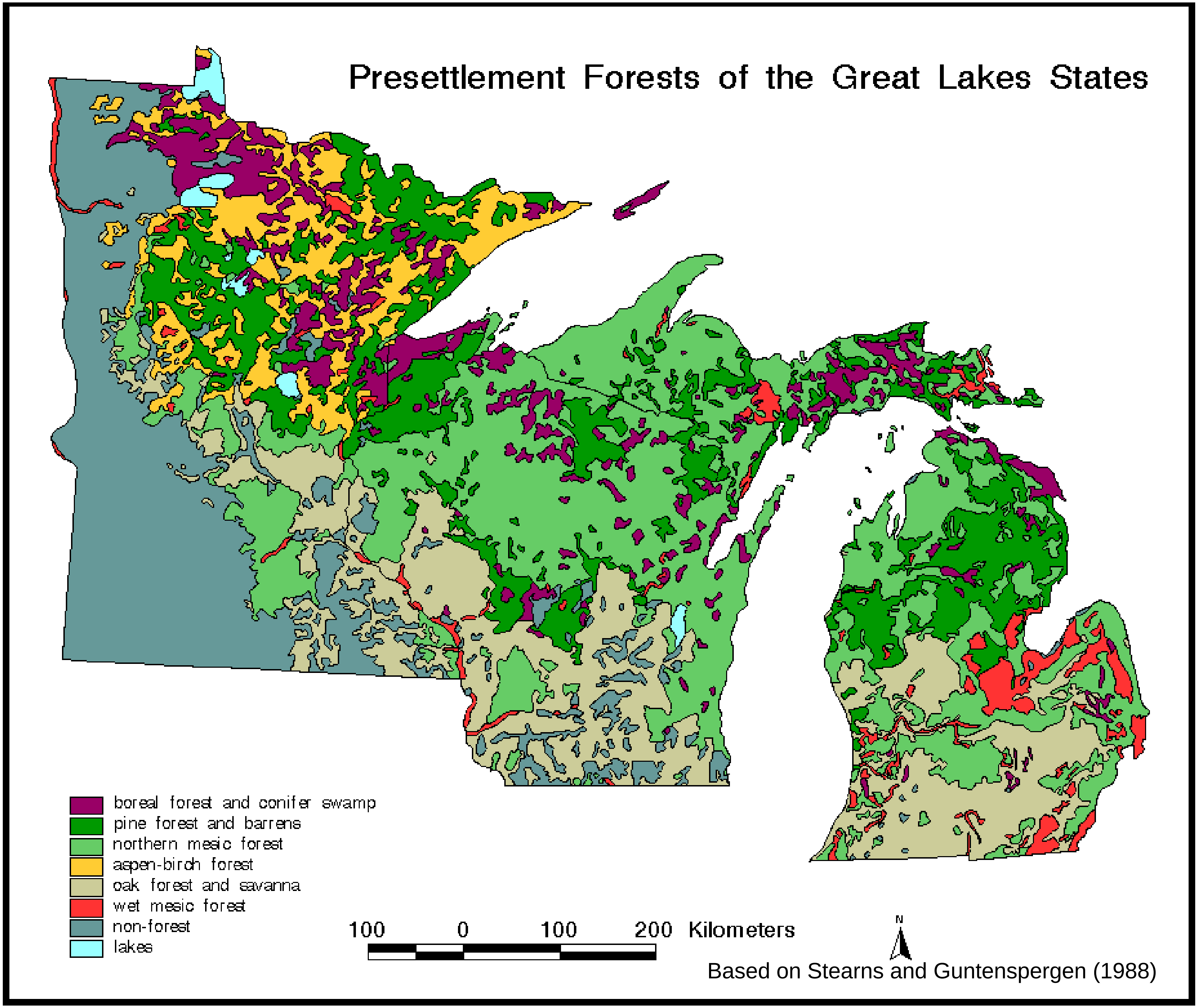
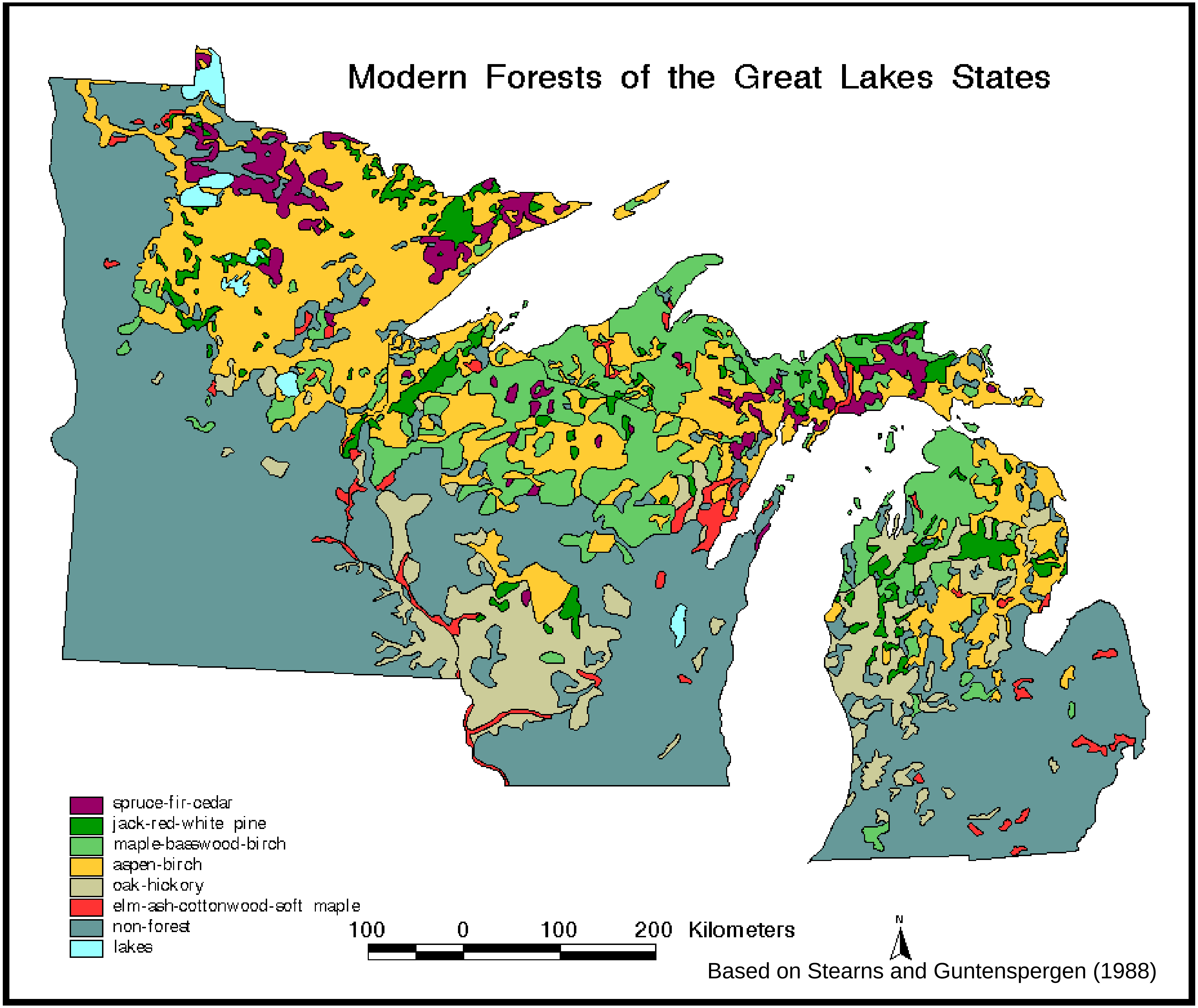

Tamarack Mine


Photo Courtesy Michigan Tech Archives


Joseph Ethier's Camp.
March 6, 1898.


Presettlement Forests of the Great Lakes States
boreal forest and conifer swamp
pine forest and barrens
northern mesic forest
aspen-birch forest
oak forest and savanna
wet mesic forest
non-forest
lakes
100 0 100 200 Kilometers
N
Based on Stearns and Guntenspergen (1988)

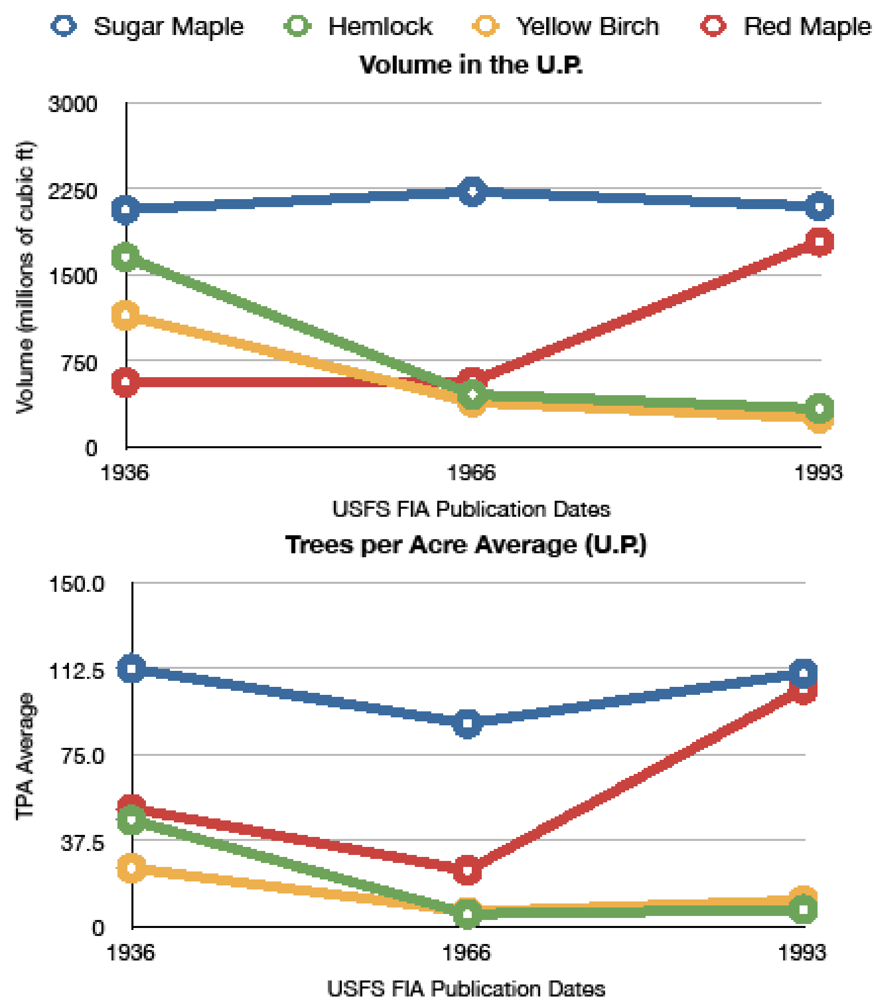


Modern Forests of the Great Lakes States
spruce-fir-cedar
jack-red-white pine
maple-basswood-birch
aspen-birch
oak-hickory
elm-ash-cottonwood-soft maple
non-forest
lakes
100 0 100 200 Kilometers
N
Based on Stearns and Guntenspergen (1988)

Species change over 60 years

Forest Service FIA (Forest Inventory and Analysis) data from the Upper Peninsula of Michigan:

1. Yellow birch and eastern hemlock show marked declines in volume and density prior to 1966, then steady
2. Red maple abundance and volume have increased since 1966
3. Sugar maple abundance and volume remain steady
4. Few but large trees removed
5. SM trend combined with the increase in red maple indicates an overall greater number of smaller trees, with fewer large trees



W. Previant, unpublished data

Historical changes in the forests of the Luce District of the Upper Peninsula of Michigan

Researchers in this study used General Land Office (GLO) survey notes, current land cover from satellite imagery, and Forest Inventory and Analysis (FIA) plots to examine vegetation changes for a portion of the Upper Peninsula.

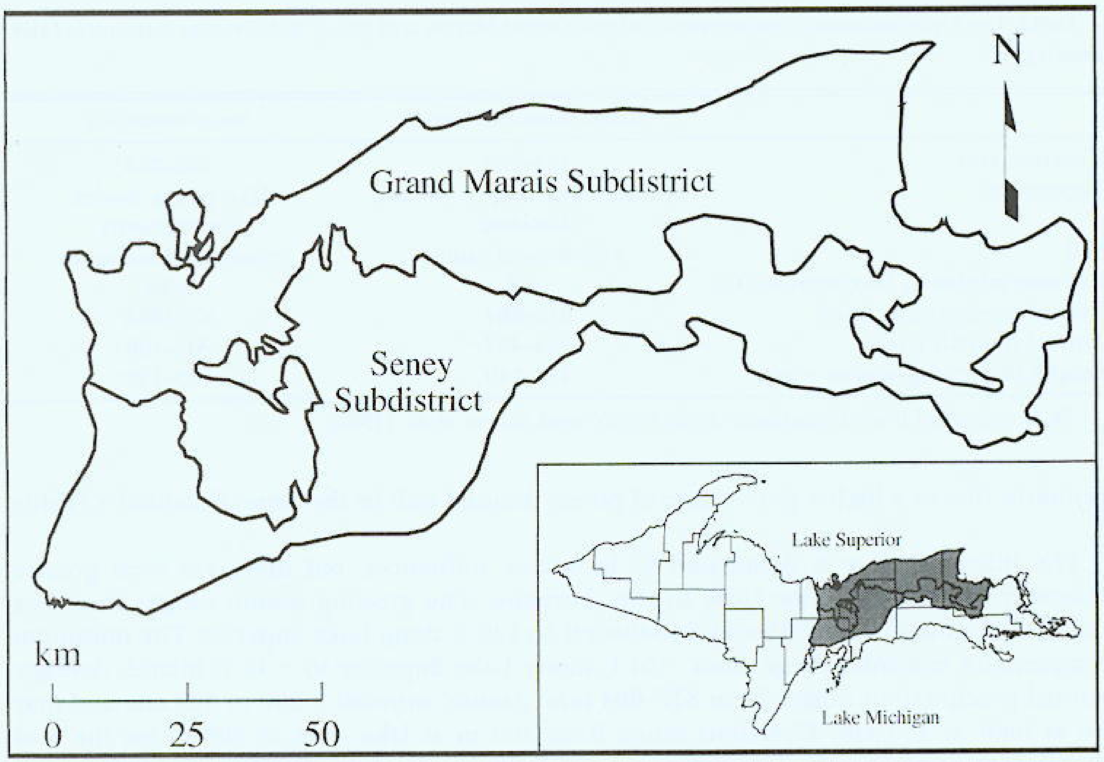
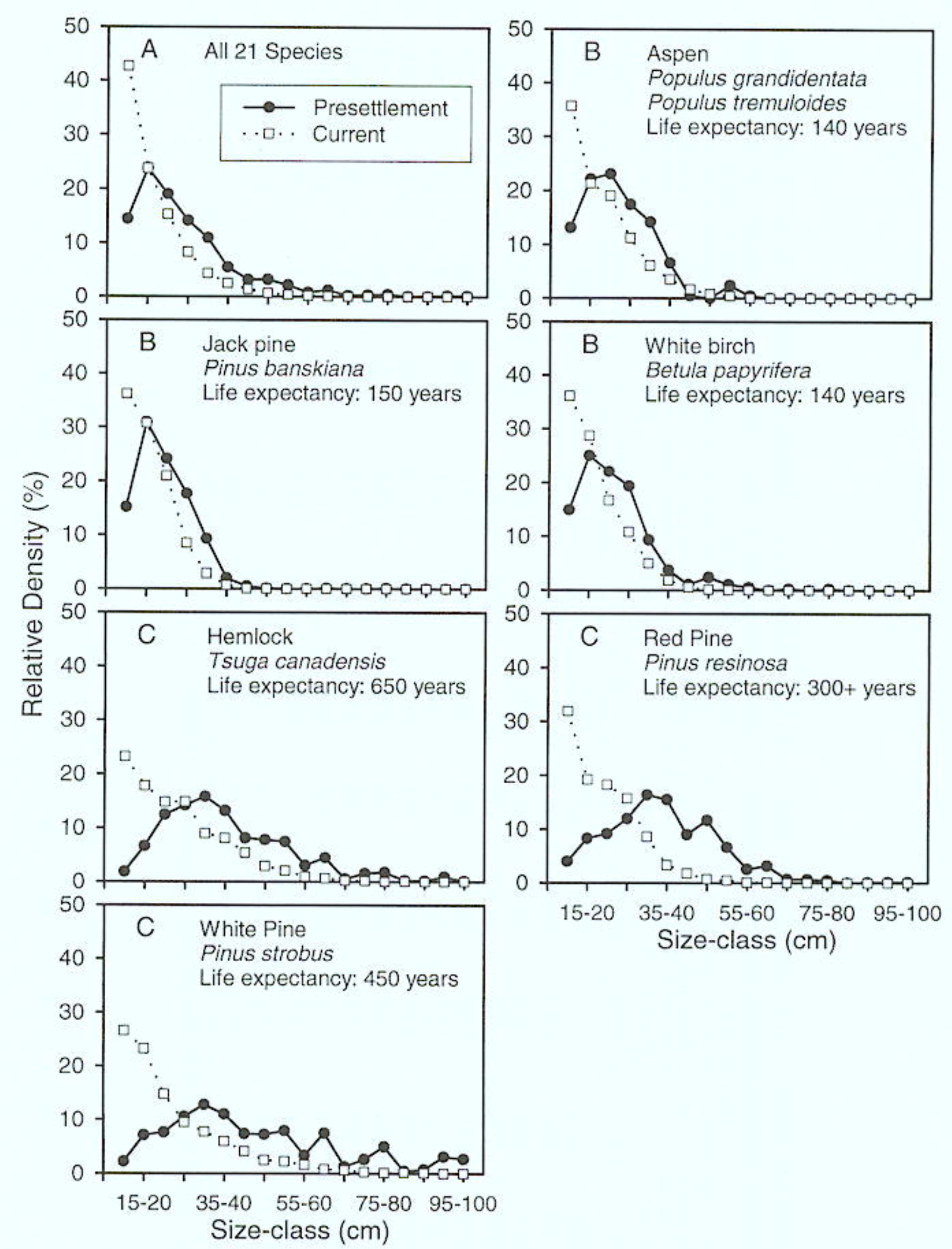


FIG. 1.—The Luce District encompasses approximately 902,000 ha of the Upper Peninsula of Michigan (inset) and has been subdivided into two subdistricts, Grand Marais and Seney, based on differences in climate, physiography and vegetation (Albert *et al.*, 1986)

Zhang et al., 2000



Historical changes in the forests of the Luce District of the Upper Peninsula of Michigan

Tree size-class frequency distributions for trees >20cm in the Luce District of the UP. (A) all 21 species; (B) relatively short-lived species (<200 yrs); (C) relatively long-lived species (>300 yrs).

