Quantifying the Influence of Stand Spatial Structure and Species Composition on Forest Growth and Regeneration Patterns

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Spatially explicit measures of stand structural complexity are able to detect differences in forest structure among various management regimes. Commercial thinning can substantially alter within-stand dynamics and these alterations vary with thinning method and intensity.

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http://www.nsrcforest.org

Project Summary

Rationale

- Forest management, stand structure, and tree growth are highly intercorrelated but studies on the relationship of forest growth and stand structural complexity have resulted in mixed outcomes.

Project Objectives

Using a series of regional, comprehensive, multi-year, replicated, and fully stem mapped commercial thinning studies of the spruce-fir (*Picea-Abies*) forests of the Acadian Region we examined:

- the effect of various thinning treatments on forest structure
- how overall stand and individual-tree growth correlate with changes in forest structure, and
- the influence of distance from the forwarder trails on individual-tree growth.

Approach

- To study variation in forest structure and growth among treatments and over time several sophisticated and often spatially explicit growth and structural measures were evaluated.

Project Summary

Major findings

- Irrespective of the method, thinning mostly reduced stand structural heterogeneity compared to the non-thinned control which was at least partly attributable to increased post-treatment mortality rates.
- The spatial arrangement of trees changed from fully random (control) to a more clustered (dominant) or regular distribution (low thinning) while thinning-induced changes in forest structure were often reflected in tree size diversity.
- Overall stand growth exhibited varying trends across the treatments and in the course of the study with increasing (control, low thinning) or decreasing growth dominance of large trees (crown thinning).
- Forwarder trials added another important structural element to the thinned stands and increased basal area growth of individual trees up to a trail distance of approximately 5 m.

Implications for the Northern Forest region

- Commercial thinning can substantially alter within-stand dynamics and these alterations may vary with thinning method and intensity.
- Medium-aged suppressed and intermediate balsam fir and red spruce trees released in the dominant thinning treatments proved to be highly responsive.

Background and Justification

- Forest management, stand structure, and tree growth are highly intercorrelated.
- Quantifying forest structural complexity and respective changes from management activities allows for the subsequent evaluation of its influence on stand dynamics and hence stand and tree growth.
- E.g., using a variety of measures of forest structural heterogeneity, previous studies successfully differentiated between various forest management regimes including silvicultural systems and thinning treatments.
- However, studies on the relationship of forest or tree growth and stand or neighborhood structural complexity, respectively, have resulted in mixed outcomes with varying or limited success in revealing ecological reasoning.
- E.g., structural complexity metrics often turned out to be significant predictors in stand and tree growth modelling efforts but improvement in overall model accuracy was mostly marginal.
- The majority of existing studies used simple spatially implicit (distance-independent) first-order characteristics to characterize forest structure such as stand density – the only way to quantify structural heterogeneity until recently.

Background and Justification

- Given the wider availability of stem mapped permanent measurement plots and the necessary computing technology to make spatially explicit estimates of competition and structure, a new, more detailed and precise assessment of how structural complexity influences growth and stand dynamics is possible.
- In fact, distance-dependent measures have the potential to be much more efficient in detecting even minor variation in stand structure.
- In addition, effects of several different management regimes such as various thinning treatments on the relationship between structure and growth have only rarely been studied comprehensively over a longer time period in naturally regenerated forest stands.
- Using a controlled and fully stem-mapped commercial thinning experiment at six locations across the Acadian Forest of Maine we examined
  1) the effect of various thinning treatments on forest structure
  2) how overall stand and individual-tree growth correlate with changes in forest structure, and
  3) the influence of distance from the forwarder trails on individual-tree growth.

Methods

- Measurements from 6 study locations across northern Maine, which are part of the University of Maine's Cooperative Forestry Research Unit's Commercial Thinning Research Network (CTRN) were used.
- None of the stands had been thinned before the study was initiated.
- In addition to a non-thinned control, commercial thinning treatments included a factorial combination of thinning method (low, dominant, or crown) and level of relative density (ratio of stand density index (SDI) and maximum SDI) reduction (33 or 50%).
- Forwarder as well as ghost trails were created during the thinning operations and included in the research plot design (except non-thinned control).
- Stands were stem-mapped and DBH measured annually for 10 post-treatment years.

