Relative Influence of the Components of Timber Harvest Strategies on Landscape Pattern

Eric J. Gustafson

Abstract: Forest managers seek to produce healthy landscape patterns by implementing harvest strategies that are composed of multiple management components such as cutblock size, rotation length, even-aged or uneven-aged residual stand structure, conversion to plantations, and the spatial dispersion of harvest units. With use of the HARVEST model and neutral landscapes, a factorial simulation experiment was conducted to determine how each management component influenced measures of spatial pattern. There was a significant overall effect of all components on response variables defined by age class and on all but the rotation length component for response variables defined by forest type. Increasing cutblock size, rotation length, and clustering of cutblocks generally reduces measures of age class fragmentation, and increasing the use of even-aged management increases fragmentation. The response of forest type variables was consistently dominated by the component (percent plantation) that changed the abundance of a forest type. Dispersion also had a significant effect because conversions were allocated in space through the dispersion treatment. The results can be used to develop strategies to mitigate negative effects of certain silvicultural activities by showing which other components have opposite effects. Managers can better predict how specific strategy components will contribute to the cumulative landscape pattern. FOR. SCI. 53(5):556–561.

Keywords: timber management, silviculture, clearcutting, even-aged, uneven-aged, landscape pattern, HARVEST simulation model, sustainable forestry

CONSERVATION OF BIODIVERSITY and ecological sustainability are important issues to many forest managers, including those managers concerned primarily with production or economic returns. Silvicultural and other vegetation management practices are widely implemented to produce stand conditions that improve the ecological values within forest stands. However, the spatial pattern of forested landscapes is now recognized as an equally important determinant of ecosystem health and function (Crow and Gustafson 1997). Many forest managers therefore seek to develop and implement management strategies that produce healthy landscape patterns of the forested mosaic. Because the effects of such strategies are evident over broad spatial and temporal scales and are the result of interactions among multiple actions and ecological responses, the development and testing of forest landscape management strategies have proven difficult.

Most forested landscapes are owned by multiple owners, with each having his or her own management objectives. These objectives are usually achieved through the implementation of forest management plans that include specific silvicultural techniques and harvest strategies. These strategies are composed of multiple components such as cutblock size, rotation length, even-aged or uneven-aged residual stand structure, riparian buffers, forest type conversion, and spatial dispersion of harvest units. The cumulative effects of these independently applied silvicultural activities across ownerships determine landscape composition and spatial structure, with consequences for biodiversity and forest productivity (Bettinger and Sessions 2003, Gustafson et al. 2007). The effects on landscape pattern of some of these management strategy components have been studied (e.g., spatial dispersion and size of cutblocks [Li et al. 1993, Gustafson and Crow 1994], adjacency constraints [Gustafson and Rasmussen 2002], and riparian buffers [Hanowski et al. 2002]), but the relative influence of the components on landscape pattern has not been studied comprehensively and systematically. Managers wishing to modify management practices to achieve landscape pattern goals do not know which components of management strategies will most effectively produce the desired results at landscape scales.

Landscape pattern is the result of spatial variation in multiple ecosystem characteristics (e.g., cover type, vegetation vertical structure, and seral stage) that influences the ecological function of a landscape. A large number of metrics have been developed to quantify landscape pattern, but no single metric that completely captures all nuances of landscape pattern has yet been discovered (Gustafson 1998). However, several investigators have identified major components of spatial pattern that collectively quantify the important elements of landscape pattern (e.g., Li and Reynolds 1994, Riitters et al. 1995). This study is focused on general components of landscape pattern as they relate to forest ecosystem functioning, rather than on specific relationships between pattern metrics and ecological response. This approach is similar to that taken by the Montreal Process Working Group (1999) when they identified the

Eric Gustafson, US Forest Service Northern Research Station, 5985 Highway K, Rhinelander, WI 54501—Phone: (715) 362-1152; Fax (715) 362-1166; egustafson@fs.fed.us.

Acknowledgments: Funding was provided through an Agenda 2020 grant from the Northern Research Station. Sue Lietz provided technical support to prepare, conduct, and analyze the simulations. Critical reviews by Brian Palik, Jeremy Wilson, and two anonymous reviewers helped to improve the manuscript.