Short-lived species show similar diameter distributions, while the longer-lived species have fewer trees in the larger diameter classes.

Zhang et al., 2000

Northern hardwoods today

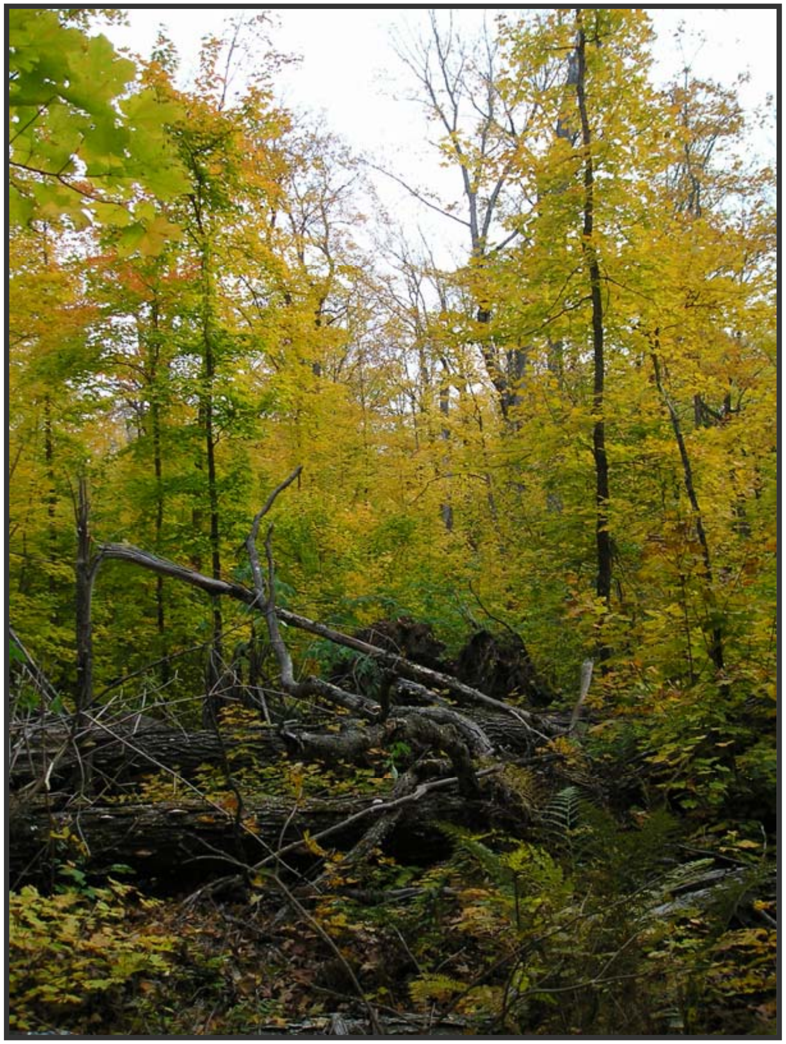
- Dominated by sugar maple

- Other major species include: yellow birch, eastern hemlock, red maple, basswood, and ironwood

Northern hardwoods – disturbance

- Wind is the primary disturbance, which occurs frequently and creates gaps
  - low-intensity disturbances remove <20% of the canopy
  - rotation periods of 50-200 yr
  - large-scale disturbances are infrequent, rotations approach 1000 yr

    (Frelich and Lorimer 1991)



Disturbance

Uneven-aged Management

- Uneven-aged management is typically dominated by single tree and small group selection
- Approximates natural disturbance regimes
- Diameter distributions are commonly used to describe stand structure and can be used as a structural guide for management

Uneven-aged management: Single tree selection

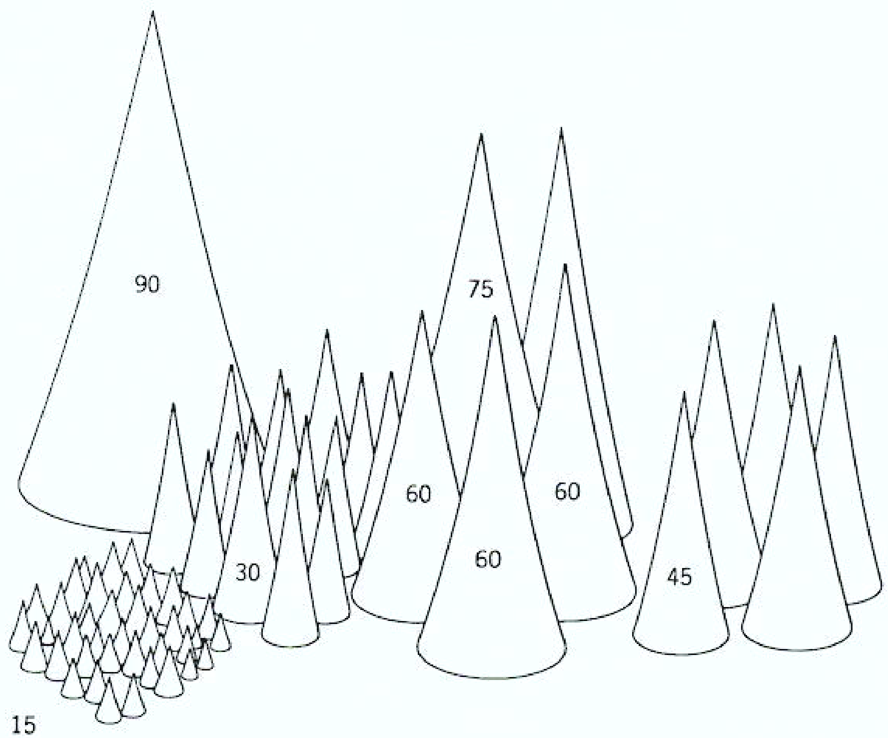
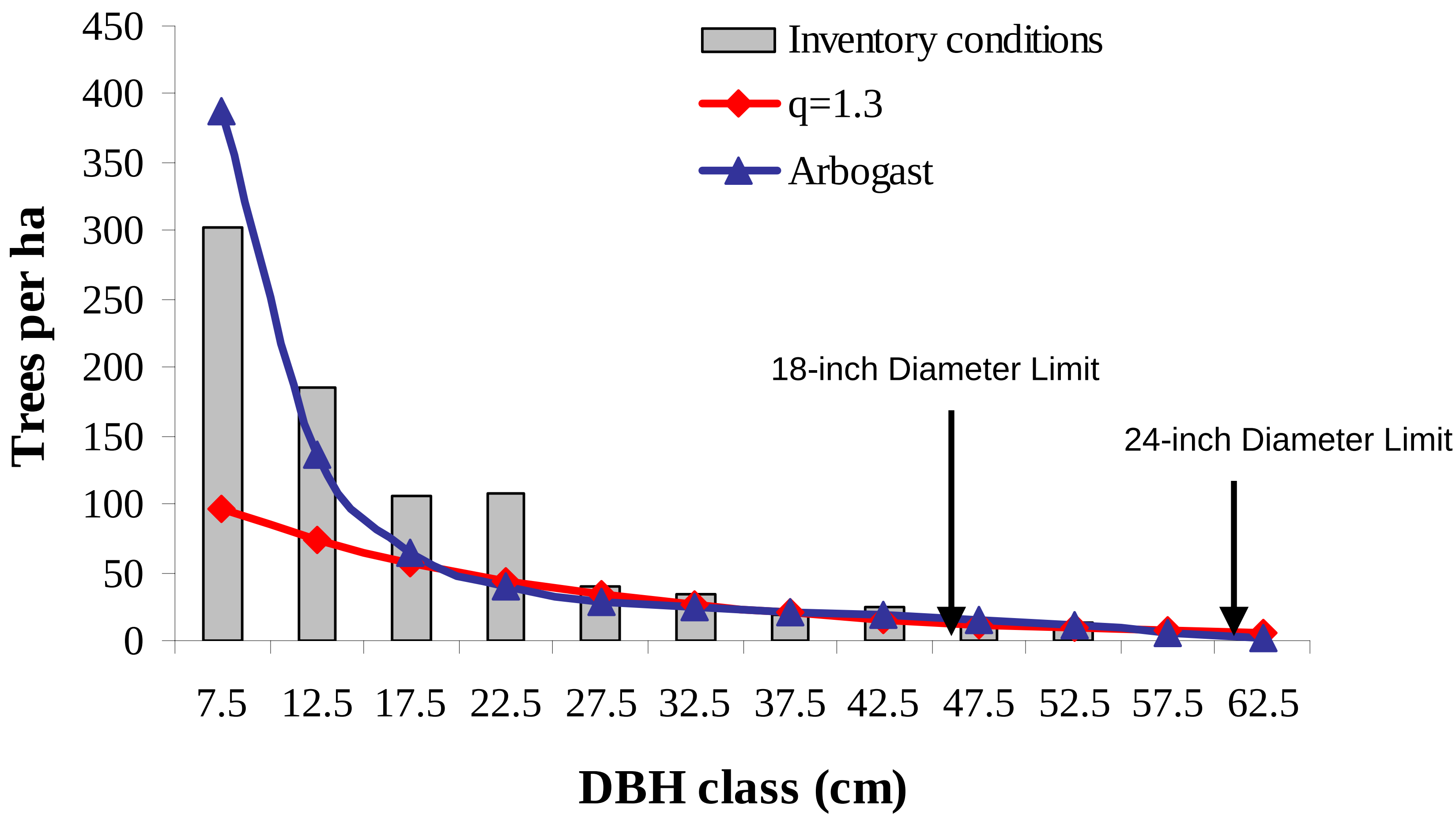


Figure 15.1 Schematic oblique view of a 1/10 hectare segment of a balanced uneven-aged stand being managed by the single-tree selection system on a 90-year rotation with a 15-year cutting cycle. Each tree is represented by a cone extending to the ground; the numbers indicate the ages. Each age group occupies about 1/60 hectare. The 90-year-old tree is now ready to be replaced by numerous seedlings while the numbers of trees in the middle-aged groups are appropriately reduced by thinning.

Smith et al. 1997

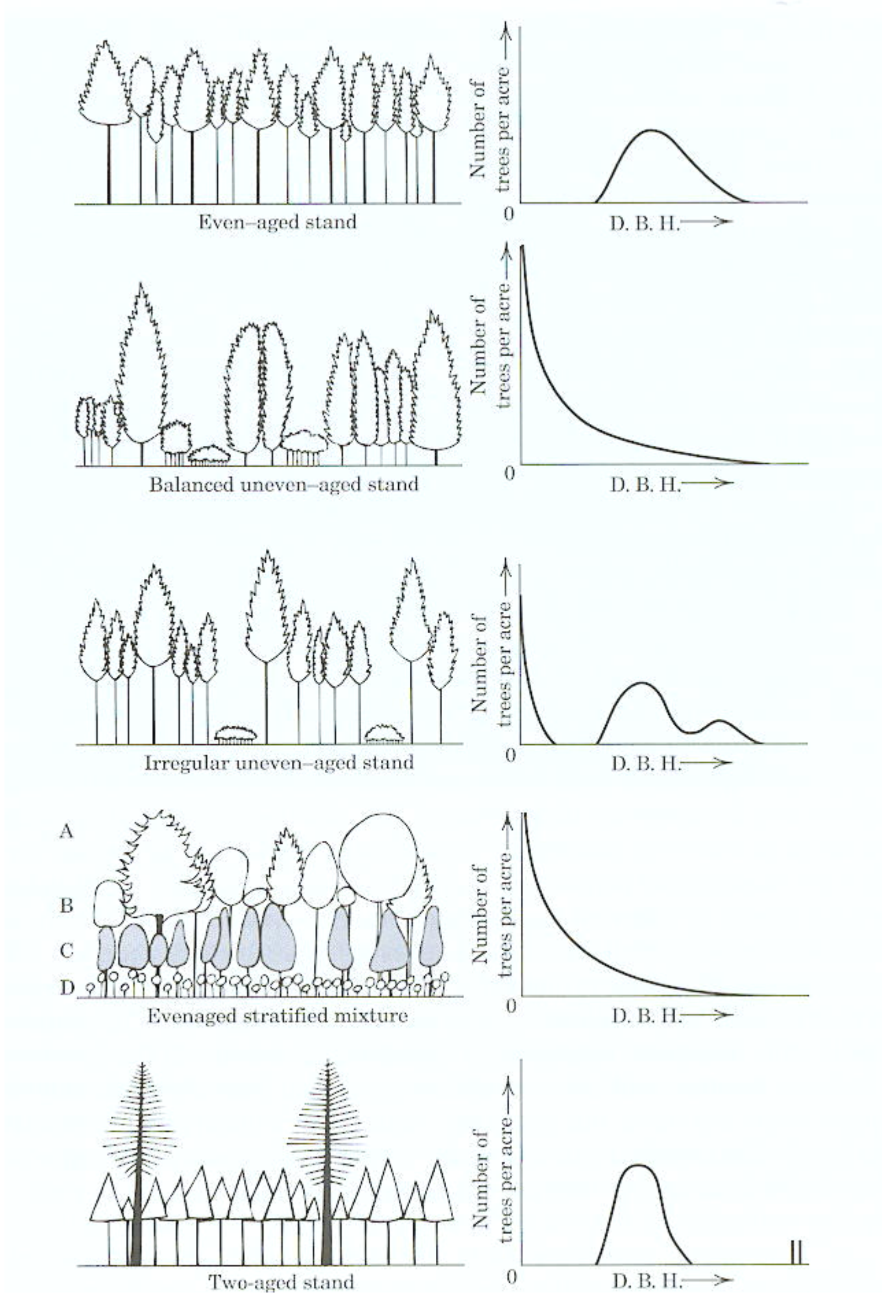
Selection system structural targets



Single Tree Selection Silviculture

- Why so widely used among all classes of landowners for the past 50 years?
  - Dependable, periodic removals
  - Maintains high levels of crown cover
  - Preserves aesthetic values at all times
  - Maintains populations of late successional species
  - A reasonably faithful imitation of natural canopy gap dynamics in quiescent decades