- Stand characteristics (mean ± standard deviation, min & max):

Characteristic	
Breast height age (2000, years)	51.3 ± 14.0 (32-68)
Site index (m)	15.9 ± 3.2 (13.1-21.5)
Pre-treatment QMD (cm)	12.3 ± 2.5 (7.8-16.8)
Pre-treatment basal area (m^2 ha^{-1})	44.3 ± 5.9 (31.9-55.9)
Pre-treatment spruce/fir proportion (%)[1]	83.5 ± 14.0 (33.9-99.3)
Basal area reduction (%)	51.0 ± 11.2 (23.1-70.3)
Post-treatment QMD (cm)	13.7 ± 3.0 (8.7-20.1)
Post-treatment basal area (m^2 ha^{-1})	26.0 ± 10.3 (12.8-54.0)
Post-treatment spruce/fir proportion (%)[1]	96.3 ± 7.8 (66.2-100.0)

Methods

- To study variation in forest structure and tree growth among treatments and over time several spatially-explicit structural measures were evaluated, namely
  - structural complexity index, SCI: measure of the vertical size differentiation and horizontal spatial positioning of triangles formed by neighboring trees with a value of one when all trees have the same size, regardless of spatial pattern, and no upper bound, in order to calculate SCI as a means to quantify stand structural heterogeneity and variability in individual-tree growth, we used stem DBH and annual basal area growth (ΔBA, cm^2 yr^{-1}), respectively.
  - pair correlation function, *g*(r): inter-tree distance-dependent summary statistic that identifies the tree-to-tree distance r at which deviations from complete spatial randomness (*g*=1) occur, and whether these deviations indicate clumping (*g*>1) or regularity (*g*<1), and
  - mark variogram, $\gamma_m(r)$: inter-tree distance-dependent summary statistic for marked point patterns that helps highlighting deviations from independence (no autocorrelation, γ_m=mean mark variance) occurs, and whether these deviations indicate positive (mark (e.g. tree DBH or height) similarity, γ_m< mean mark variance) or negative autocorrelation (mark dissimilarity, γ_m>mean mark variance), large γ_m values reveal large differences in e.g. DBH between neighboring trees

Methods

- To further gain insights into the dynamics of treatment induced growth patterns at the stand level we examined
  - Growth dominance statistic, G: the cumulative proportional contribution to stand growth by individual trees in relation to the cumulative proportional contribution of the sizes of those trees, measure that detects and quantifies whether the larger (positive G) or the smaller trees (negative G) of a forest stand dominate total stand growth,
- Effect of forwarder trails on tree growth was evaluated by means of
  - Tree-specific distance to trail, TDIST: calculated using tree x-y coordinates
  - Relative basal area growth, RelΔBA: percentage of species- and site-specific diameter basal are growth of the control treatment
  - Linear mixed effects modelling: with each CTRN location treated as random to detect potential differences between species and treatments in TDIST and RelΔBA relationship, $\mathrm{Rel}\Delta\mathrm{BA} = a + b \cdot \ln(\mathrm{TDIST})$

Results

- Total post-treatment tree mortality over the course of the 10 year study was especially high in the crown and dominant thinning treatments (36-62%).
- Dead trees were mostly smaller in comparison to live residual trees with control and crown thinning treatments exhibiting the greatest differences.
- Thinning in conjunction with post-treatment mortality had a strong influence on DBH and ΔBA: mean DBH increased in the crown and low thinning treatments by approximately 20 and 50%, respectively, but not in the dominant thinning treatment while mean ΔBA increased by at least 30% in all thinning treatments when compared to the non-thinned control.
- Differences in DBH and ΔBA between thinned and non-thinned treatments either remained at the observed initial levels or further intensified towards the end of the study.