Manuscript received October 13, 2006, accepted March 2, 2007

seven essential components of the sustainable management of forests and developed indicators that are specifically related to the landscape composition and pattern aspects of ecosystem diversity.

Conducting forest management experiments at landscape scales is nearly impossible because they must be conducted over large areas and long time frames and are difficult to replicate. Simulation models can be used to overcome these difficulties, especially when the processes simulated are well understood. The HARVEST timber harvest simulator (Gustafson and Rasmussen 2002) is well suited to predict the spatial effects of strategic forest management actions (Gustafson 1999). By providing control over timber harvest parameters that represent strategic management components, HARVEST can be used to conduct powerful virtual experiments to provide insight into the relative effects of these components on landscapewide patterns. Experience has shown that conducting such experiments using real landscape patterns are confounded because the initial stand conditions reflect past management actions of the various owners (Gustafson and Loehle 2006), and such patterns can persist for a long time (Wallin et al. 1994). Neutral model landscapes provide an ideal solution to this problem by using algorithms to produce patterns that are neutral (random) relative to all spatial processes except the ones being experimentally manipulated (Gardner et al. 1987, Gustafson and Parker 1992). By generating neutral stand maps that are independent of past management, the response of stand conditions to experimental variation of management components will not be confounded by the initial conditions. The objective of this study was to quantify the relative effects of five components of silvicultural strategies on seven components of spatial pattern of forested landscapes using a simulation model and neutral landscapes.

Methods

The experiment was designed as a fully factorial experiment with the components of silvicultural harvest strategies as the main effects. The silvicultural harvest strategies varied by forest type and were similar to those used by the owners of a Menominee County Michigan landscape studied by Gustafson et al. (2007). The strategies were decomposed into five major components that represent the most significant tools that managers can wield in shaping the spatial pattern of the forest mosaic. The experiment manipulated five main effects (components), with two levels for each main effect (Table 1). The simulation of the components was designed so that the components could be varied independently. The experiment was also designed to hold the intensity of timber harvest (amount of timber removed) as constant as possible among experimental treatments. Therefore, the experimental design does not realistically represent harvest strategies but rather realistic silvicultural components applied independently.

Table 1. Main effects of the fully factorial MANOVA experimental design

Main effect (component)	Levels
Cutblock size (ha)	8, 24 (small, large)
Rotation length (yr)[1]	40, 80 (small, large)
Even-aged (%)[2]	25, 37.5 (low, high)
Plantations (%)[3]	2, 12.5 (low, high)
Spatial dispersion of cutblocks	Random, clustered

[1]This component was applied to even-aged treatments only.
[2]Percentage of landscape maintained as even-aged hardwoods.
[3]Percentage of upland uneven-aged hardwood stands converted to even-aged plantations (pine).

The cutblock size component varied the average cutblock size (Table 1). The rotation length component held the area of land dedicated to harvest constant but varied the length of time between cuttings of stands. Although the short rotation length treatment cuts that land twice as often, the wood volume produced by the long rotation length treatment would be only somewhat reduced by a lower mean annual increment. The rotation length component was applied only to forest types managed by even-aged methods. The percent plantation component varied the amount of the landscape that was maintained in conifer plantations. The "low" treatment maintained existing plantations (2% by area) through all time steps, while additional stands were converted from northern hardwood to plantations over the course of 40 years for the "high" treatment. The percent even-aged component varied the proportion of northern hardwood stands that were harvested using even-aged versus uneven-aged techniques, while holding forest type constant. The Dispersion component varied the spatial dispersion of cutblocks.

The experimental design resulted in 32 unique combinations of main effects, which were replicated three times for a total of 96 model runs. Each combination was simulated for 160 years (two rotations under the longest rotation scenario) using a 10-year time step, producing maps of forest age and forest type at each time step.