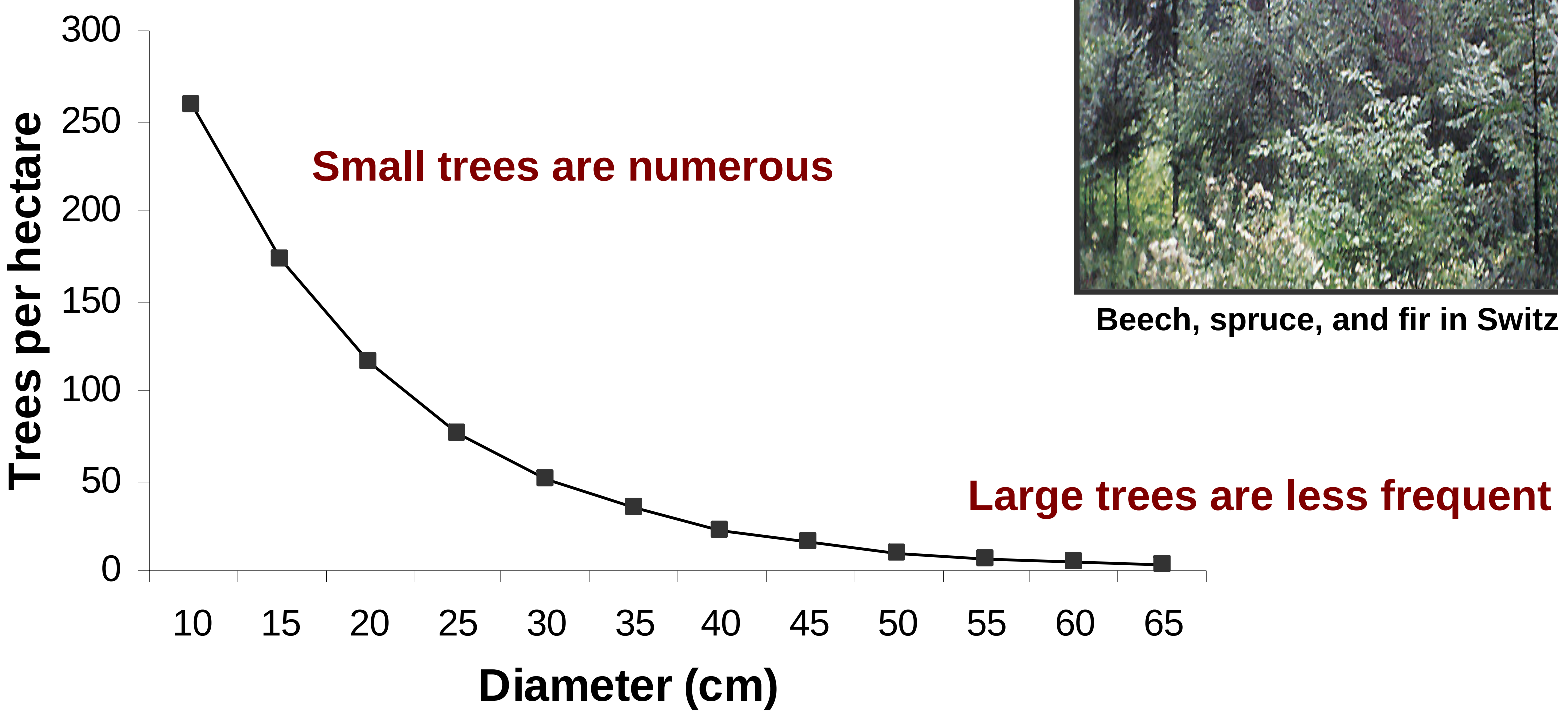
Crow et al. 2002, Hanson and Lorimer 2007



Smith et al. 1997

Diameter Distributions

- F. de Liocourt (1898) first described the reverse-J shape in managed uneven-aged fir forests in France



Beech, spruce, and fir in Switzerland

Structure, Growth, and Drain in Balanced Uneven-Aged Forests[1]

H. Arthur Meyer
Professor of forestry, The Pennsylvania State College, State College.

A BALANCED UNEVEN-AGED FOREST is one in which the current growth can be removed annually or periodically while maintaining at the same time the structure and initial volume of the forest. It is, or may be considered, a forest with a normal growing stock, capable of producing a sustained yield. In a balanced virgin forest, the current growth is offset by current mortality, and the existing balance between growth and mortality makes it possible for such a forest to perpetuate itself indefinitely. From experimental investigations on balanced managed and certain undisturbed virgin forests, considerable knowledge has been gained concerning the diameter distribution in these forests. Experimental work has shown that the diameter distribution is of the inversed J-shaped form, which when plotted on semi-logarithmic paper yields a straight line (*2, 3, 5*). Actual examples of balanced diameter distributions are shown in Figure 1.

Balanced forests with a rather well defined diameter distribution are encountered not only in well managed forests and in virgin forests, but in any large forest area which contains a reasonable amount of pole timber and light and heavy saw timber, such as is the case with the forests of an entire county or state. In all the examples shown in Figure 1, a curve of the exponential type fits the actual data

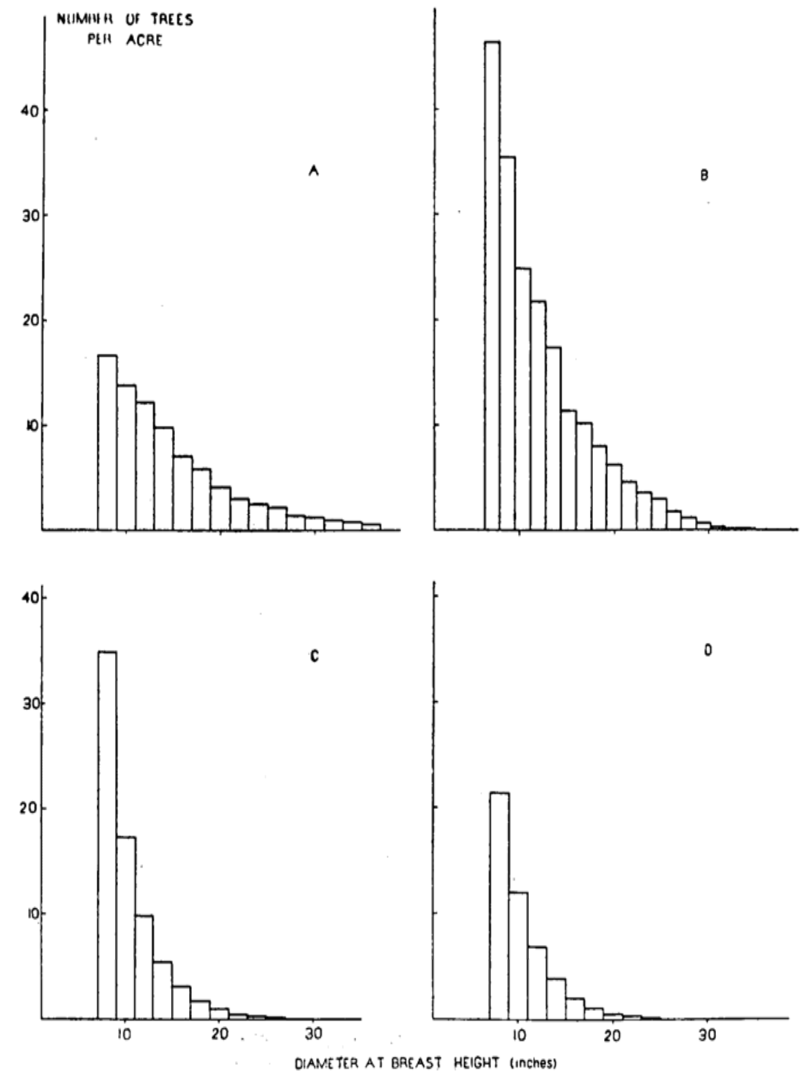
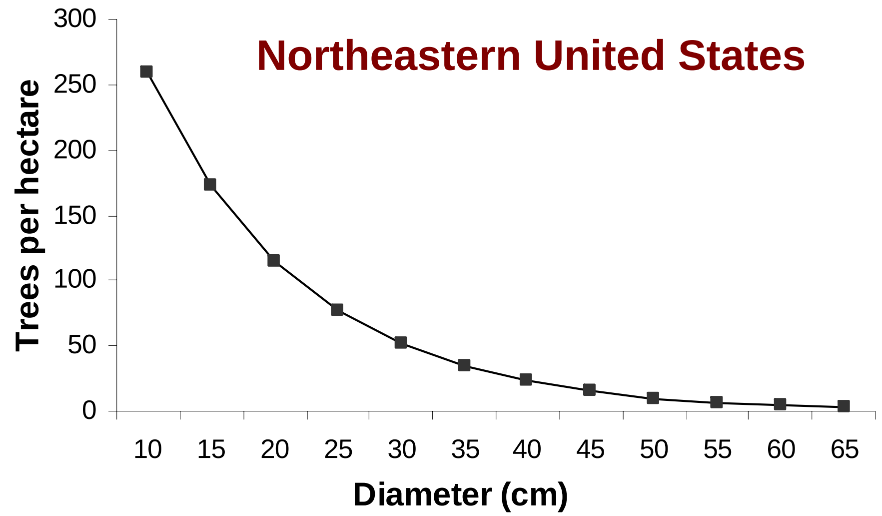
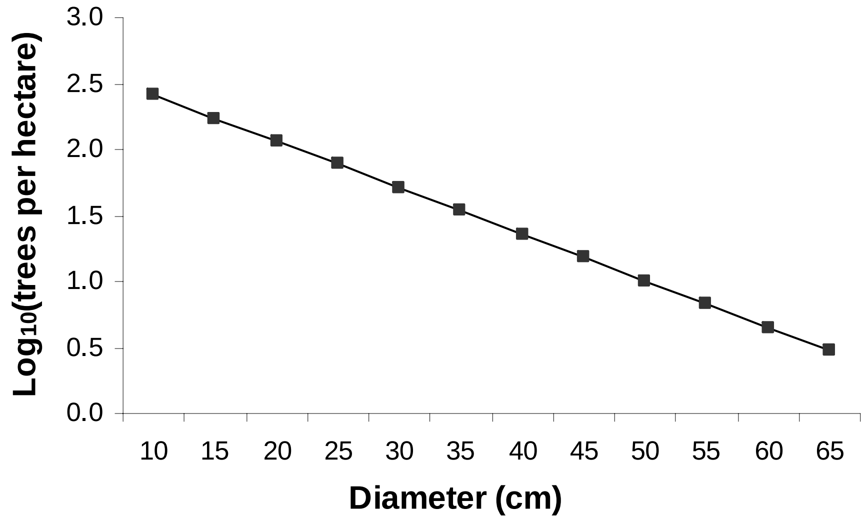


FIG. 1.—Balanced diameter distributions: *A.* Virgin beech-birch-maple-hemlock forest in northern Pennsylvania; *B.* Selection forest, Switzerland; *C.* New Hampshire timber survey data; *D.* timber survey of softwood type, Scott County, Miss.

Diameter Distributions

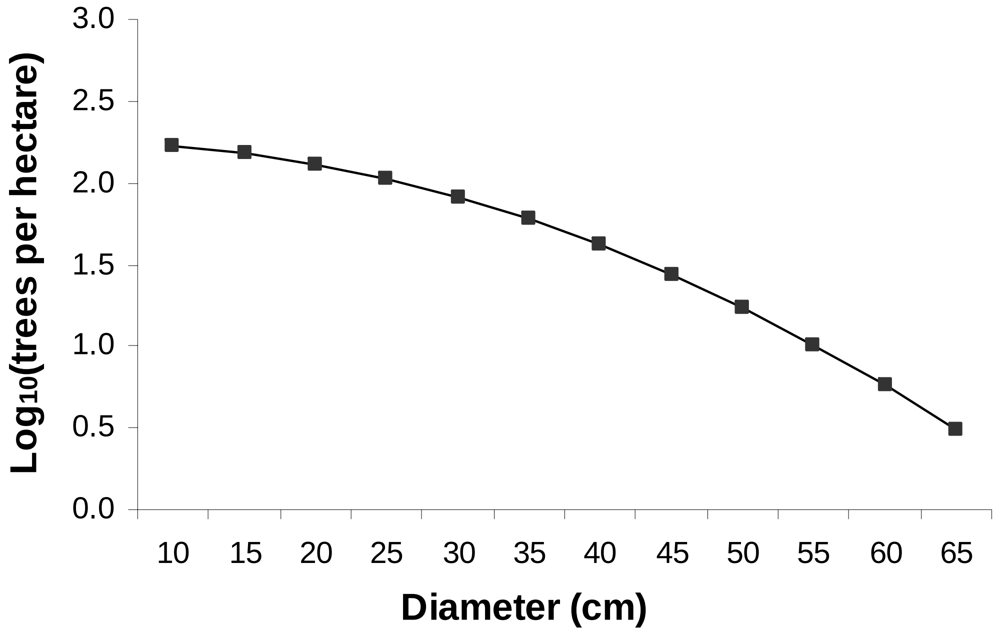
- Meyer (1952) determined that plotting "virgin" distributions on semi-logarithmic axes created a straight line
- Referred to as the "negative exponential" shape
- Believed shape occurred in all large forested areas
- The "balanced" stands were assumed to be capable of yielding a constant volume while maintaining the structure
- Meyer (1952) also developed the *q*-ratio which describes the slope of the line
- Higher *q*-ratios reflect larger decreases in tree density





Diameter Distributions

- Other distribution shapes have been observed
  - Increasing-*q* (Leak 1964)



Diameter Distributions

- Other distribution shapes have been observed
  - Rotated sigmoid (Schmelz & Lindsay 1965, Goff and West 1975)

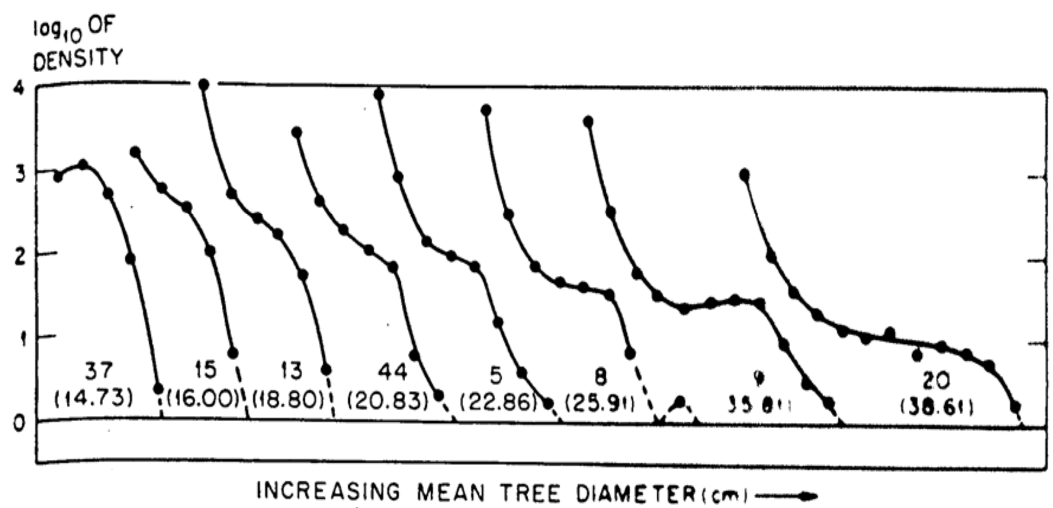
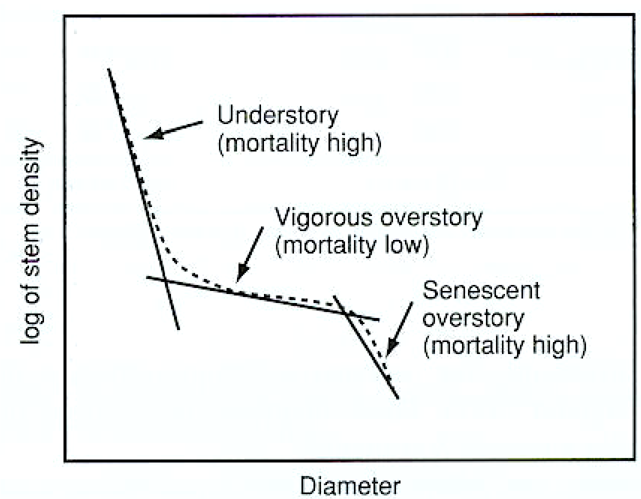


FIGURE 2. *Stand structural series formed by typical upland stands from young post-disturbance hardwood (left) to old-growth hemlock-hardwood (right). Stand numbers are followed parenthetically by stand mean diameter [trees 4.0 inches (10.2 cm) and over]. Stands are arranged in order of increasing mean diameter.*



Goff and West 1975

Diameter Distributions

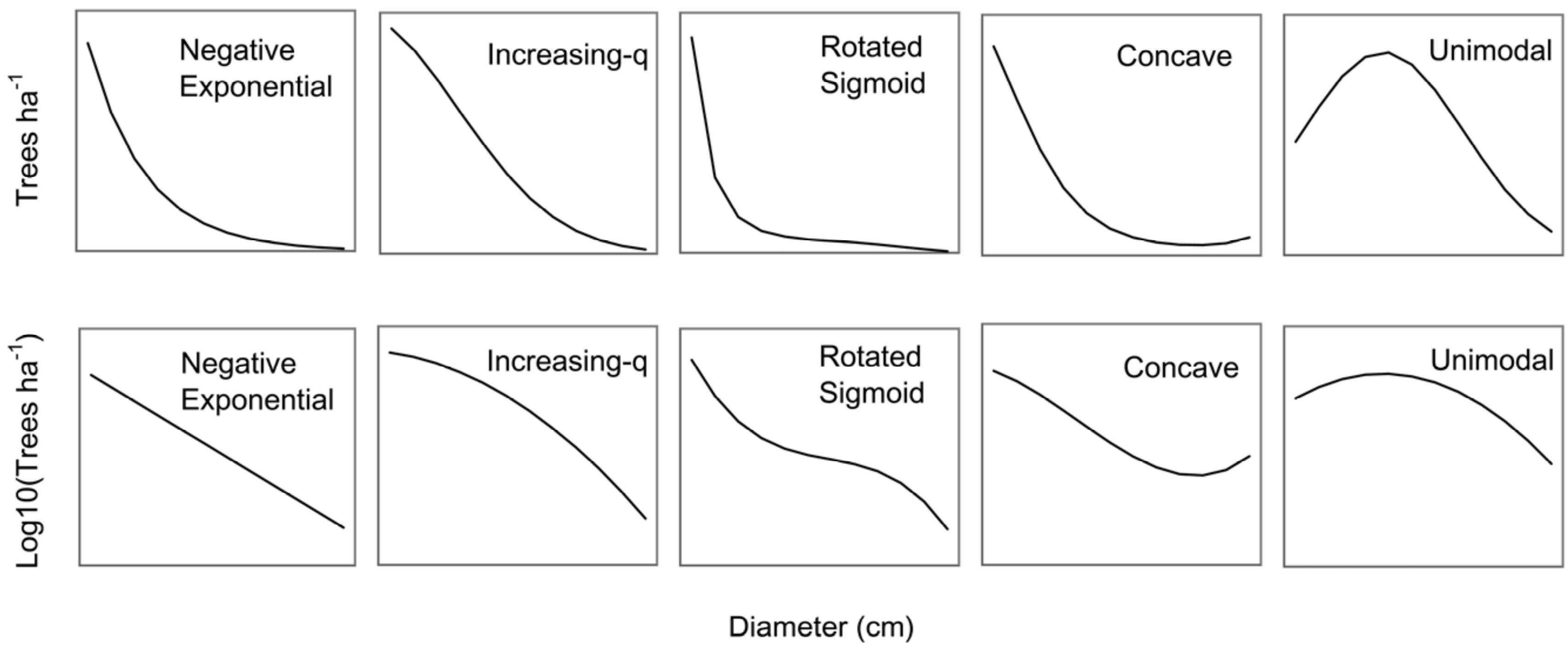
- There is no consensus in the literature regarding what distribution shapes are most common
  - Unmanaged Stands
    - Rotated sigmoid (Schmeltz & Lindsay 1965, Goff & West 1975, Goodburn & Lorimer 1999)
    - Negative exponential (Meyer 1952, Leak 1996, Crow et al. 2002)
  - Managed Stands
    - Negative exponential (Leak & Filip 1977, Leak 1996, Goodburn & Lorimer 1999, Crow et al. 2002, Schwartz et al. 2005)
    - Rotated sigmoid (Goodburn & Lorimer 1999, Leak 1996, Schwartz et al. 2005)
    - Increasing-*q* (Leak 1996, Schwartz et al. 2005)

