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Effects of parcelization and land divestiture on forest sustainability in simulated forest landscapes

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Abstract

Ownership parcelization of forest land and divestiture of industrial forest land is increasing throughout the U.S. This may affect (positively or negatively) the ability of forested landscapes to produce benefits that society values, such as fiber, biodiversity and recreation. We used a timber harvest simulator and neutral model landscapes to systematically study how parcelization and divestiture affect measures of forest composition and fragmentation, timber production and public access. We studied parcelization effects by systematically varying the probability that ownerships would be parcelized at three different spatial scales (9216, 256, 16 ha). We found that parcelization of industrial landscapes significantly increased most measures of forest fragmentation, but did not affect measures of forest composition. Parcelization did not reduce the volume of wood extracted or the area of land available for public recreation, but it did reduce the patch size of land open for recreational use. We studied divestiture effects by systematically varying the proportions of two industrial owners with concurrent changes in the proportion of non-industrial private forest owners (NIPF). We also simulated conversion of NIPF forest land to developed uses. The effect of divestiture depends on which owner is divesting, with the owner that has the most unique effect on a given response variable having the greatest influence. The industrial owner that emphasized even-aged silvicultural techniques had the greatest effect on age class characteristics. The industrial owner that practiced some conversion of other forest types to northern hardwood influenced some cover type characteristics. The proportion of NIPF had the greatest effect on the temporal trend of fragmentation because of conversion of some forest to developed uses. Divestiture of industrial land caused up to a 55% reduction in the volume of wood extracted and reduced the area and patch size of land available for public recreation.
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1. Introduction

Most forested landscapes are owned by multiple owners, each having their own objectives, resulting in a mosaic of management activities (including no management) distributed across the landscape. The cumulative effects of these (usually uncoordinated) activities determine landscape composition and spatial structure, with consequences for biodiversity and forest productivity (Gustafson et al., in press). Most industrial and public land owners have committed themselves to sustaining multiple forest land values, including forest productivity, biodiversity and recreation. Non-industrial private forest land owners have a variety of reasons for owning land, resulting in activities ranging from no management to heavy exploitation of timber to conversion to other land uses (Butler and Leatherberry, 2004).

Ownership parcelization of forest land is increasing throughout the U.S. (Mehmood and Zhang, 2001). Parcelization results when tracts are divided among heirs or are subdivided for economic gain. This trend is also evident in landscapes where timber production has traditionally been the dominant land use, likely because non-timber value exceeds timber value on certain tracts (Zhang et al., 2005). The owners of newly created parcels often have different objectives for owning land than those of the prior owner of the larger tract, and the management (or non-management) practices of the new owners may cumulatively create changes in the landscape mosaic. These changes may affect the ability (positively or negatively) of such landscapes to produce benefits that society values, such as fiber, recreation, biodiversity, and clean water (Brooks, 2003; Alig, 2005; Kline and Alig, 2005).

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There is also an accelerating trend of divestiture of forest lands by forest products companies (e.g., paper companies). For example, in Maine 70% of industrial forest lands have been sold over the past 20 years (Hagan et al., 2005). The upper Michigan industrial lands examined in the case study by Gustafson et al. (in press) have changed hands three times through merger and divestiture (Escanaba Timber) or been placed on the market (International Paper) since 2002. Most divested industry land will be sold to Timber Investment Management Organizations (TIMOs) or similar organizations and managed for timber. However, some of the divested land will be sold to non-industrial private forest (NIPF) owners, and other sites will be converted to residential (permanent or seasonal) or recreational (ski resorts, golf courses) uses. Approximately half of NIPF owners do not harvest any trees on their land (National Woodland Owners Survey, B. Butler, personal communication) for reasons that include recreation, aesthetic preference and preserving potential second home sites (Zhang et al., 2005). Some of these owners use the land for hunting and personal recreation and do not allow public access. Consequently, the transfer of industrial land to non-industrial owners will reduce public access to forested lands, reduce timber output and result in the creation of some permanent openings that will fragment the forest. While considerable attention has been paid to urbanization and other land use changes (e.g., Brown et al., 2005), effects of changing ownership patterns are not well studied.

Little research has been conducted to understand how the varying management objectives and strategies of multiple land owners interact to produce landscape patterns (Bettinger and Sessions, 2003; Polasky et al., 2005; Gustafson et al., in press). Furthermore, it has been difficult to predict the effects of these interacting objectives on biodiversity and ecosystem sustainability. The HARVEST timber harvest simulator (Gustafson and Rasmussen, 2002) is well suited to predict the cumulative effects of multiple owner actions on forest spatial pattern (Gustafson and Crow, 1999). Because HARVEST targets management strategies to mapped spatial zones, it can readily simulate the strategies of multiple owners on alternative ownership patterns. By providing researchers control over timber harvest parameters that represent strategic management objectives, HARVEST can be used to conduct virtual experiments to provide insight into the interaction of the actions of multiple forest land owners to produce landscape-wide patterns. Included in the output of HARVEST are maps of future forest age and composition, which can be used to calculate measures of forest fragmentation and landscape pattern. Tabular output of area harvested by forest type can be used to estimate timber production.