Mean (± standard deviation, minimum and maximum) of stand density (N, trees ha^{-1}), diameter at breast height (*DBH*, cm), and annual basal area growth (Δ*BA*, cm^2 yr^{-1}) for the different CTRN treatments 1 and 10 years after thinning (n = 6 per treatment)

	Control	33% crown	33% dominant	33% low	50% crown	50% dominant	50% low
				1 year post-treatment			
N	4822±2169 (1963-7258)	1761±617 (988-2654)	2481±1123 (1407-4333)	1473±478 (1074-2185)	1446±550 (926-2432)	1979±1185 (1049-3975)	874±187 (654-1197)
DBH	10.2±5.0 (0.8-47.8)	12.0±5.3 (1.0-30.5)	10.3±4.0 (1.3-23.1)	14.6±4.6 (1.3-35.1)	11.7±5.8 (1.3-32.3)	10.1±3.8 (1.3-29.7)	16.9±4.7 (2.5-31.2)
ΔBA	1.98±3.75 (0-40.28)	3.43±5.40 (0-52.44)	2.65±3.87 (0-44.39)	4.94±5.74 (0-49.57)	5.00±7.17 (0-54.12)	2.93±4.86 (0-50.72)	6.93±6.91 (0-44.39)
				10 year post-treatment			
N	3259±1076 (1703-4320)	1107±428 (506-1605)	1378±824 (568-2679)	1323±436 (951-2049)	796±462 (432-1691)	866±781 (173-2210)	710±212 (506-1062)
DBH	13.0±5.5 (1.5-52.6)	15.4±6.4 (2.0-36.3)	13.5±5.0 (1.5-29.7)	17.3±5.2 (2.3-43.9)	16.2±7.4 (1.3-36.1)	13.3±4.9 (2.5-32.0)	20.3±5.0 (4.8-36.6)
ΔBA	2.87±5.30 (0-73.37)	6.89±8.85 (0-65.11)	6.17±8.00 (0-72.97)	7.29±8.50 (0-64.61)	8.73±12.17 (0-88.17)	7.65±9.98 (0-78.44)	10.29±10.04 (0-61.57)

Results

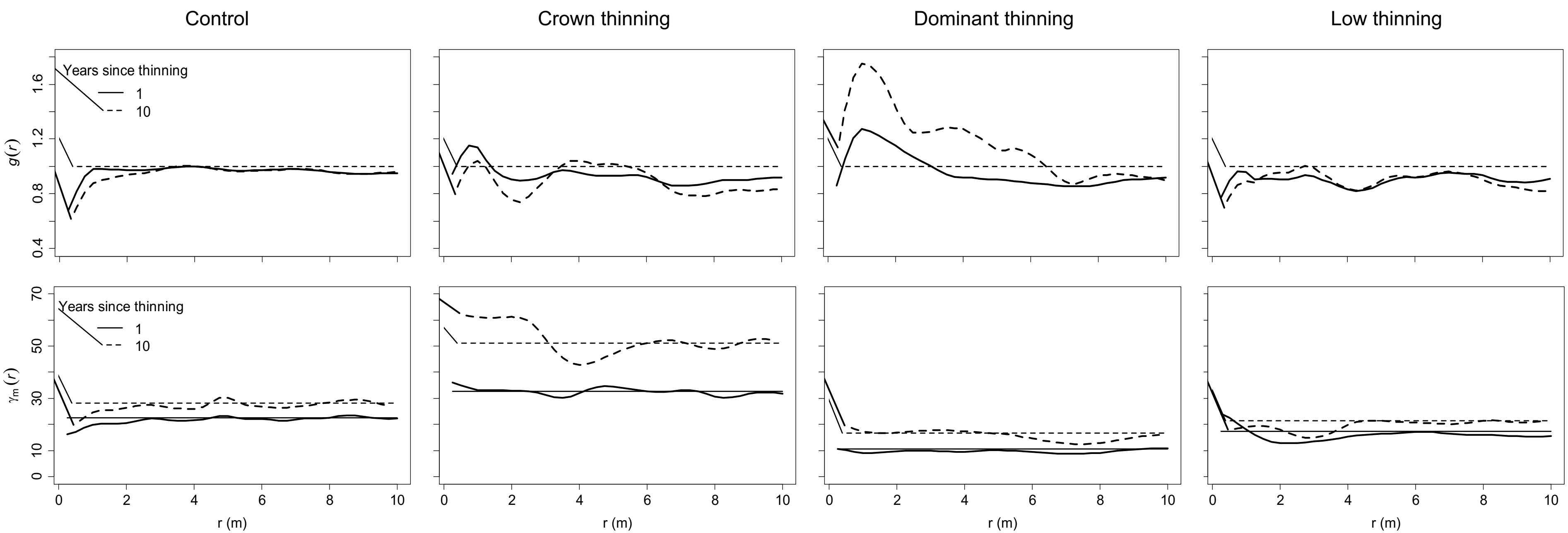
- Irrespective of method and intensity, thinning treatments reduced stand structural heterogeneity as reflected in lower DBH-based structural complexity indices (SCI) when compared to the non-thinned control.
- Stand structural heterogeneity decreased marginally in the majority of treatments towards the end of the study except for the two low thinning treatment.
- Variation in ΔBA among trees in the different treatments generally followed trends observed for stand structural heterogeneity: initial ΔBA varied most in the control and was most homogeneous in the dominant and low thinning treatments.
- Variation in ΔBA mostly increased in all treatments 8-10 years after thinning but heterogeneity in DBH and ΔBA remained highest in control and crown thinning treatments.