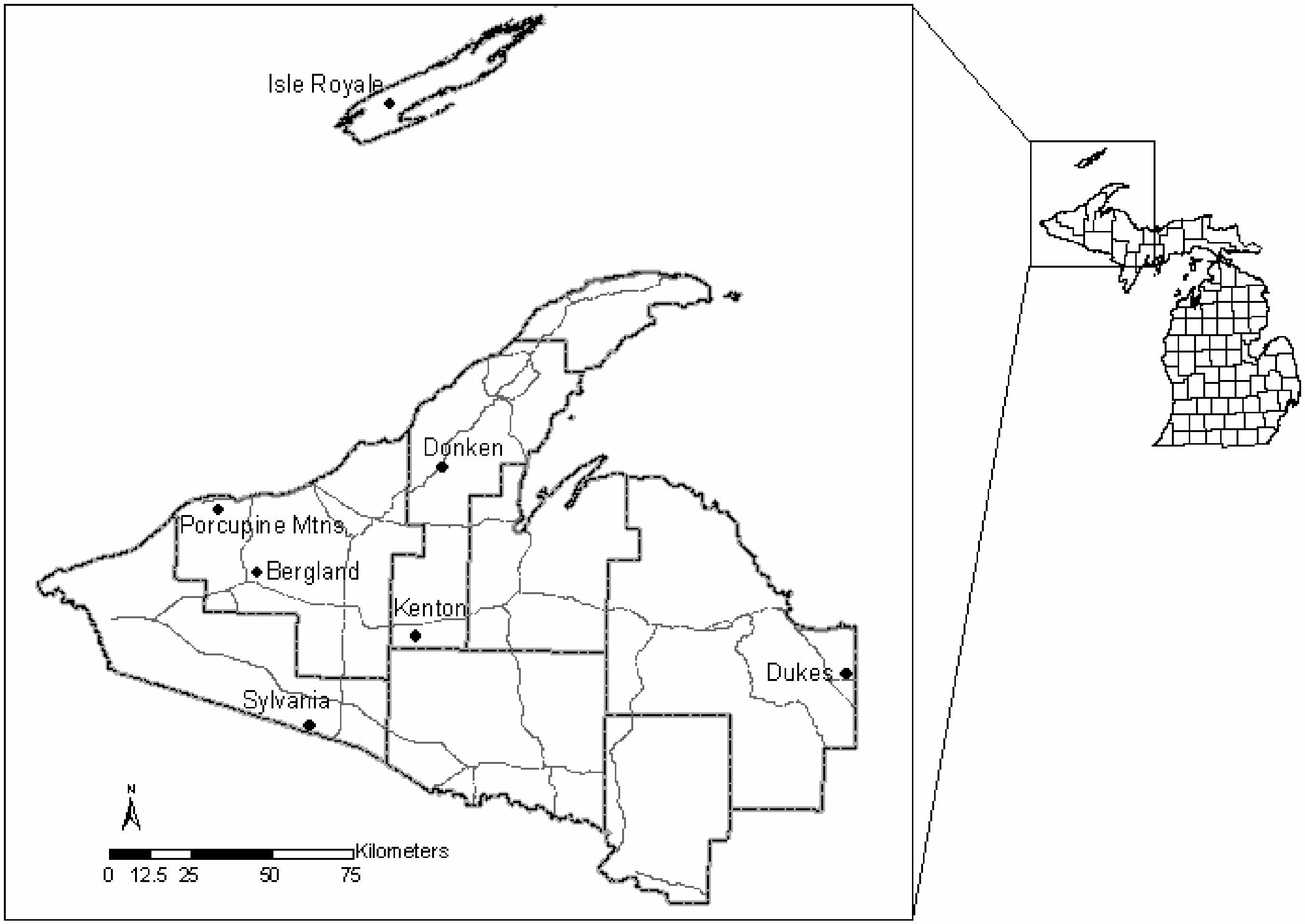
Diameter Distributions

- Spatial scale
  - Forests, landscapes
    - Negative exponential (de Liocourt 1898, Meyer 1952)
    - Small-scale irregularities and even-aged structures averaged over large areas
- Some of the early work regarding diameter distributions in North America was conducted in uneven-aged northern hardwoods of the Lake States (Eyre and Zillgitt 1953, Arbogast 1957)

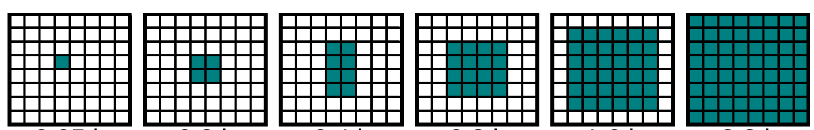
What structures exist across the landscape?

- Five diameter distribution shapes observed in the UP



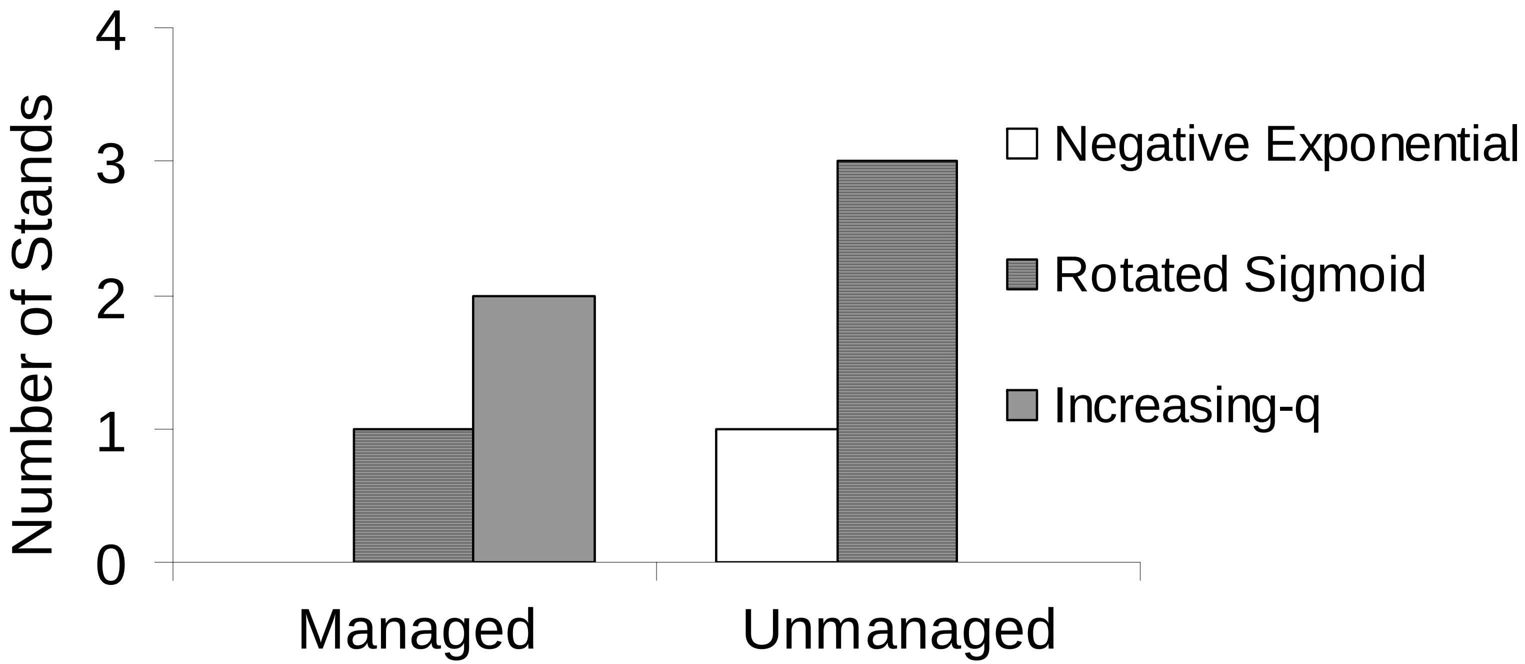


Systematic sampling



Janowiak, M.K., L.M. Nagel and C.R. Webster. Spatial scale and stand structure in northern hardwood forests: implications for quantifying diameter distributions. *In review, Forest Science.*

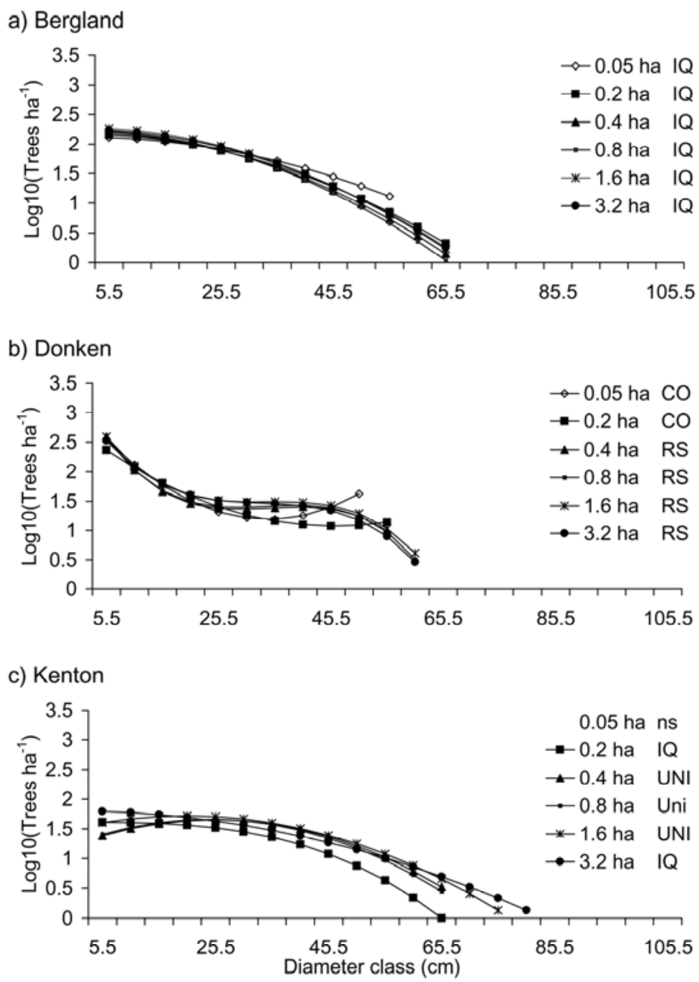
Diameter Distributions

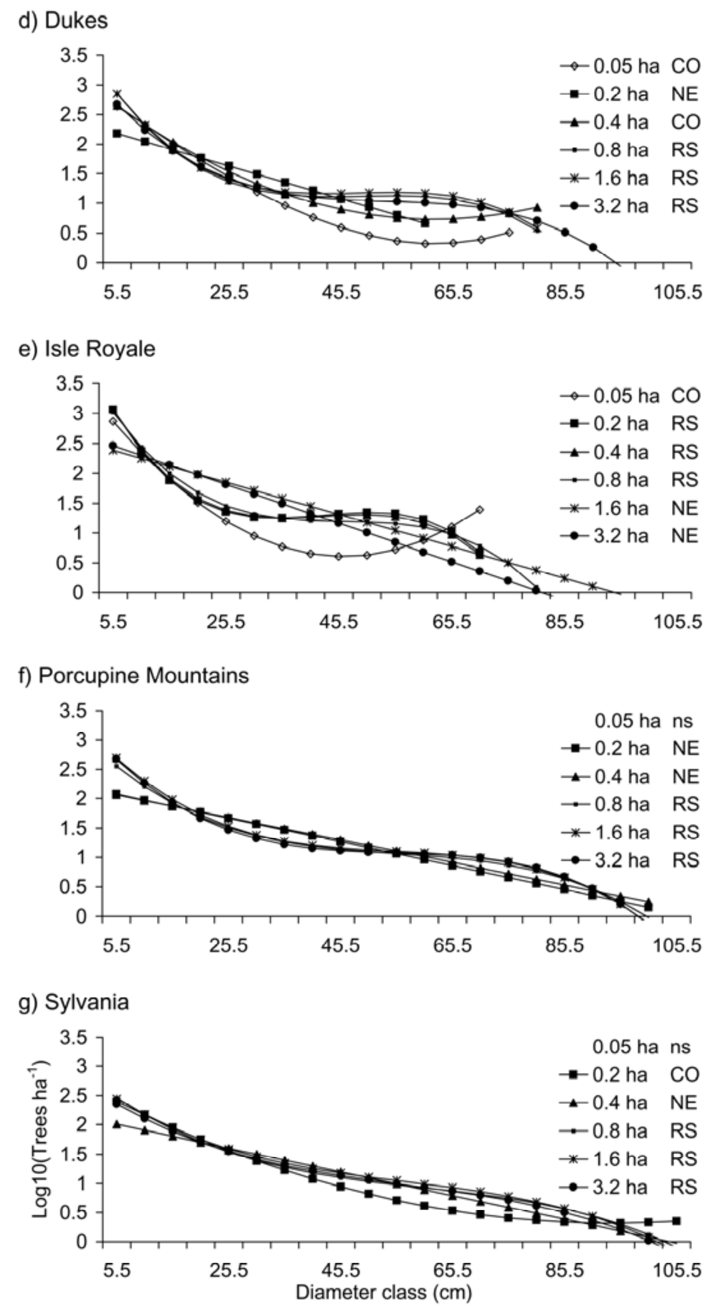


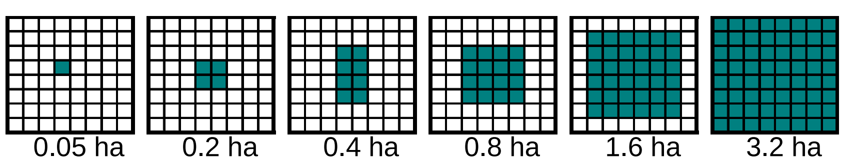
Janowiak et al. *In review*

Managed

Unmanaged

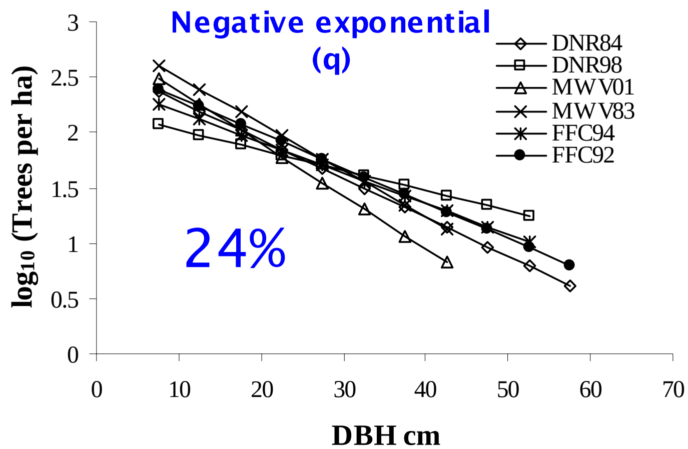


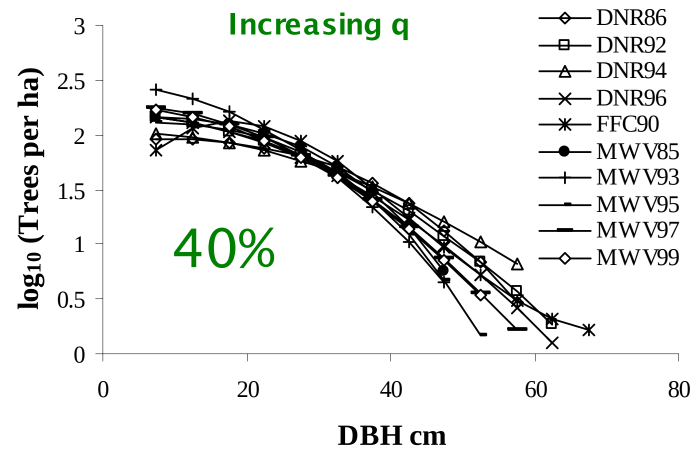




Janowiak et al. *In review*

Diameter Distributions



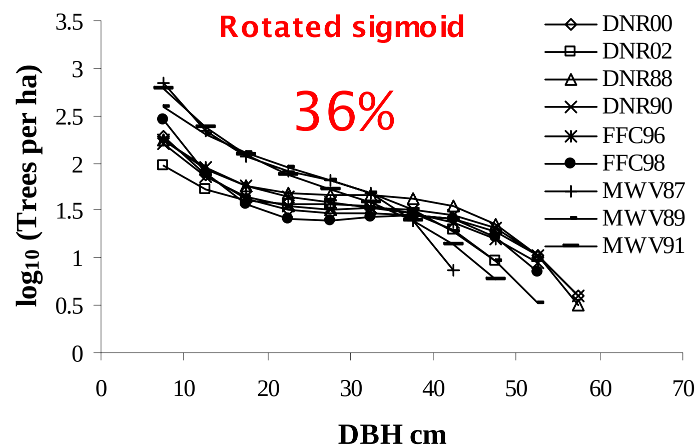


Three ownerships:

Michigan DNR

Ford Forestry Center

MeadWestvaco (Plum Creek)



Schwartz, J.W., L.M. Nagel and C.W. Webster. 2005. Effects of uneven-aged management on diameter distribution and species composition of northern hardwoods in Upper Michigan. *For. Ecol. Manage.* 211:356–370.