The experiment was conducted using a timber harvest simulation model HARVEST version 6.1 (Gustafson and Rasmussen 2005). HARVEST is a rule-based stochastic model that simulates the timber management of forested landscapes by applying silvicultural techniques to maps of forest mosaics. The silvicultural techniques applied can vary among forest types and spatial units (e.g., ownership blocks). The model mimics the process of selecting stands for silvicultural treatment in space and time, and these treatments change either stand age, forest type, or both, depending on the silvicultural technique or process (e.g., type conversion) being simulated. Silvicultural techniques are targeted to specific forest types and are specified by several parameters: cutblock size, stand age constraints, rotation length, spatial dispersion of cutblocks, effect of cutting on stand age and forest type, adjacency constraints, and total area to be cut. Stands are stochastically selected and harvested to satisfy the criteria of the parameters. With HARVEST, the object is not to find a scheduling solution (i.e., determining the sequence of harvest activities to optimize the achievement of a specific objective), but to predict the expected spatial pattern of the forest mosaic under a specific management strategy. It has been verified that HARVEST can mimic patterns produced by past timber management activity (Gustafson and Crow 1999).

To allow comparisons with earlier related studies, the forest composition and harvest regimes of Gustafson et al.

(2007) and the neutral forest stand map of Gustafson and Loehle (2006) was used. The extent of the neutral landscape was 73,728 ha. The neutral stand map was generated by dividing the landscape into square, 4-ha stands. The forest type and age of each stand was probabilistically assigned based on the distribution of forest types and stand ages found on US Forest Service Forest Inventory and Analysis (FIA) plots ($n = 218$) within the Watson Till/Wetland Complex Land Type Association of upper Michigan, which includes the study area used in Gustafson et al. (2007). For each stand, an FIA plot was randomly selected (with replacement), and the stand was assigned to the dominant forest type and age found on that plot. Forest types used were northern hardwood, aspen (*Populus tremuloides* Michx.), upland softwood, red pine (*Pinus resinosa* Ait.) plantations, lowland conifer, white cedar (*Thuja occidentalis* L.), lowland hardwood, and eastern hemlock (*Tsuga canadensis* L.). The neutral stand map had the essential property of having a spatial pattern that was not confounded by past disturbance, landform, or management legacies. In this study the landscape was not subdivided into multiple ownerships, so the entire landscape was simulated as a single ownership. All input maps were gridded to a cell size of 33.3 m, which is divisible into the 200-m width of the 4-ha stands and approximates the 30-m resolution used in Gustafson et al. (2007).

Response variables were spatial pattern indices chosen to represent the major components of landscape pattern (Riitters et al. 1995) and indices relevant to forest sustainability as defined by the Montreal Process (Table 2). The indices were calculated using the analytical functions of HARVEST and APACK (Mladenoff and DeZonia 2004). Forest type classes were analyzed directly from the forest type output maps generated by HARVEST. Age class maps for analysis were produced by recoding the age maps into five age classes (1–15, 16–30, 31–55, 56–70, and >70 years) and an uneven-aged class consisting of all northern hardwood or hemlock cells with an age >70 years, and all upland softwood cells >60 years of age. These types tend to develop an uneven age structure by age 70 when actively managed. Response variables were calculated by forest type and by age class for each 10-year time step. An eight-neighbor rule was used to delineate habitat patches, where cells adjacent on either an edge or a diagonal are part of the patch.

The results of the experiment were analyzed using multivariate analysis of variance (MANOVA) models, which allow for global hypothesis tests of factor effects for multiple dependent variables (Johnson and Wichern 1992). The mean values (over 16 time steps) of seven response variables were calculated for both age class and forest type, and the main effects were the five components. The MANOVA models used the error SSCP (residual) matrix, and the results were evaluated using type III sums of squares. The relative influence of each main effect was assessed by comparing the percentage of the total sums of squares explained by each effect. Significance was assessed conservatively with $\alpha = 0.01$ because statistical noise was expected to be low in such a tightly controlled experiment.

Results

The MANOVA global tests of hypotheses indicated that there was a significant overall effect (exact F test) of all main effects (components) on response variables defined by age class (Table 3), and all but the rotation length main effect for response variables defined by forest type (Table 4). The components explained differing amounts of the variation in response variables, depending on the response variable, and for all but one response variable (age-contagion) there was a clearly dominant component.