Mean (± standard error, minimum-maximum) DBH-based stand structural heterogeneity and ΔBA-based tree growth variation in the different CTRN treatments (n = 6 per treatment) quantified using the structural complexity index (SCI) 1 to 3 and 8 to 10 years since thinning (YST)

Treatment	Structural heterogeneity		Growth variation	
YST	1-3	8-10	1-3	8-10
Control	5.81 ± 0.08 (5.20 – 6.40)	5.58 ± 0.07 (5.20 – 6.13)	4.51 ± 0.17 (3.44 – 5.85)	4.94 ± 0.19 (3.32 – 6.45)
33% Crown	4.20 ± 0.19 (3.21 – 5.69)	4.18 ± 0.21 (2.91 – 5.68)	4.50 ± 0.35 (2.24 – 7.93)	5.22 ± 0.34 (2.75 – 7.67)
33% Dominant	3.47 ± 0.21 (1.99 – 4.89)	3.37 ± 0.31 (1.78 – 5.56)	3.81 ± 0.28 (2.56 – 7.45)	4.86 ± 0.51 (2.47 – 8.95)
33% Low	3.07 ± 0.15 (2.24 – 4.25)	3.42 ± 0.16 (2.59 – 4.73)	4.25 ± 0.24 (2.39 – 6.04)	5.26 ± 0.36 (2.55 – 7.47)
50% Crown	4.26 ± 0.17 (2.88 – 5.41)	3.91 ± 0.24 (2.85 – 5.87)	4.79 ± 0.33 (2.75 – 7.81)	5.30 ± 0.38 (2.75 – 8.28)
50% Dominant	2.76 ± 0.15 (1.94 – 3.68)	2.49 ± 0.23 (1.58 – 4.03)	3.82 ± 0.40 (1.72 – 7.83)	4.73 ± 0.63 (1.65 – 9.97)
50% Low	2.46 ± 0.07 (1.98 – 2.97)	2.53 ± 0.10 (2.19 – 3.47)	4.15 ± 0.24 (2.65 – 6.17)	4.78 ± 0.31 (3.18 – 7.45)

Results

- Pair correlation functions *g(r)* revealed complete spatial randomness in the control (*g*~1), clustering of trees at small inter-tree distances (r) in the dominant and crown thinning (*g*>1), and a tendency to regular spacing (*g*<1) in crown and low thinning at varying inter-tree distances
- Overall post-treatment DBH variance as depicted in mark variograms $\gamma_m(r)$ decreased in dominant and low thinning and increased over the 10 year study period in the crown thinning
- DBH dissimilarity (γ_m>mean variance) in neighboring individuals at small inter-tree distances became evident in the crown thinning while DBH similarity (γ_m<mean variance) at larger tree-to-tree distance appeared to establish in the low thinning towards the end of study



Estimated mean pair correlation functions $g(r)$ and estimated mean mark variograms $\gamma_m(r)$ for *DBH* (average mark variances are depicted as horizontal lines) of CTRN treatments (50% relative density reduction, n = 6 per treatment) 1 and 10 years after thinning.