Although HARVEST is well-suited to studying the effects of experimentally varied patterns of ownership, using the stand conditions of real landscapes would confound such an experiment because the underlying stand conditions were determined by the actions of the existing owners. Neutral model landscapes provide an ideal solution to this problem by producing randomly generated patterns that are neutral to all spatial processes except the one being experimentally manipulated (Gardner et al., 1987; Gustafson and Parker, 1992), which in this case is ownership pattern. For example, in a neutral stand map, forest types and age classes are assigned randomly while in the real world forest types and age classes are often the result of owner activities. By generating neutral stand maps that are independent of ownership, the response of stand conditions to experimental variation of ownership patterns will not be confounded by the initial stand conditions.

Sustainable forestry is the stated goal of most forest managers, but quantifying the characteristics of sustainably managed forests is difficult. The Montreal Process Working Group is a seven-nation collaborative working to advance the development of internationally agreed-upon criteria and indicators for the conservation and sustainable management of temperate and boreal forests at the national level (Montreal Process Working Group, 1999). The seven criteria identified in the Montreal Process are the essential components of the sustainable management of forests, including biodiversity, forest productivity and recreational access. This study focuses on a subset of Montreal Process indicators that is specifically related to the landscape composition and pattern aspects of ecosystem diversity, forest productivity and recreation.

The objective of our study was to systematically evaluate effects of parcelization and divestiture in industrial landscapes on measures of forest composition and fragmentation, timber production and public access. Our approach was to: (1) generate a single neutral map of initial stand conditions to use as input for all simulations, (2) generate replicated neutral ownership maps with different levels of parcelization and divestiture of ownership, (3) use HARVEST to simulate the management activities of all owners under experimentally varied levels of parcelization and divestiture and (4) assess how parcelization and divestiture affect specific Montreal Process indicators. These factorial landscape experiments allow discovery of the fundamental relationship between the main effects (parcelization and divestiture) and indicators of forest sustainability.

2. Methods

2.1. Neutral ownership and stand maps

The extent of the neutral (random) landscape was eight townships (totaling 73,728 ha) arranged in a grid of two rows and four columns. This configuration was chosen to allow comparisons with the results of an earlier study of an industrial landscape in Menominee County, MI, USA (Gustafson et al., in press). As in that study, we consider two separate paper industry (IND) owners, a public land management agency (PUB) and a generic non-industrial private forest (NIPF) land owner.

We wrote a program to hierarchically assign ownership at spatial scales corresponding to townships (9216 ha), sections (256 ha) and forties (16 ha). These spatial entities are based on the Public Land Survey, which was used to subdivide land prior to settlement in the 19th century. Townships have a square shape, and are divided into 36 square sections, which have commonly become subdivided into 16 forty-acre (16 ha) parcels (thus being called forties). First, the ownership of each

Table 1
Experimentally manipulated values of p and proportion of the study area held by each owner type (Where a range is indicated, intermediate values were multiples of 0.125)

Variable	Parcelization experiment	Divestiture experiment
p	0.0, 0.25, 0.5, 0.75	0.25
Proportion of IND1	0.25	0.0–0.25
Proportion of IND2	0.125	0.0–0.25
Proportion of PUB	0.125	0.125
Proportion of NIPF	0.5	0.375–0.875

township (O_t) was randomly assigned to one of the four owner categories based on an approximation of the proportion of owners in the Menominee Co. study area (Table 1). Second, section ownership was assigned. The ownership of sections within each township (O_s) was initially equal to O_t, but individual sections were reassigned to an owner other than O_t with probability p (probability of parcelization). For each section, a uniform random deviate was compared to p, and if the deviate was $<p$, an owner other than O_t (O'_s) was assigned according to the cumulative probability distribution of the remaining three owners. To preserve the original proportion of owners, a section in a township owned by O'_s was then randomly chosen and assigned to owner O_s. Finally, this process was repeated to assign ownership to all forties (O_f), with the assignment of O_f being dependent on O_s and p. When the assigned owner was NIPF, the forty was assigned to either a 'managed' (probability = 0.6) or 'unmanaged' NIPF class (probability = 0.4). We did not simulate the creation of parcels smaller than 16 ha, which is consistent with the parcelization of industrial forest landscapes.

Neutral forest stand maps were generated by dividing each forty into four, 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 USDA Forest Service Forest Inventory and Analysis (FIA) plots (n = 218) within the Watson Till/Wetland Complex LTA, which includes the study area used in Gustafson et al. (in press). For each stand, we randomly selected (with replacement) an FIA plot and assigned the stand to the dominant forest type and age found on that plot. Forest types used were northern hardwood, aspen (*Populus* spp.), upland softwood, red pine (*Pinus resinosa*) plantations, lowland conifer, white cedar (*Thuja occidentalis*), lowland hardwood and eastern hemlock (*Tsuga canadensis*). Ownership and stand maps were gridded to a cell size of 110 feet (33.53 m), which is compatible with the width of the 4 ha stands and approximates the 30 m resolution used in Gustafson et al. (in press).