The response of the age class variables (Table 3) suggests that the spatial characteristics of residual patches (patches surrounding a cutblock) determine the influence of the main effects, rather than the cutblocks themselves. For example, the patch size of age classes was most influenced by dispersion, with clustered dispersion resulting in larger patches, whereas the variation explained by cutblock size was an order of magnitude smaller. Cutblock size had the dominant effect only on edge density, with smaller cutblocks producing more edge than larger ones. The response of distance to edge was determined primarily by rotation length and the amount of even-aged cutting (percent plantation and percent even-aged). These variables determine the number of harvest openings created in a time step, which greatly affects distance to edge. The contagion index had a weak response to the main effects ($R^2 = 0.29$). Contagion is a pixel-level index (image texture), and the experimental treatments had relatively little effect at that scale. Age class diversity was affected only by rotation length, with the 80-year rotation briefly producing uneven-aged conditions in stands. These conditions developed by a somewhat arbitrary rule in the classification of age classes for northern hardwood. In real forests, where uneven-aged conditions do not develop within the rotation interval, this effect on age diversity would not be observed. The signs given in Table 3 show that increasing cutblock size, rotation length, and clustering of cutblocks generally reduce measures of fragmentation (Table 2), and increasing the use of even-aged

Table 2. Response variables

Variable	Attribute quantified	Increasing values mean	Reference
Mean perimeter-area ratio	Average patch compaction, patch shape	More irregular patch shape	Riitters et al. 1995
Contagion	Image texture	More clumped	Riitters et al. 1995
Fractal dimension	Perimeter-area scaling	Broader array of shapes	Riitters et al. 1995
Mean distance to edge	Forest fragmentation	Less fragmented	Ripple et al. 1991
Edge density	Habitat fragmentation	More fragmented	McGarigal and Marks 1995
Mean patch size	Habitat fragmentation	Less fragmented	McGarigal and Marks 1995
Shannon-Weaver diversity	Cover type diversity	More diverse	Shannon and Weaver 1949

Table 3. Relative influence of the main effects on the mean (through time) of the response variables as defined by forest age class

Response variable	Main effect					R^2
	Cutblock size	Rotation length	% plantation	% even-aged	Spatial dispersion	
Mean perimeter-area ratio	0.6	**10.52 (−)**	**1.40 (−)**	0.03	**77.66 (+)**	0.90
Contagion	0.76	**14.68 (+)**	**12.08 (+)**	0.81	**0.26**	0.29
Fractal dimension	**15.56 (−)**	**17.07 (−)**	**3.28 (+)**	0.17	**48.44 (+)**	0.84
Mean distance to edge	**0.60 (+)**	**68.98 (+)**	**11.60 (−)**	**13.39 (−)**	**4.12 (+)**	0.99
Edge density	**37.88 (−)**	**13.20 (−)**	**3.90 (+)**	**5.65 (+)**	**10.63 (−)**	0.71
Mean patch size	**6.60 (+)**	1.82	0.51	1.33	**63.46 (+)**	0.74
Shannon-Weaver diversity	0.00	52.33 (+)	0.52	0.36	0.00	0.53
Exact *F* for overall effect[1]	**68.48**	**2260.63**	**496.47**	**451.54**	**518.75**	—

Values are the percentage of the total MANOVA type 3 sums of squares explained by each main effect, with significant values ($\alpha = 0.01$) shown in bold. The sign of the relationship between the response variable and the main effect is given in parentheses, with spatial dispersion represented as the degree of clustering of cutblocks (none, some).
[1] Wilks' λ exact *F* test.