Results

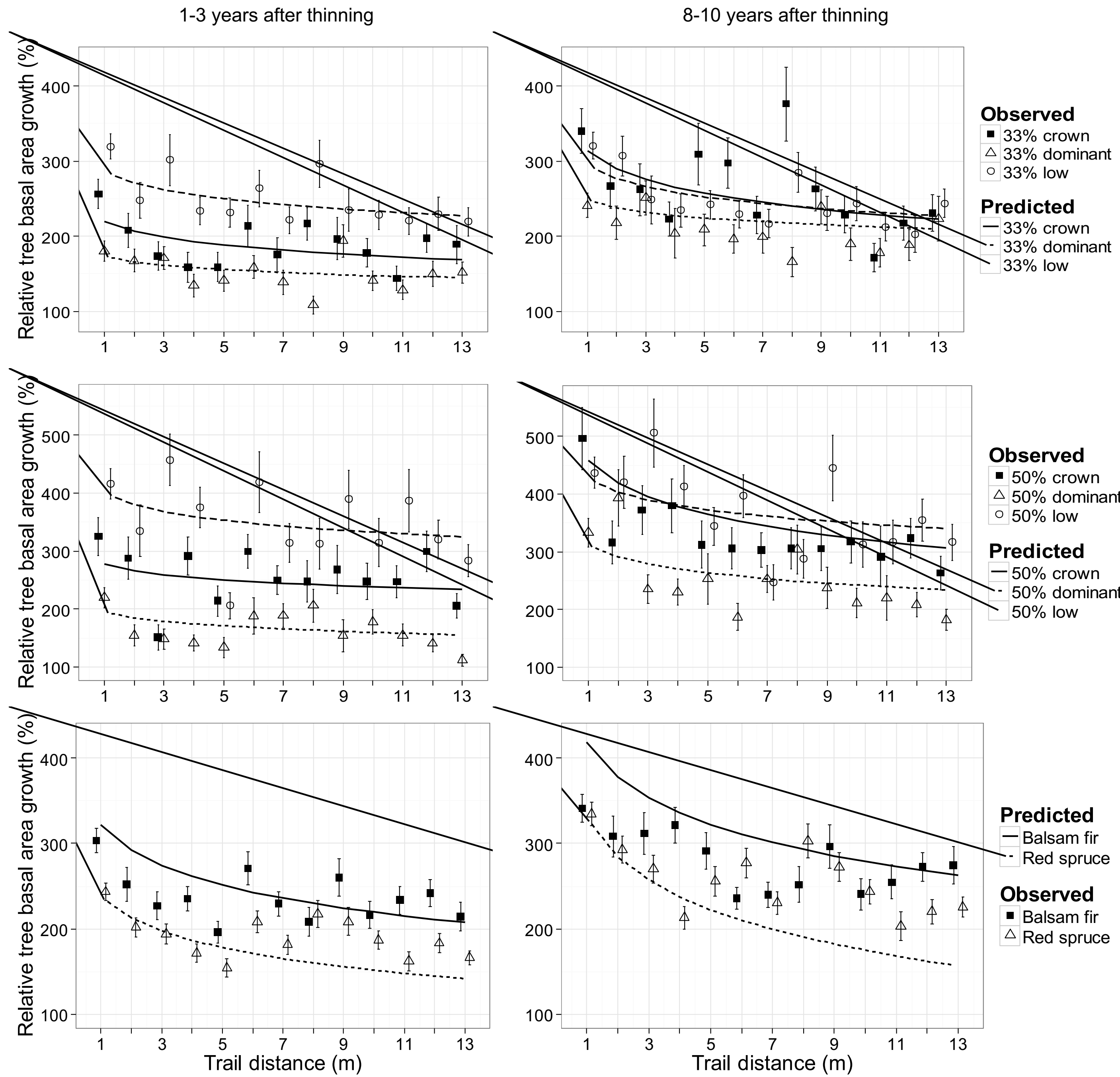
- Irrespective of treatment, growth dominance (G) was found to be positive throughout the 10 year study period, however, trends in G showed distinct variation among thinning treatments.
- Initially large positive values signaling strong G of larger trees in the control further slightly increased in the second half of the 10-year study period.
- G of large trees also increased in the low thinning treatments over time, but was almost not evident at the beginning of the study.
- In contrast, initial G in larger trees in the crown and dominant thinning slightly decreased or remained fairly stable over the course of the study, respectively.