Diameter Distributions

	1961	2004
Unmanaged		
Stand 1 (n = 3)	NE	IQ
Stand 2 (n = 3)	NE	IQ
Stand 3 (n = 2)	IQ	NE
Managed		
Stand 1 (n = 5)	NE	IQ
Stand 2 (n = 8)	RS	IQ
Stand 3 (n = 9)	RS	IQ
Stand 4 (n = 5)	NE	NE
Stand 5 (n = 10)	IQ	IQ

Note: n is the number of plots within each stand.

Neuendorff, J.K., L.M. Nagel, C.R. Webster and M.K. Janowiak. 2007. Stand structure and composition in a northern hardwood forest after 40 years of single-tree selection. *North. J. Appl. For.* 24(3):197-202.

Species Composition

Mean (± 1 SE) relative abundance and importance (Importance Value = [Relative Basal Area + Relative Density‡]/2) of common overstory species

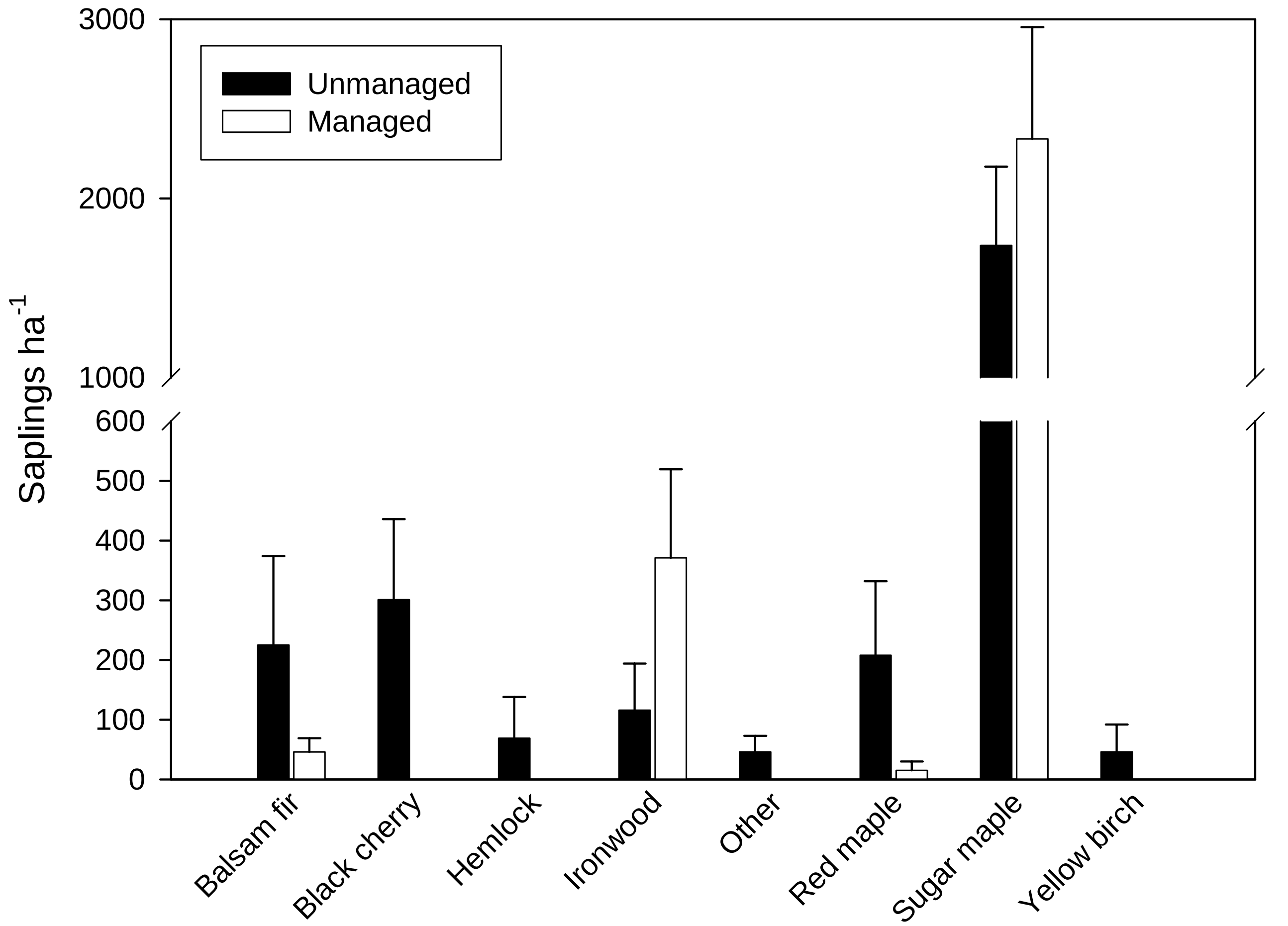
	Unmanaged		Managed		
	1961	2003/04	1961	2003/04	P-value*
Eastern Hemlock					
Relative BA	8.5 ± 8.5	11.6 ± 11.2	17.0 ± 9.5	15.6 ± 9.1	0.070
Relative Density	8.6 ± 8.6	8.6 ± 8.0	16.6 ± 8.9	11.0 ± 6.7	0.071
Importance Value	8.5 ± 8.5	10.1 ± 9.6	16.8 ± 9.2	13.3 ± 1.4	0.065
Sugar Maple					
Relative BA	70.1 ± 18.4	64.9 ± 21.8	55.8 ± 12.4	64.8 ± 12.8	0.104
Relative Density	64.4 ± 21.2	62.0 ± 21.7	57.6 ±12.7	68.2 ±11.3	0.011
Importance Value	67.2 ± 19.8	63.4 ± 21.7	56.7 ± 12.4	66.5 ± 12.0	0.031
Yellow Birch					
Relative BA	15.0 ± 7.8	14.8 ± 7.5	18.2 ± 5.1	9.7 ± 2.6	0.093
Relative Density	11.3 ± 6.8	11.5 ± 7.1	14.2 ± 2.9	8.5 ± 2.6	0.039
Importance Value	13.2 ± 7.3	13.2 ± 7.2	16.2 ± 3.9	9.1 ± 2.6	0.062

‡ Trees ha^{-1} of a given species expressed as a percentage of the total number of trees ha^{-1}

* Based on a paired t-test comparing differences between time periods for the 5 managed stands

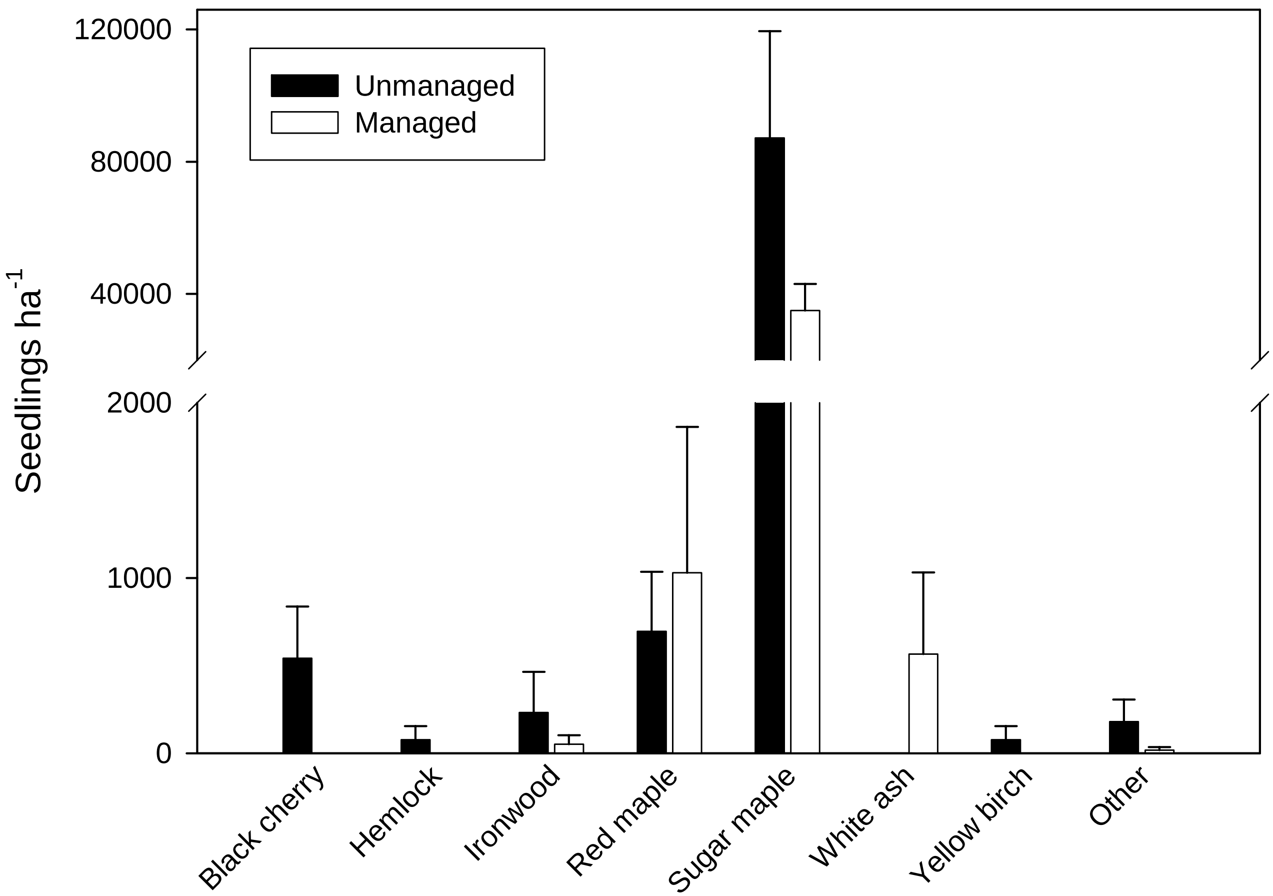
Neuendorff et al. 2007

Species Composition



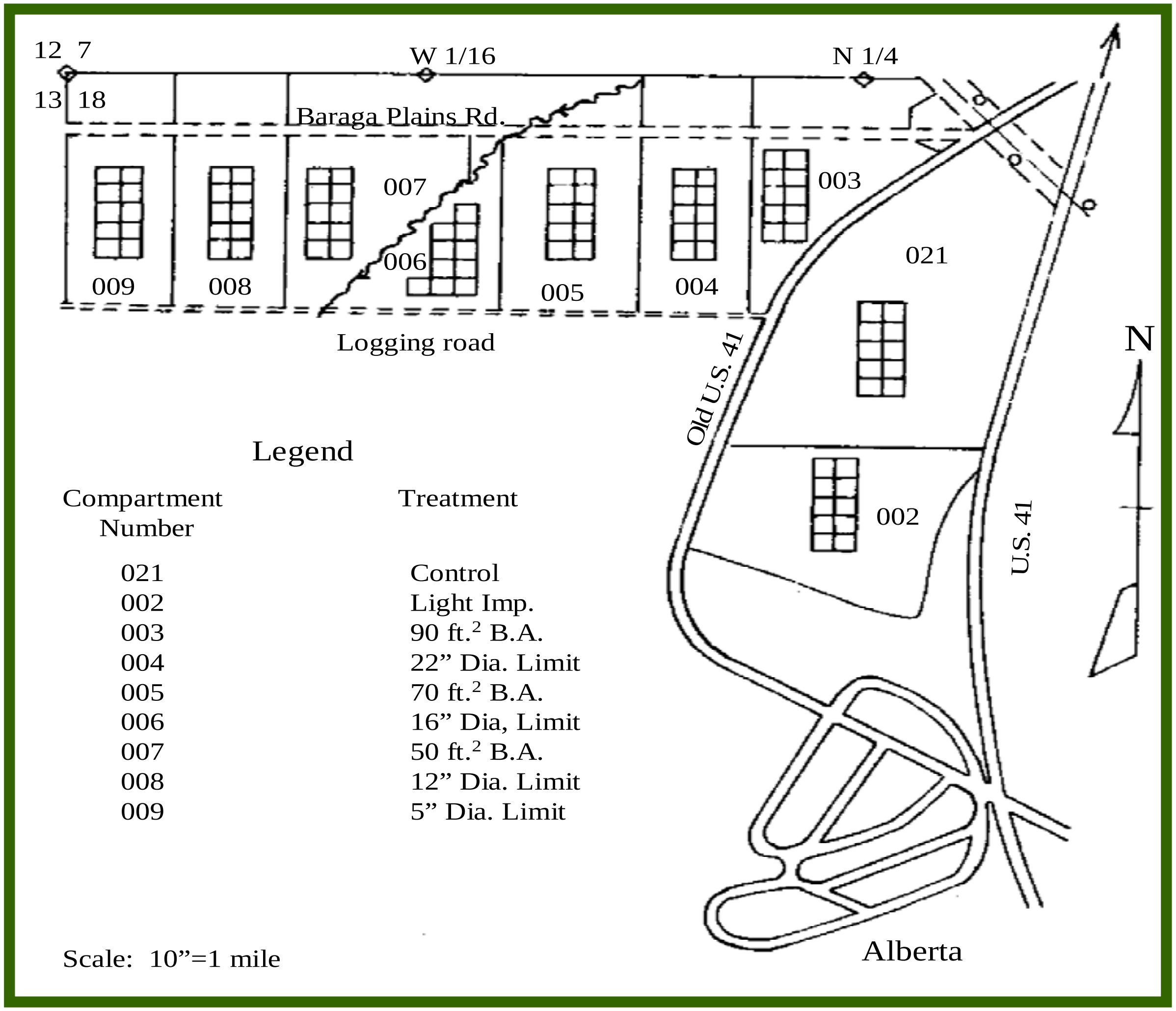
Neuendorff et al. 2007

Species Composition



Neuendorff et al. 2007

Ford Forestry Center Cutting Trial



<u>Single Tree Selection</u>

Residual BA = 90, 70, 50 ft^2/ac

q-factor ~ 1.3

Max Diameter = 20-22in

Ford Forestry Center
Cutting Trial

Ford Forestry Center Cutting Trial

Ford Forestry Center Cutting Trial

Residual volume over the 42-year period

	Board Foot Volume per acre[c]							
	1956[a]		1957[b]		1998[a]		1998[b]	
Treatment	**Gross**	**Net**	**Gross**	**Net**	**Gross**	**Net**	**Gross**	**Net**
Light Imp.	9950	7396	9815	7331	8754	8162	6969	6485
22 inch	7162	5227	6057	4464	9827	8677	8107	7134
16 inch	7574	6165	4954	4087	5828	5464	2946	2708
12 inch	8739	7718	1859	1785	1866	1768	1866	1768
5 inch	6491	5089	0	0	1408	1372	0	0
90 ft.^{2}	10779	7457	8899	6078	10988	9805	7933	7049
70 ft.^{2}	8623	6921	6923	5846	8963	8504	5850	5522
50 ft.^{2}	4863	4182	3793	3320	6158	5928	3590	3445
Control	10487	6985	10487	6985	13941	11816	13941	11816

[a]Prior to harvest

[b]After harvest

[c]International 1/4 inch rule

Ford Forestry Center Cutting Trial

Total net scaled board foot volume by treatment and year of harvest[a]

	Year of Harvest						
Treatment	**1957**	**1968**	**1978**	**1980***	**1988**	**1998****	**Total**
LI	65	551	1910	0	1926	1562	6014
22"	682	275	0	543	0	1441	2941
16"	2048	1292	2020	360	2543	2784	11047
12"	5913	0	0	930	3966	0	10809
5"	5039	0	0	0	0	1060	6099
90 sq.ft.	1339	293	930	610	0	3038	6210
70 sq.ft.	1020	1142	330	515	838	2639	6484
50 sq.ft.	862	916	1125	693	1059	3059	7714
Total Harvested	16968	4469	6315	3651	10332	15583	57318

[a]Board foot volumes using International 1/4 inch rule

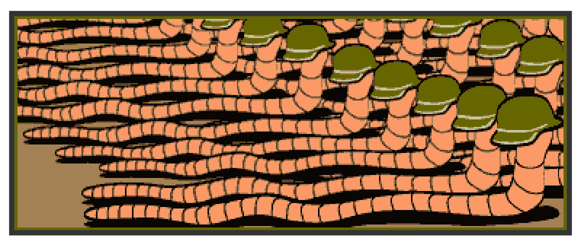
[b]In 1980 a salvage harvest was implemented to remove much of the dead and dying American Elm.