Table 4. Relative influence of the main effects on the mean (through time) of the response variables as defined by forest type

Response variable	Main effect					R^2
	Cutblock size	Rotation length	% plantation	% even-aged	Spatial dispersion	
Mean perimeter-area ratio	0.01	0.00	**81.78 (−)**	0.00	8.89 (+)	0.91
Contagion	0.00	0.00	**99.85 (−)**	0.00	0.06 (+)	1.00
Fractal dimension	0.39	0.22	**86.55 (−)**	1.07 (−)	1.64 (+)	0.90
Edge density	0.12	0.04	**86.57 (+)**	0.43	4.98 (−)	0.92
Mean patch size	0.03	0.00	**88.81 (−)**	0.06	5.23 (+)	0.94
Shannon-Weaver diversity	0.00	0.00	**100.00 (+)**	0.00	0.00	1.00
Exact *F* for overall effect[1]	**3.48**	0.81	**Infinity**	**8.26**	**16.66**	—

The mean distance to edge response variable was omitted because it is unaffected by forest type conversions. Values are the percentage of the total MANOVA type 3 sums of squares explained by each main effect, with significant values ($\alpha = 0.01$) shown in bold. The sign of the relationship between the response variable and the main effect is given in parentheses, with spatial dispersion represented as the degree of clustering of cutblocks (none, some).
[1]Wilks' λ exact *F* test.

management (percent plantations and percent even-aged) increases fragmentation.

In contrast to the response of the age class variables, the response of forest type variables was consistently dominated by the same treatment (percent plantation, Table 3) because it was the only treatment that changed the abundance of a forest type. Dispersion also had a significant effect because conversions were allocated in space through the dispersion treatment. Conversion of type makes the forest type mosaic more fragmented and composed of simpler shapes (Table 2) but increases type diversity. The significant response of fractal dimension of forest type to the percent even-aged treatment was caused by an interaction with percent plantation. Both treatments were applied to uneven-aged northern hardwood stands, and there was a stochastic competition for such stands when both treatments were at their high levels.

Discussion

A key strength of this study is that it discovers general, first principles relating components of silvicultural strategies to landscape pattern. The initial landscape was free of confounding spatial legacies and dependencies. The experiment was designed to meet the assumptions of the analytical technique. However, for these reasons, the landscapes studied in this experiment were not realistic, in that the spatial dependencies and historical legacies found in real landscapes were explicitly excluded to avoid confounding the experiment. These features are important to keep in mind when the results are interpreted. There are also some limitations of the study. Each component was made as independent of the others as possible, but this process was not always straightforward. The specific treatment levels were not the only ones possible. The potentially confounding factor that was most difficult to control was timber output. HARVEST tracks only harvested area and not timber volume. Although the treatments were designed to keep timber output relatively constant, this was not explicitly modeled, and it is possible that the timber output of some components may vary significantly.

The results show that each management component (cutblock size, rotation length, even-aged or uneven-aged stand structure, conversion to plantations, and the spatial dispersion of harvest units) has a significant effect on some aspect of the spatial pattern of the mosaic of age classes. Of these, spatial dispersion and rotation length are consistently important. Clustering of harvest activities has been advocated as a means to reduce fragmentation, and these results dramatically illustrate the relative power of such a simple and cost-effective technique. Several authors have advocated lengthening rotation intervals as a means to increase age class diversity and improve ecological indicators (e.g., Busing and Garman 2002). The results of this study lend support to this recommendation by showing that it has a relatively powerful effect on forest pattern. Cutblock size was the most important component determining the response of edge density. A related component that was not studied is cutblock shape. In this study, cutblocks always took relatively simple angular shapes, being composed of either two or six adjacent 4-ha square stands. Edge density in real landscapes is also closely related to cutblock shape, with irregular shapes increasing linear edge.

Increasing cutblock size is known to reduce fragmentation of the age class mosaic by reducing the number of cutblocks needed to achieve timber volume objectives (Li et al. 1993, Gustafson and Crow 1994). The results of this study indicate that other factors such as rotation length and spatial dispersion have an even greater effect. Spatially aggregating harvests has been shown to reduce fragmentation in other studies (Li et al. 1993, Gustafson and Rasmussen 2002). The results of this study indicate that, for most age class variables, dispersion is the most important factor and, for forest type variables, it critically determines the magnitude of the effect of silvicultural type conversions (plantations).