Change in mean (± standard error, minimum-maximum) growth dominance G in the different CTRN treatments (n = 6 per treatment) 1 to 3 and 8 to 10 after thinning. *G* values greater than 0 signal growth dominance of larger trees (i.e. contribution to stand total growth by larger trees is greater than their contribution to stand total size) whereas negative *G* values signal growth dominance of smaller trees.

Treatment	Years since thinning	
	1-3	8-10
Control	0.36 ± 0.02 (0.25 – 0.49)	0.40 ± 0.02 (0.28 – 0.54)
33% Crown	0.32 ± 0.02 (0.20 – 0.44)	0.29 ± 0.02 (0.14 – 0.46)
33% Dominant	0.23 ± 0.03 (0.04 – 0.42)	0.24 ± 0.03 (0.06 – 0.47)
33% Low	0.16 ± 0.03 (-0.10 – 0.30)	0.22 ± 0.03 (-0.02 – 0.36)
50% Crown	0.27 ± 0.02 (0.11 – 0.41)	0.21 ± 0.03 (-0.02 – 0.49)
50% Dominant	0.22 ± 0.03 (-0.03 – 0.44)	0.23 ± 0.04 (-0.10 – 0.45)
50% Low	0.10 ± 0.02 (0.00 – 0.22)	0.19 ± 0.02 (0.06 – 0.32)

Results

Forwarder trails added additional structural heterogeneity resulting in increased tree growth in the proximity of the trails



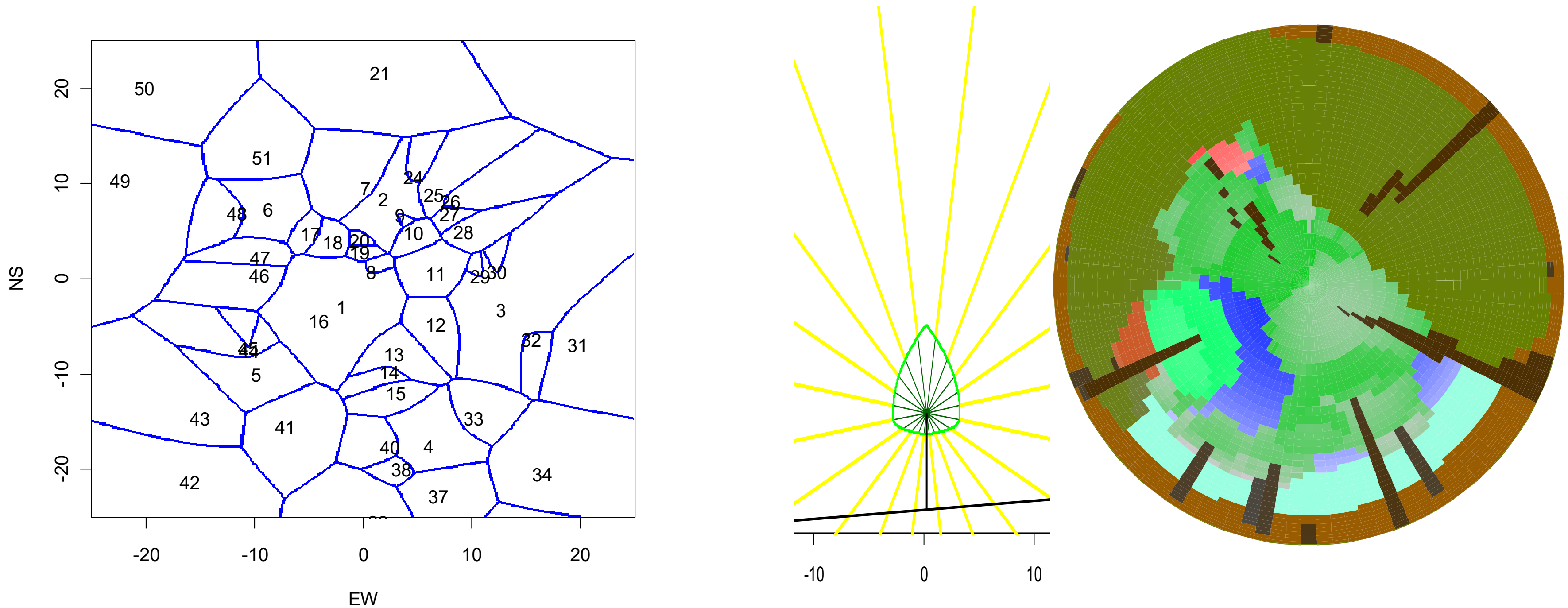
Effect of distance to forwarder trail on relative annual tree basal area growth ($cm^2\ yr^{-1}\ (cm^2\ yr)^{-1}$, percentage of species- and site-specific growth of control treatment with control = 100%) as a function of thinning treatment and species 1-3 and 8-10 years after thinning. Observed values represent classified means ± one standard error.