[c]Individual tree selections (90, 70, and 50 sq. ft. residual basal area) have been altered slightly from the original prescription. The previous harvests thinned the stand to the prescribed residual level in all trees 10" dbh and larger. Now, all trees 5" dbh and larger are figured in the thinning.



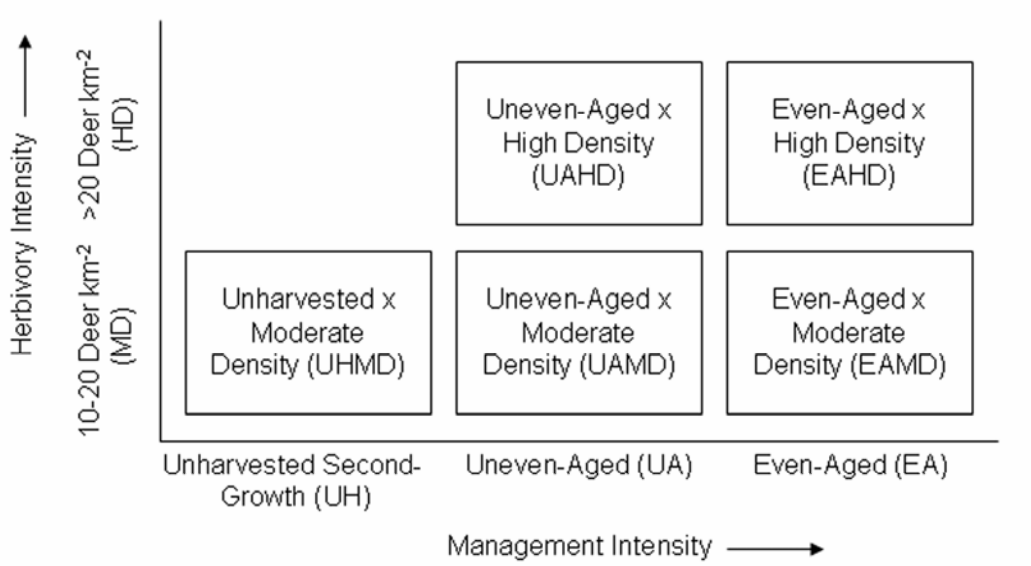
UGA0002039





Sugar maple regeneration dynamics in northern Wisconsin

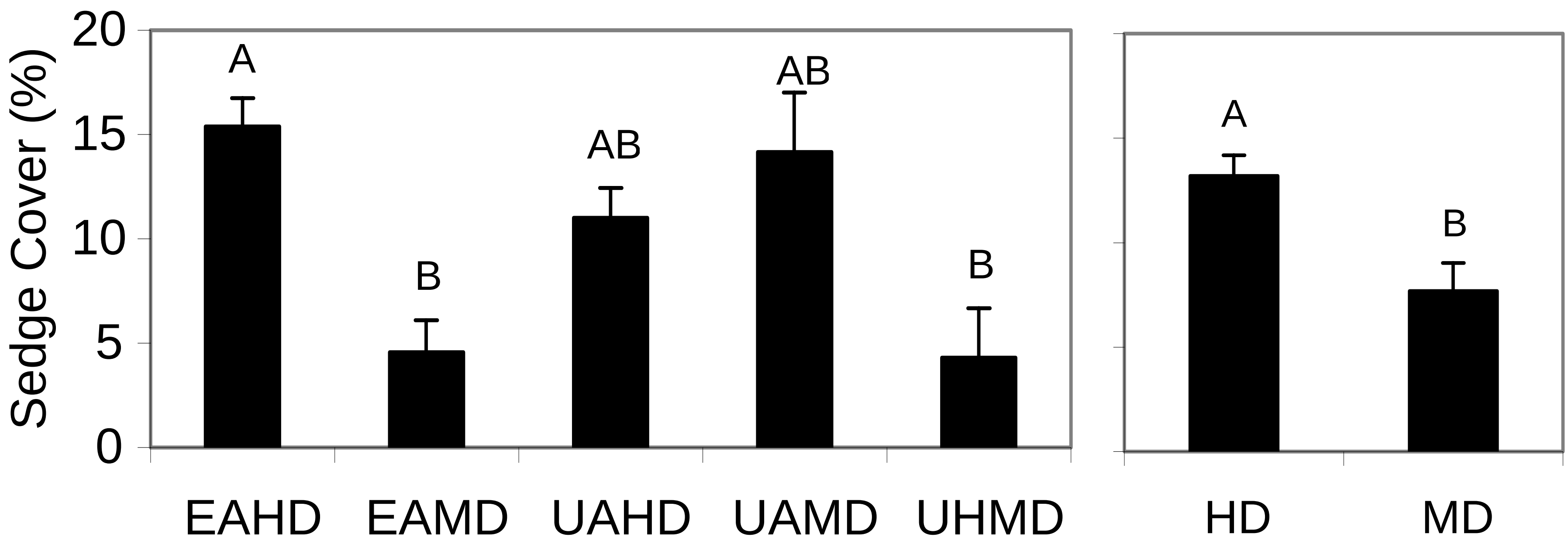
- Recruitment failures associated with Pennsylvania sedge mats
- Transition of northern hardwood stands into sedge savannas



Powers, M.D. and L.M. Nagel. *In press*. Disturbance dynamics influence Pennsylvania sedge abundance in a northern hardwood forest. *Journal of the Torrey Botanical Society.*

Sugar maple regeneration dynamics in northern Wisconsin

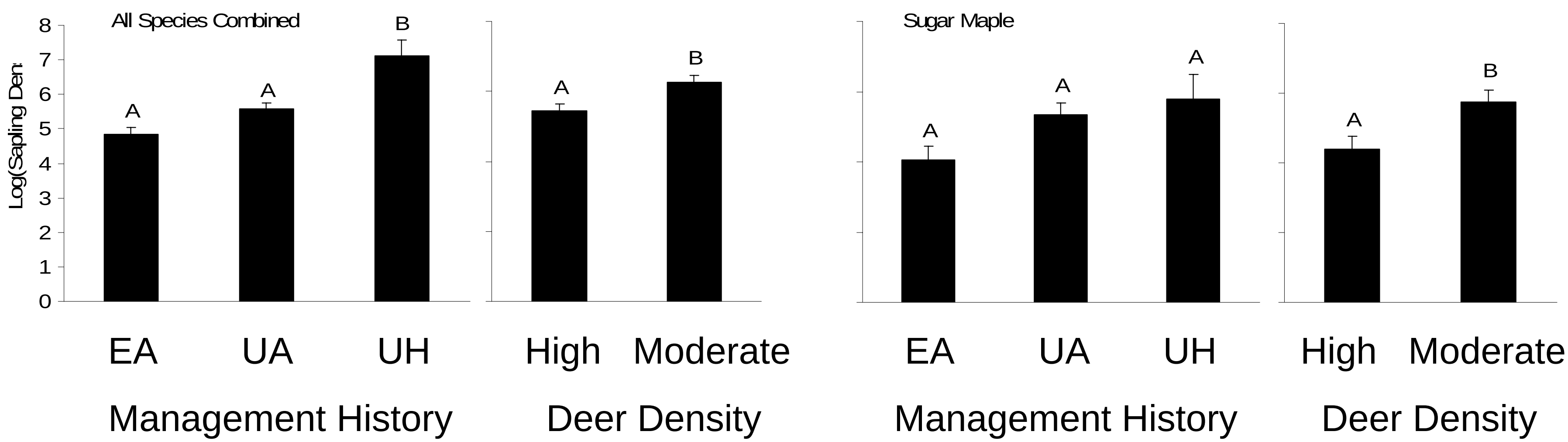
Sedge cover (%) under different management histories and deer densities. EA = even-aged, UA = uneven-aged, UH = unharvested second-growth, high = >20 deer/km^2, and moderate = 10-20 deer/km^2.



Powers and Nagel *In press*

Sugar maple regeneration dynamics in northern Wisconsin

Sapling densities under different management histories and deer densities. EA = even-aged, UA = uneven-aged, UH = unharvested second-growth, high = >20 deer/km^2, and moderate = 10-20 deer/km^2.



Powers and Nagel *In prep*

Sugar maple regeneration dynamics in northern Wisconsin

- Potential mechanisms
  - Interactions between intensive forest management and high deer density
  - Possible interaction with exotic earthworm activity
- Consequences
  - Low diversity of tree regeneration
  - Low density of tree regeneration when combined with intensive management

What have we learned?

- Long-term single tree selection silviculture in northern hardwoods of the Great Lakes states alters species diversity
- Managed and unmanaged stands exhibit clear differences in stand structure as described by diameter distributions
- Idealized structures (*reverse-J*) aren't as common across the landscape as we might think
- Many factors play a role in regeneration failure
- Gap dynamics with single tree selection differ from natural canopy gaps

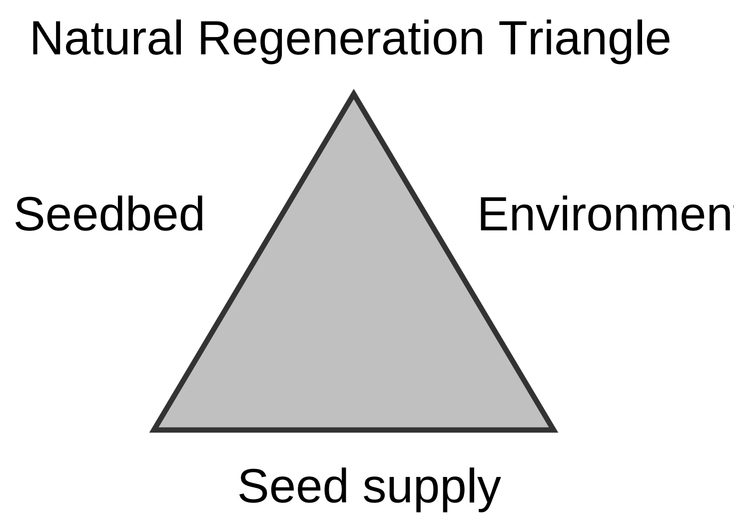
To promote under-represented species,
we need to think outside the box

Management Strategies

- Create canopy gaps
  - Favorable light environment
  - Alter the microenvironment

Management Strategies

- Site preparation
  - Reduce competition
  - Prepare the seedbed
  - Alter the microenvironment



Possible solutions

- Irregular multi-cohort management

  "…*some form of multi-cohort management that involves spatially variable harvest intensity may be desirable as an occasional feature of uneven-aged management to avoid declines in species diversity and to emulate natural processes more closely*."

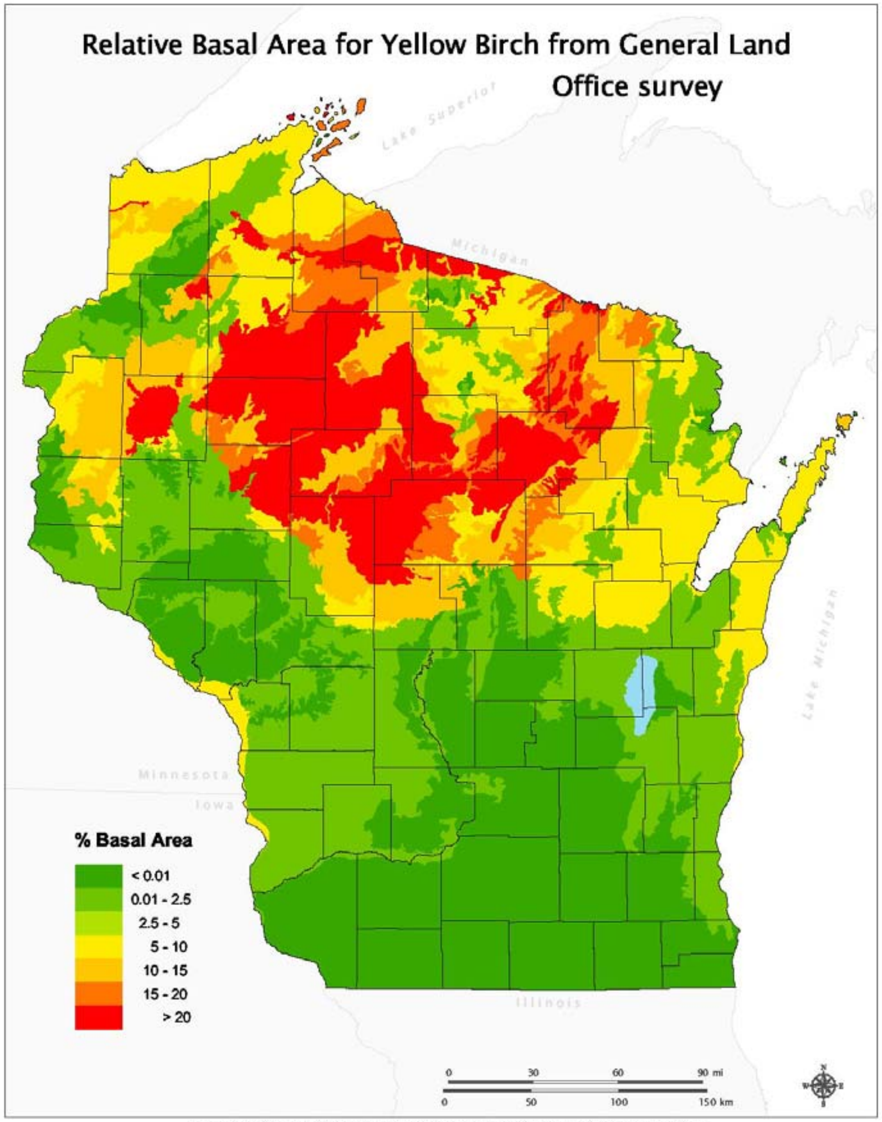
Hanson, J.J. and C.G. Lorimer. 2007. Forest structure and light regimes following moderate wind storms: implications for multi-cohort management. *Ecological Applications* 17:1325-1340.