The experiment did not incorporate management constraints such as road networks, access limitations, reserves, or unique environmental conditions to avoid confounding the experiment. However, such factors do constrain the ability of managers to achieve their landscape objectives. Furthermore, real landscapes have legacies of past management and natural disturbances that may have a profound impact on the effectiveness of management options. Nevertheless, this study can provide managers with insight into which management components are the most likely to help achieve generic landscape pattern objectives. As such, they provide generic guidance to managers considering various management options for achieving landscape goals, but must be applied within the context of the specific land base and management situation.

These results can be used to develop strategies to mitigate negative effects of certain silvicultural activities. For example, a manager wishing to increase the area of plantations while minimizing forest fragmentation might cluster the plantations and increase the rotation length. Table 3 suggests that even a modest increase in rotation length may significantly increase mean distance from edge. As another example, a manager wishing to control edge density as a wildlife management tool should focus first on cutblock size. The results of this study can also inform policy strategies. For example, it is clear from multiple studies (e.g., Li et al. 1993, Gustafson and Crow 1994) that increased cutblock size reduces fragmentation. However, the political capital required to gain public acceptance of such a policy change would be high, and this study suggests that the effectiveness of such a change may not be worth the political investment. It may be more expedient to focus on clustering harvests and extending rotation lengths.

These results may also be useful to understand the contribution of multiple owners to the overall landscape pattern produced by their combined actions. As an example, the results of a prior study were examined in light of this study. In Gustafson et al. (2007) our objective was to predict the cumulative effects of multiple owners with different management objectives on the overall landscape pattern. We used HARVEST to simulate the harvest strategies of four real owners (including a generic nonindustrial private forestland owner) on a real 68,000-ha landscape in Menominee County Michigan. Over 100 years, the trend for the size of uneven-aged patches was essentially flat, whereas the average size of patches of the oldest and youngest age classes increased and the size of patches of the remaining age classes decreased. When we completed that study, we wondered how each owner's actions contributed to the overall pattern. The present study suggests that the trends we found were related to cutblock size and spatial dispersion of cuts as it affected residual patches. Cutblocks followed existing stand boundaries for all owners, and the mean stand size of nonindustrial private forestland stands was substantially smaller than that of other owners. One industrial owner practiced some clustering of harvests. Additionally, in the real-landscape forest, fragmentation generally declined, but edge density of age classes increased. Similarly, the present results suggest a link between fragmentation and rotation length and the amount of even-aged and plantation management. Private and state owners control 56% of the Menominee County land base, and they generally have longer rotations than industrial owners, with 40% of private owners not cutting timber at all. Three of the four owners use little even-age and plantation silviculture. Given that the majority of the land is managed using silvicultural components that reduce fragmentation, it is not surprising that the entire landscape is predicted to have less fragmentation in the future. It is important to note that the habitat diversity in the Menominee County landscape was enhanced by the activities of the owner that contributed the most to fragmentation. This suggests that landscape diversity and sustainability may require a diversity of management strategies applied across the landscape. The results of the present study can help landscape managers better predict how each strategy (with its constituent components) will contribute to the cumulative landscape pattern.

Literature Cited

BETTINGER P, AND J. SESSIONS. 2003. Spatial forest planning—To adopt, or not to adopt? *J. For.* 101(2):24–29.

BUSING, R.T., AND S.L. GARMAN. 2002. Promoting old-growth characteristics and long-term wood production in Douglas-fir forests. *For. Ecol. Manag.* 160:161–175.

CROW, T.R., AND E.J. GUSTAFSON. 1997. Concepts and methods of ecosystem management: Lessons from landscape ecology. P. 54–67 in *Ecosystem management: Applications for sustainable forest and wildlife resources*, Boyce, M.S., and A. Haney (eds.). Yale University Press, New Haven, CT.

GARDNER, R.H., B.T MILNE., M.G. TURNER, AND R.V. O'NEILL. 1987. Neutral models for the analysis of broad-scale landscape pattern. *Landsc. Ecol.* 1:19–28.

GUSTAFSON, E.J. 1998. Quantifying landscape spatial pattern: What is the state of the art? *Ecosystems* 1:143–156.

GUSTAFSON, E.J. 1999. HARVEST: A timber harvest allocation model for simulating management alternatives. P. 109–124 in *Landscape ecological analysis: Issues and applications*, Klopatek, J., and R.H. Gardner (eds.). Springer-Verlag, New York, NY.