Implications and applications in the Northern Forest region

- Although confounded by high post-treatment mortality rates in some of the thinned stands, overall changes in forest structure and growth observed in our study highlighted the interrelationship of forest management, stand structure, and tree growth.
- Medium-aged suppressed and intermediate balsam fir and red spruce trees released in the dominant thinning treatments proved to be highly responsive to newly available growing space - a finding that seems to justify utilization of the largest trees and the release of lower canopy strata individuals in order to promote their development in this type of forest ecosystem.
- Growth rates in the low thinning treatments remained at relatively high levels throughout the study period suggesting ongoing productivity potential in the stands that were significantly less structurally modified by the management interventions.

Future directions

- Better quantification of individual-tree responses using distance-dependent competition indices such as area potentially available (APA) or point of view index (POV) that can effectively capture the spatial variability created by thinning.



Schematic illustrations of summarizing the competitive status of trees using area potentially available (quantification of available growing space, left) and point of view index (quantification of tree crown surface area facing sky, right).

Modified from Waskiewicz J. and Weiskittel A.R. 2011.
An R package of spatially-explicit competition and structural indices.
Presentation at NorthEastern Mensurationists Organization (NEMO) Annual Meeting in State College, PA.

List of products

Peer-reviewed publication

- Kuehne C., Weiskittel A.R., Fraver S., and Puettmann K.J. 2015. Effects of thinning induced changes in structural heterogeneity on stand growth, ingrowth, and mortality in secondary Douglas-fir forests. Canadian Journal of Forest Research 45: 1448-1461.

Peer-reviewed publication in press

- Bose, A.K., Weiskittel, A., Wagner, R.G., and Kuehne, C. 2016. Assessing the factors influencing natural regeneration patterns in the diverse, multi-cohort, and managed forests of Maine, USA. Journal of Vegetation Science.

Peer-reviewed publication in review

- Kuehne C., Weiskittel A.R., Pommerening A., and Wagner R.G. Temporal and spatial variability in structure and growth for 10 years following commercial thinning in spruce-fir forests of northern Maine, USA. Submitted to Canadian Journal of Forest Research.

Presentation

- Kuehne C., Weiskittel A.R., Pommerening A., and Wagner R.G. 2016. Temporal and spatial variability in stand structure and individual-tree growth for 10 years following commercial thinning in spruce-fir forests of northern Maine. Western Mensurationists Annual Meeting. Stevenson WA, USA.

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