Yellow birch

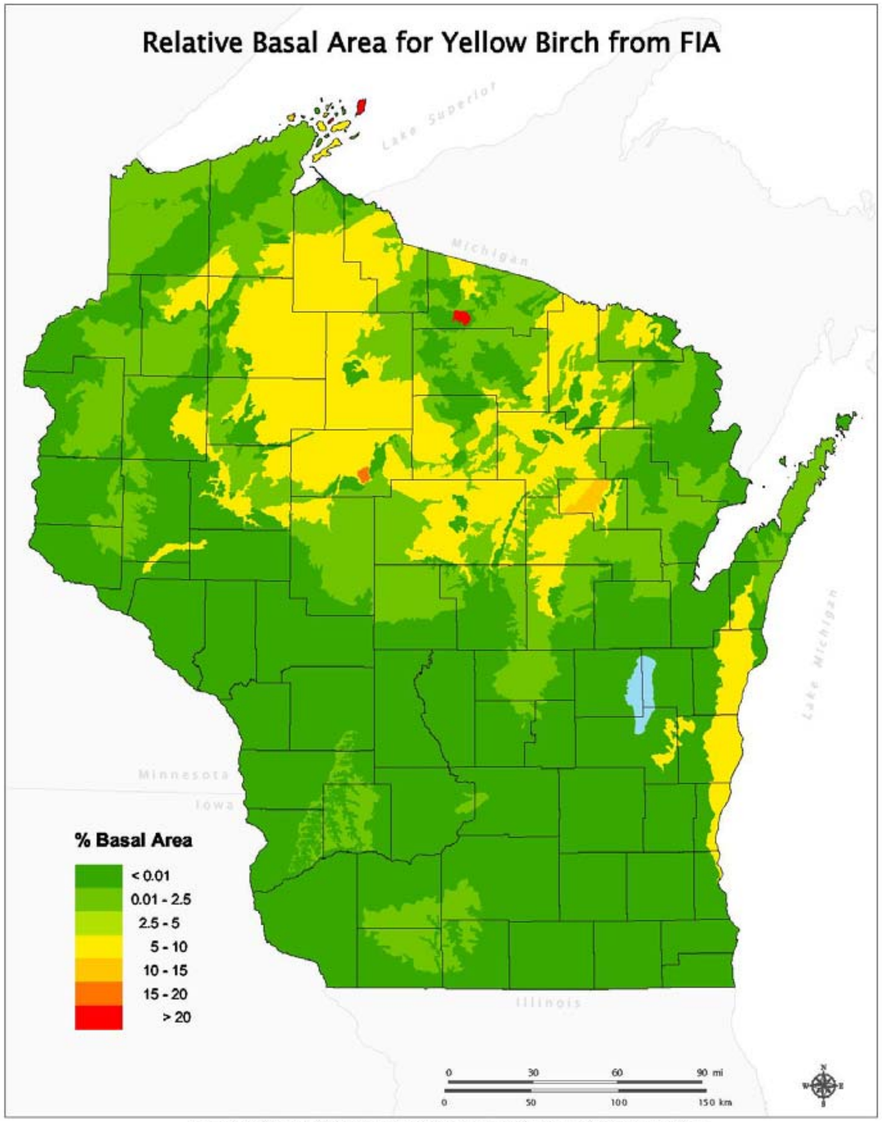
Bill Cook, Michigan State University, www.forestryimages.org

Yellow birch

- Supports higher densities of song birds than just about any other northern hardwood
  - Higher insect densities
  - Architecture and leaf arrangement provide a variety of foraging niches
- Regional decline



Map produced 28 March 2002 at the Forest Landscape Ecology Lab, University of Wisconsin-Madison

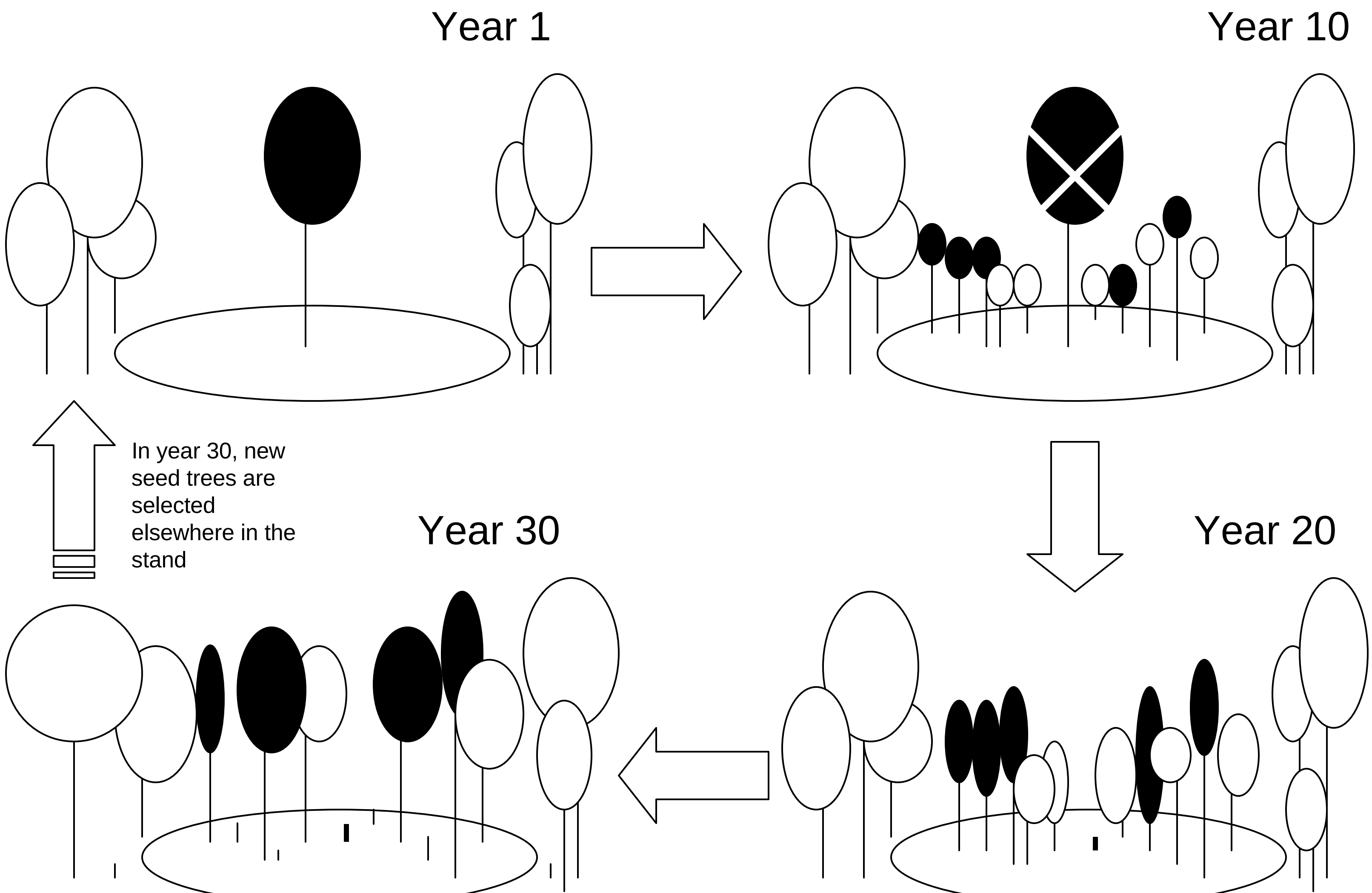


Map produced 28 March 2002 at the Forest Landscape Ecology Lab, University of Wisconsin-Madison

Group selection with seed tree retention

Group selection with seed tree retention

- Rationale
  - Favored by large infrequent openings
  - Less likely to blow down than most associated species
  - Often represented by scattered trees in contemporary managed northern hardwood stands

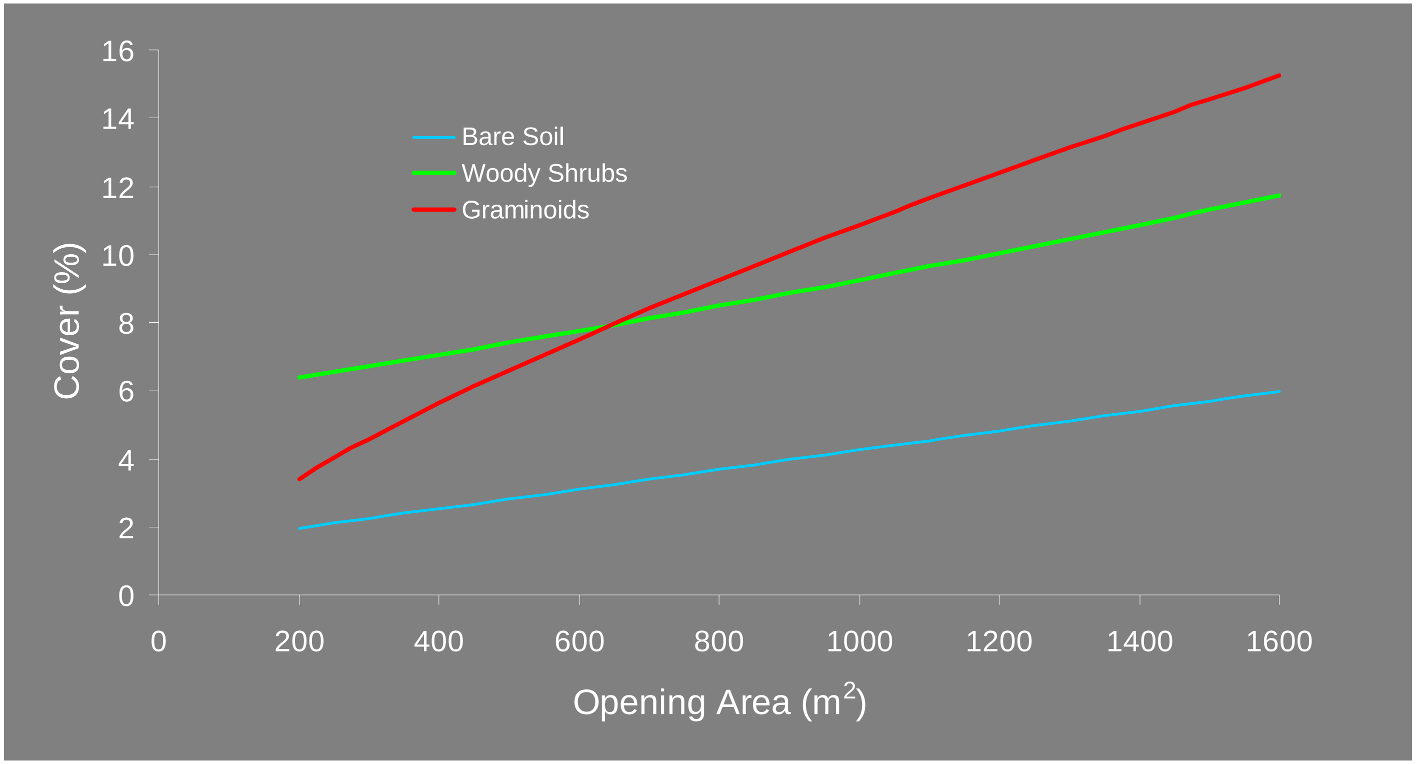


Year 1
Year 10
In year 30, new seed trees are selected elsewhere in the stand
Year 30
Year 20

Group selection with seed tree retention

- 49 openings cut in winter 2003
  - 0.5 x tree height radius (267 ± 62 m^2, n = 16)
  - 0.75 x tree height radius (642 ± 85 m^2, n = 17)
  - 1.0 x tree height radius (1192 ± 155 m^2, n = 16)
- Sampled 12 randomly located subplots in each opening and at 20 reference sites summer 2005

Group selection with seed tree retention



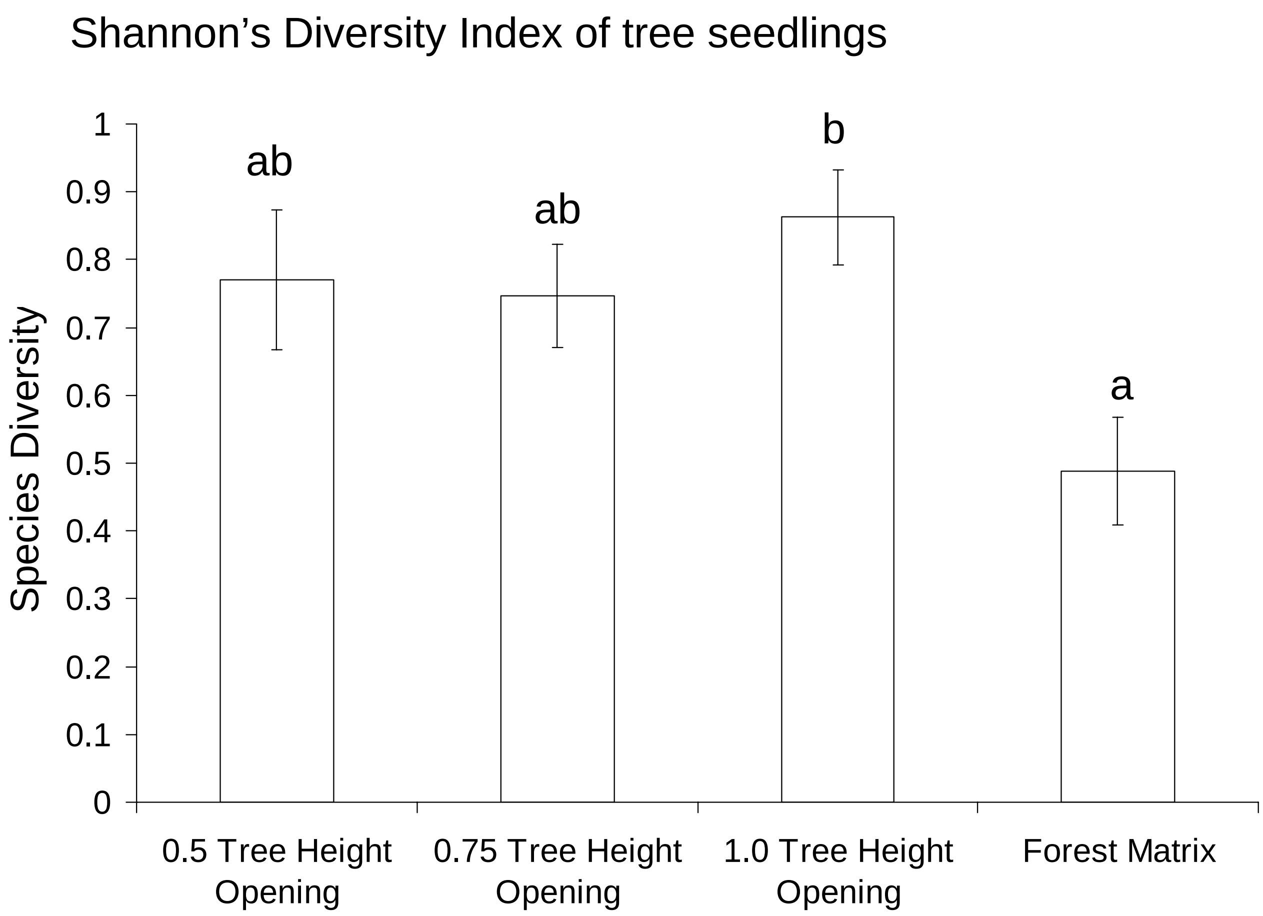
Shields, J.M., C.R. Webster, and L.M. Nagel. 2007. Factors influencing tree species diversity and *Betula alleghaniensis* establishment in silvicultural openings. *Forestry* 80 (3): 293-307.

Group selection with seed tree retention

- Significantly more yellow birch in openings than on control plots
  - A minor component of the gap cohort
    - 6% of seedlings, 1% of saplings
  - Sugar and red maple dominated gap cohorts
    - 87% of seedlings, 92% of saplings in largest openings

Shields et al. 2007

Group selection with seed tree retention



Shields et al. 2007

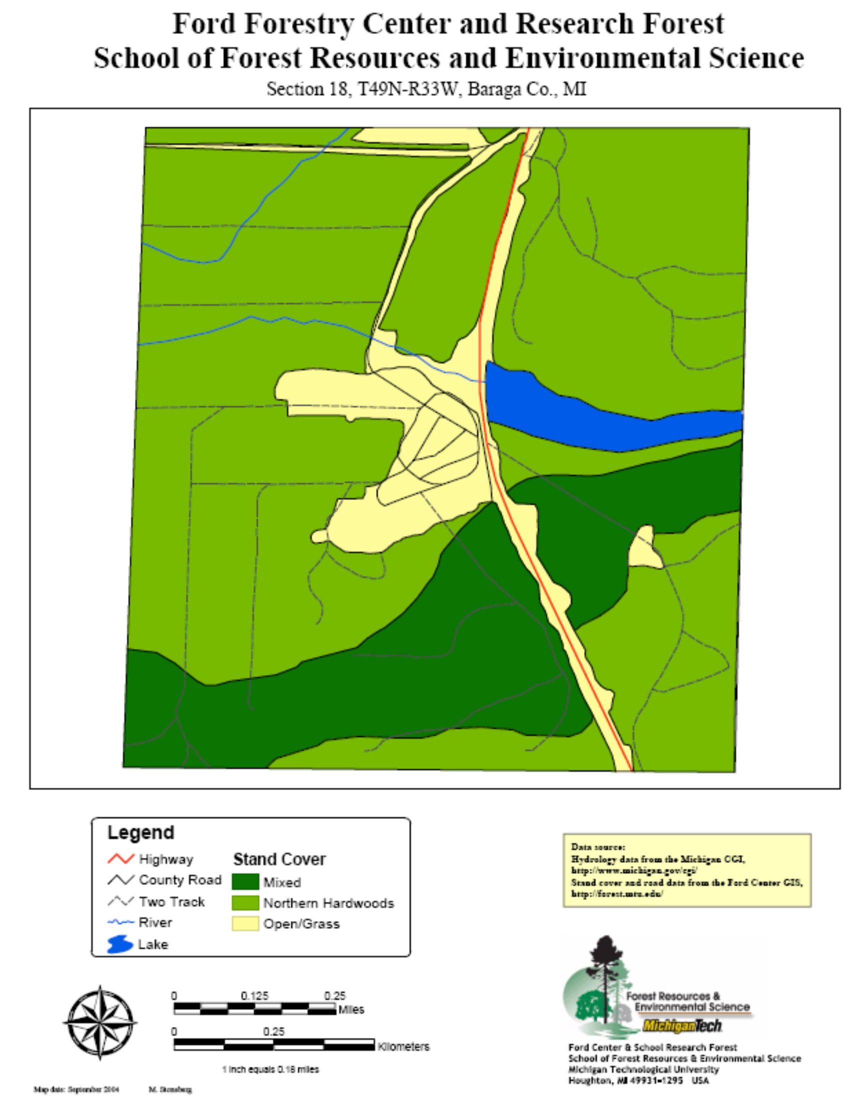
Eastern hemlock

Section 18 – Canopy Gaps

S. Holmes, et al. *In prep*

- **Objective:** assess effectiveness of group-selection openings with deer exclosures for natural hemlock regeneration