GUSTAFSON, E.J., AND T.R. CROW. 1994. Modeling the effects of forest harvesting on landscape structure and the spatial distribution of cowbird brood parasitism. *Landsc. Ecol.* 9:237–248.

GUSTAFSON, E.J., AND T.R. CROW. 1999. HARVEST: Linking timber harvest strategies to landscape patterns. P. 309–332 in

Spatial modeling of forest landscapes: Approaches and applications, Mladenoff, D.J., and W.L. Baker (eds.). Cambridge University Press, Cambridge, UK.

GUSTAFSON, E.J., AND C. LOEHLE. 2006. Effects of parcelization and land divestiture on forest sustainability in industrial forest landscapes. *For. Ecol. Manag.* 236:305–314.

GUSTAFSON, E.J., D.E. LYTLE., R. SWATY, AND C. LOEHLE. 2007. Simulating the cumulative effects of multiple forest management strategies on landscape pattern and biodiversity. *Landsc. Ecol.* 22:141–156.

GUSTAFSON, E.J., AND G.R. PARKER. 1992. Relationships between landcover proportion and indices of landscape spatial pattern. *Landsc. Ecol.* 7:101–110.

GUSTAFSON, E.J., AND L.V. RASMUSSEN. 2002. Assessing the spatial implications of interactions among strategic forest management options using a Windows-based harvest simulator. *Comput. Electron. Agr.* 33:179–196.

GUSTAFSON, E.J., AND L.V. RASMUSSEN. 2005. *HARVEST version 61 user's guide.* Available online at www.nrs.fs.fed.us/tools/harvest/Harv61_user.pdf; last accessed Jun. 22, 2007.

HANOWSKI, J.M., P.T. WOLTER., AND G.J. NIEMI. 2002. Effects of prescriptive riparian buffers on landscape characteristics in northern Minnesota, USA. *J. Am. Water Res. Assoc.* 38:633–639.

JOHNSON, R.A., AND D.W. WICHERN. 1992. *Applied multivariate statistical analysis.* Prentice Hall, Englewood Cliffs, NJ. 642 p.

LI, H., J.F. FRANKLIN, F.J. SWANSON, AND T.A. SPIES. 1993. Developing alternative forest cutting patterns: A simulation approach. *Landsc. Ecol.* 8:63–75.

LI, H., AND J.F. REYNOLDS. 1994. A simulation experiment to quantify spatial heterogeneity in categorical maps. *Ecology* 75:2446–2455.

MCGARIGAL, K., AND B.J. MARKS. 1995. *FRAGSTATS: Spatial pattern analysis program for quantifying landscape structure.* US For. Serv. Gen. Tech. Rep. PNW-GTR-351. 122 p.

MLADENOFF, D.J. AND B. DEZONIA 2004. *APACK 2.23 Analysis software: User's guide*. Available online at landscape.forest.wisc.edu/projects/apack/apack.html; last accessed June 21, 2007.

MONTREAL PROCESS WORKING GROUP. 1999. *The Montreal Process*. Available online at www.mpci.org/rep-pub/1999/ci_e.html; last accessed Jun. 21, 2007.

RIITTERS, K., R.V. O'NEILL, C.T. HUNSAKER, J.D. WICKHAM, D.H. YANKEE, S.P. TIMMINS, K.B. JONES, AND B.L. JACKSON. 1995. A factor analysis of landscape pattern and structure metrics. *Landsc. Ecol.* 10:23–39.

RIPPLE, W.J., G.A. BRADSHAW., AND T.A. SPIES. 1991. Measuring landscape pattern in the Cascade Range of Oregon, USA. *Biol. Conserv.* 57:73–88.

SHANNON, C., AND W. WEAVER. 1949. *The mathematical theory of communication.* University of Illinois Press, Urbana, IL.

WALLIN, D.O., F.J. SWANSON., AND B. MARKS. 1994. Landscape pattern response to changes in pattern generation rules: Land-use legacies in forestry. *Ecol. Appl.* 4:569–580.