- **Study design:**
  - 20 gaps created (winters of 2003-2004 and 2004-2005)
    - 7 small gaps : 50 – 150 m^2
    - 7 medium gaps: 151 – 250 m^2
    - 6 large gaps: 251 – 400 m^2
  - 4 – 12 randomly located, 1 m^2 subplots per gap
    - Up to 3 randomly chosen for mini-hoop deer exclosures



Underplanting

White pine

Yellow birch

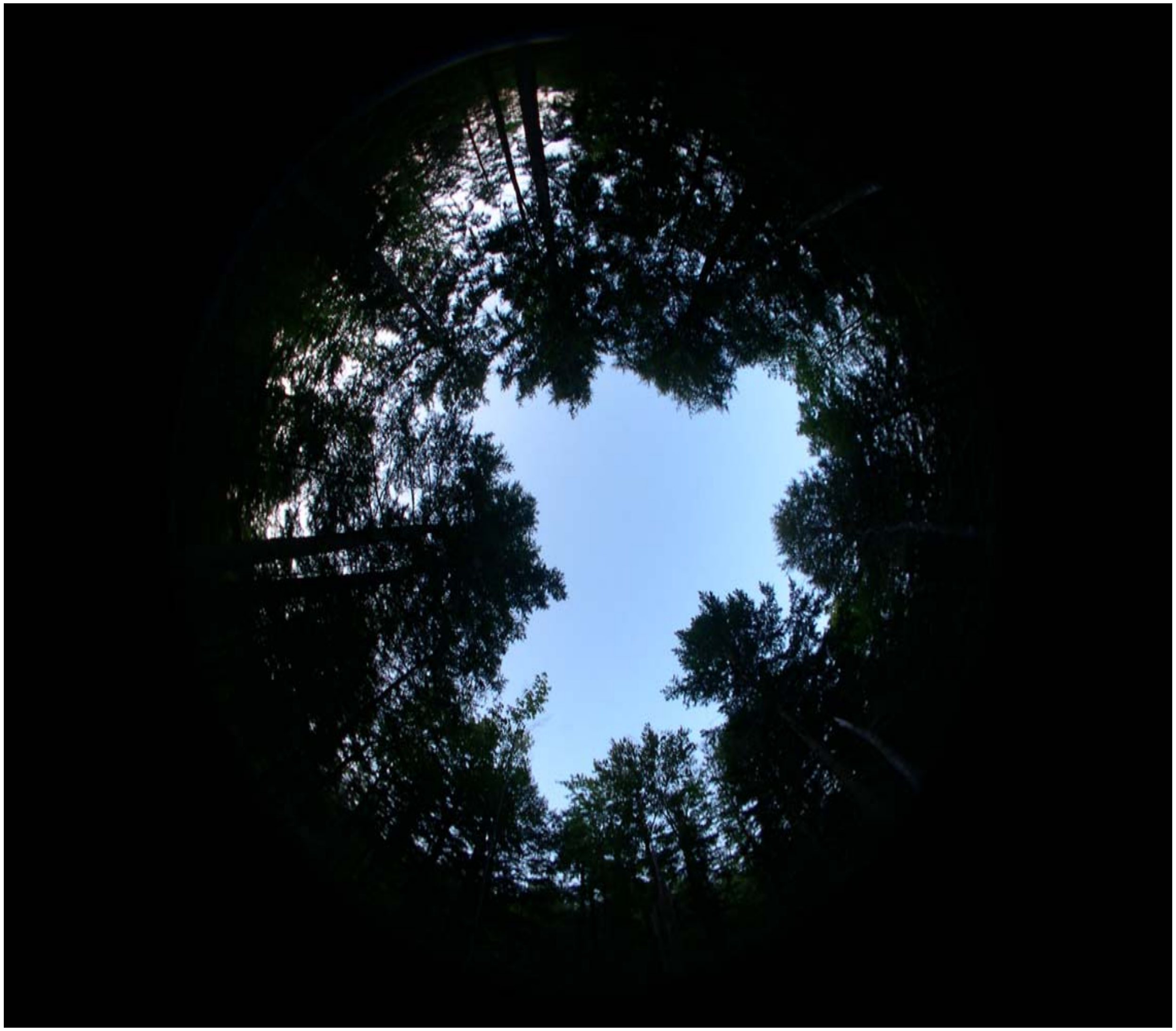
Hemlock

S. Holmes, et al. *In prep*

Section 18 – Canopy Gaps

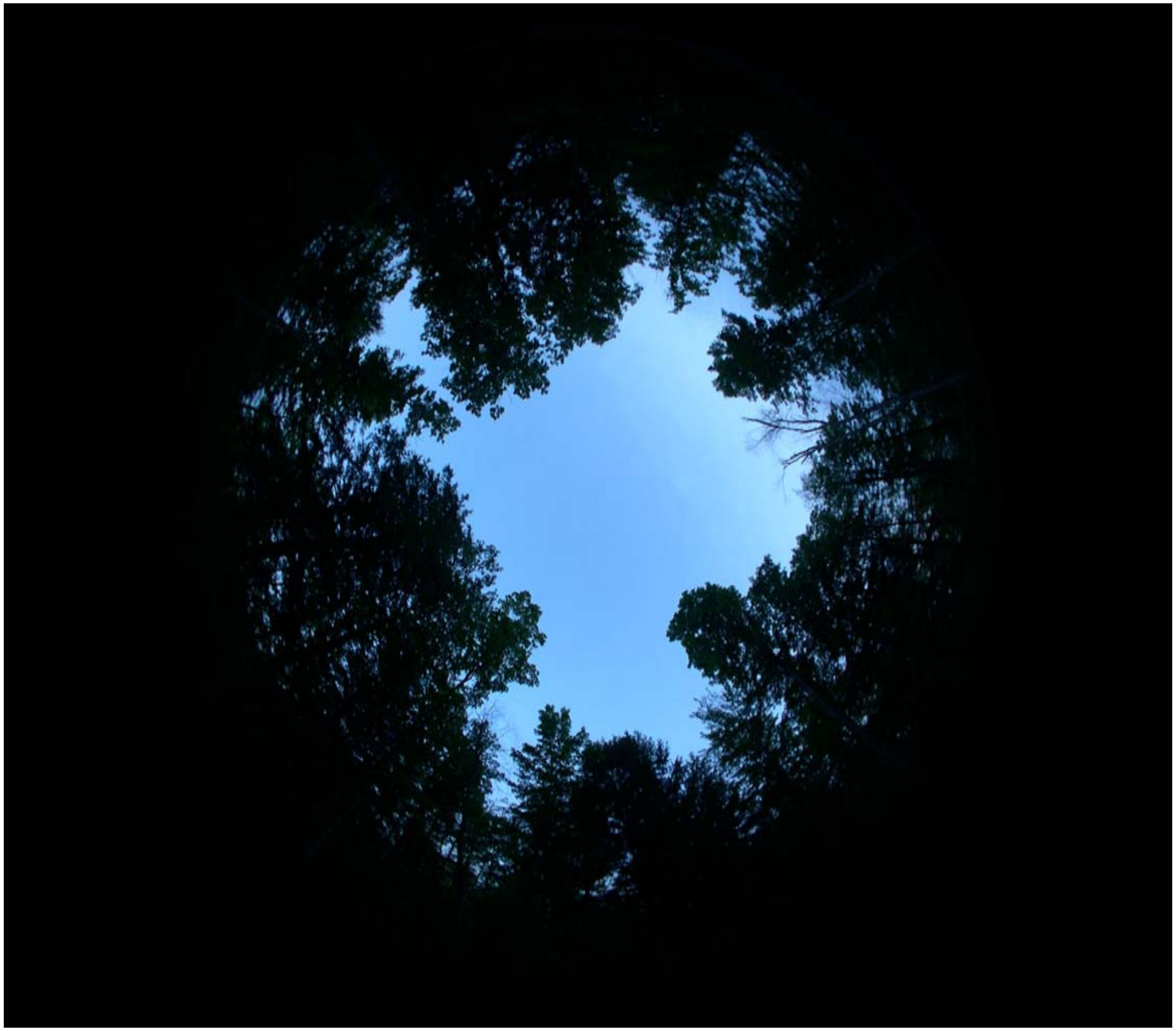
Small Gap

Section 18 – Canopy Gaps



Medium Gap

Section 18 – Canopy Gaps



Large Gap

Section 18 – Canopy Gaps

Gap Regeneration

Section 18 – Canopy Gaps

Exclosure

Control yew

Exclosure yew

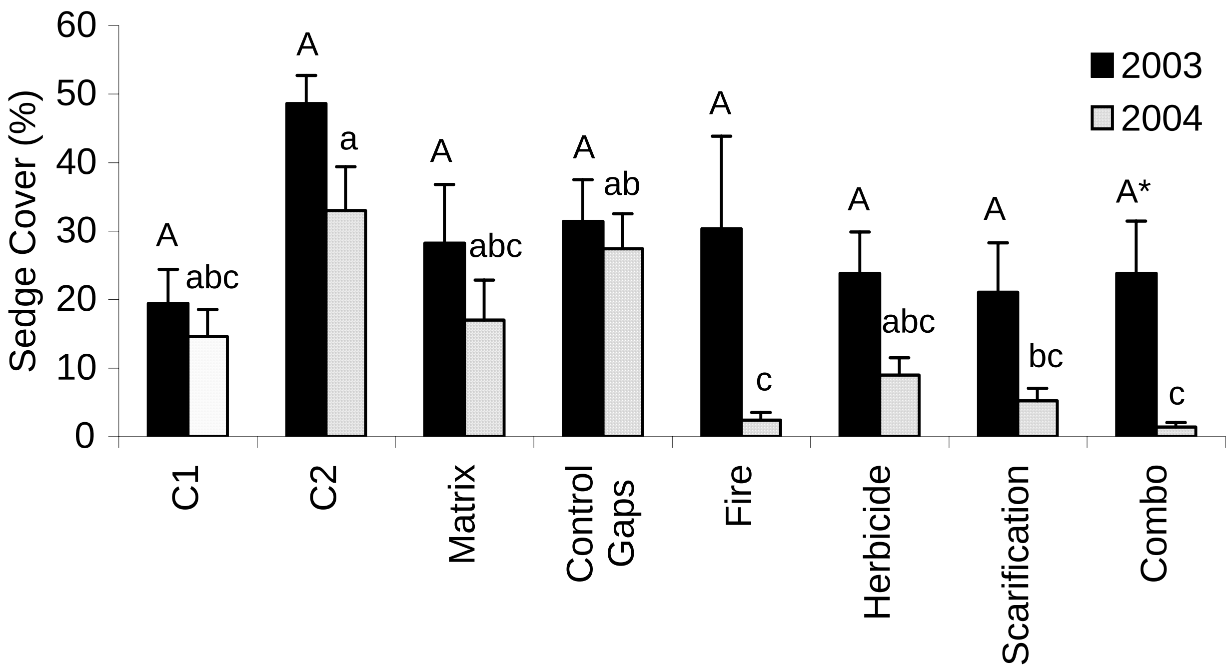
Hardwood gap study in Wisconsin

- Northern hardwood stand in Oneida Country, WI
- Sixty canopy gaps (0.03-ha or 60-ft diameter) were created during a harvest in 2003-2004
- Matrix was an single tree selection
- Two nearby stands were used as controls

Hardwood gap study in Wisconsin

- Site preparation in gaps after the harvest
  - Scarification (12)
  - Herbicide (12)
  - Fire (3)
  - Scarification and herbicide (11)
  - Untreated/Control (22)

Hardwood gap study in Wisconsin



P = 0.0044 between treatments

P < 0.0001 between years

P = 0.0521 treatment x year

Powers and Nagel *In prep*

Hardwood gap study in Wisconsin

- Only scarification followed by herbicide produced significant decreases in sedge
- The combo treatment was also associated with significant declines in tree regeneration and the understory community
- Scarification and herbicide resulted in significant impacts on tree regeneration and the understory community when used individually
- Burned gaps had lower sedge cover after treatment than controls, despite similar levels of sedge before the harvest
- Burning did not have significant impacts on tree regeneration

Summary: Species Composition

- Sugar maple dominance (relative importance) is increasing with single tree selection uneven-aged management over time
- Midtolerants such as yellow birch have tended to decrease with uneven-aged management
- The decline of midtolerants in unmanaged stands appears less pronounced

Summary: Stand Structure

- Diameter distributions – no consistent trend toward one diameter distribution shape with or without management
  - Unmanaged – rotated sigmoid most commonly observed
  - Managed – increasing-*q* most commonly observed
- The light environment and seedbed conditions resultant following typical single tree selection are not promoting midtolerants
- A myriad of factors (deer, invasive plants, earthworms, etc) are playing a role in regeneration failure
- Creative solutions are needed to maintain diversity in northern hardwoods of the Lake States

References

- Arbogast Jr., C.J. 1957. Marking guides for northern hardwoods under the selection system. USDA For. Serv. Sta. Pap. 56. Lake States For. Exp. Sta., St. Paul, MN. 21 p.
- Crow, T.R., D.S. Buckley, E.A. Nauertz and J.C. Zasada. 2002. Effects of management on the composition and structure of northern hardwood forests in Upper Michigan. For. Sci. 48:129-145.
- de Liocourt, F. 1898. De l'amenagement des sapinieres, English translation: (2001) On the amelioration of fir forests, translated by Maria Nygren. Bulletin trimestriel, Societe forestiere de Franche-Comte et Belfort, juillet 396-409.
- Eyre, E.H. and Z.M. Zillgitt. 1953. Partial cuttings in northern hardwoods of the Lake States: Twenty-year experimental results. USDA For. Serv. Gen. Tech. Bull.1076. Lake States For. Exp. Sta., St. Paul, MN. 124 p.
- Frelich, L.E. and C.G. Lorimer. 1991. Natural disturbance regimes in hemlock-hardwood forests of the upper Great Lakes region. Ecol. Monogr. 61:145-164.
- Goff, G.F. and D. West. 1975. Canopy-understory interaction effects on forest population structure. For. Sci. 21:98-108.
- Goodburn, J.M. and C.G. Lorimer. 1999. Population structure in old-growth and managed northern hardwoods: an examination of the balanced diameter distribution concept. For. Ecol. Manage. 118:11-29.
- Hanson, J.J. and C.G. Lorimer. 2007. Forest structure and light regimes following moderate wind storms: implications for multi-cohort management. *Ecological Applications* 17:1325-1340.
- Janowiak, M.K., L.M. Nagel and C.R. Webster. Spatial scale and stand structure in northern hardwood forests: implications for quantifying diameter distributions. *In review, Forest Science.*
- Leak, W.B. 1964. An expression of diameter distribution for unbalanced, uneven-aged stands and forests. For. Sci. 10:39-50.
- Leak, W.B. 1996. Long-term structural change in uneven-aged northern hardwoods. For. Sci. 42:160-165.
- Leak, W.B. and S.M. Filip. 1977. Thirty-eight years of group selection in New England northern hardwoods. J. For. 75:641-643.
- Meyer, H.A. 1952. Structure, growth, and drain in balanced uneven-aged forests. J. For. 50:85-92.
- Neuendorff, J.K., L.M. Nagel, C.R. Webster and M.K. Janowiak. 2007. Stand structure and composition in a northern hardwood forest after 40 years of single-tree selection. North. J. Appl. For. 24(3):197-202.
- Powers, M.D. and L.M. Nagel. *In press*. Disturbance dynamics influence Pennsylvania sedge abundance in a northern hardwood forest. *Journal of the Torrey Botanical Society.*
- Schmelz, D.V. and A.A. Lindsey. 1965. Size-class structure of old-growth forests in Indiana. For. Sci. 11:731-743.
- Schwartz, J.W., L.M. Nagel and C.W. Webster. 2005. Effects of uneven-aged management on diameter distribution and species composition of northern hardwoods in Upper Michigan. For. Ecol. Manage. 211:356–370.
- Shields, J.M., C.R. Webster and L.M. Nagel. 2007. Factors influencing tree species diversity and *Betula alleghaniensis* establishment in silvicultural openings. *Forestry* 80(3):293-307.
- Smith, D.M., B.C. Larson, M.J. Kelty and P.M.S. Ashton. 1997. The Practice of Silviculture: Applied Forest Ecology, 9th edition. John Wiley & Sons.
- Stearns, F.W. 1997. History of the lake states forests: Natural and human impacts. *In* Lake States Regional Forest Resources Assessment: Technical Papers. GTR NC-189.
- Zhang, Q., K.S. Pregitzer and D.D. Reed. 2000. Historical changes in the forests of the Luce District of the Upper Peninsula of Michigan. Am. Midl. Nat. 143:94-110.

Acknowledgements

- Graduate students: Joseph Schwartz, Jon Neuendorff, Maria Janowiak, Matt Powers, Josh Shields, Stacie Holmes, Wilf Previant
- Field assistants: Charlie Webster, Elsa Jensen, James Klapperich, Rachael Jarvenpaa, Mike McGowan, Frank Seilheimer
- Field and analytical support: Jim Schmierer, Jim Pickens, WI DNR, Oneida County Forestry, MI DNR, Chequamegon-Nicolet NF, Hiawatha NF, Ottawa NF, Plum Creek
- Funding: MTU School of Forest Resources & Environmental Science, McIntire-Stennis Cooperative Forestry Research Program, Ecosystem Science Center