2.2. Simulation of owner strategies

We simulated the management objectives of the four owners using a timber harvest simulation model (HARVEST v6.1, 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, stand type, or both, depending on the silvicultural technique or process (e.g., type conversion) being simulated. We used the owner-specific management parameters used by Gustafson et al. (in press) to allow our results to be compared to those obtained on a real, intensively managed landscape. These parameters reflect the silvicultural systems used, the cutting intensity, rotation interval and so forth of each owner for each forest type, and they were held constant among experimental treatments. One industrial owner (IND1) managed primarily for softwoods using even-aged methods while the other (IND2) managed primarily for hardwoods using uneven-aged methods. The PUB owner managed using a mix of even- and uneven-aged methods. 'Managed' NIPF land was simulated using a generic timber objective that represents 'typical' management practices on NIPF land in Menominee Co., and no timber cutting was simulated on the 'unmanaged' NIPF land. Based on input from local silviculturists, the simulations also included two deterministic succession processes in uncut stands on all ownerships, where aspen >100 years converted to 30-year-old northern hardwood and upland softwood >75 years reverted to 60 year upland softwood to reflect the senescence of the oldest cohort. For each experiment described below we simulated the timber cutting practices of all owners for 100 years using a 5-year time step, producing maps of forest age and forest type at each time step.

2.3. Ownership parcelization experiment

We evaluated four levels of ownership parcelization (i.e., fragmentation of ownership) by generating maps using values of p = 0.0 (no parcelization), 0.25, 0.5 and 0.75 (Table 1). Six replicates of each level of p were generated (e.g., Fig. 1), and a single random number seed was used for all runs of HARVEST so that only the ownership map varied among replicates and levels of p.

2.4. Industrial owner divestiture experiment

To determine the effect of divestiture of land by industrial owners we systematically varied the proportion of land in the input maps owned by industrial owners and NIPF owners, while holding p = 0.25. This value was chosen because it produced ownership patterns similar to those of the real landscape used by Gustafson et al. (in press). Because the industrial owners have different management strategies, the landscape effects of divestiture may depend on which owner is divesting. We therefore varied the proportion of the study area owned by each of the two industrial owners between 0.0 and 0.25 in increments of 0.125 (Table 1) to produce a balanced design (n = 9) (Fig. 2). We held the proportion of PUB constant (0.125) so that NIPF ownership increased when the combined industrial ownership decreased, reflecting an assumption that land divested by industrial owners will not be purchased by a public agency. Because some land that is divested by industry may be developed

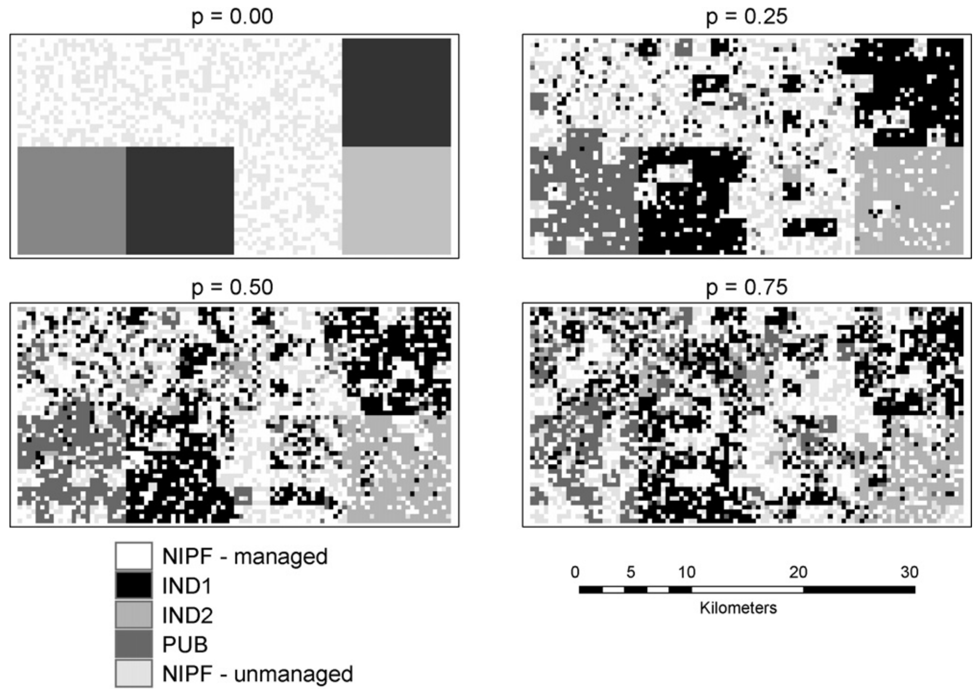

Fig. 1. One set of neutral parcelization maps. The maps were generated using a common random number sequence, varying only *p*. Five other replicate sets were also used in the study.

for a non-forested use, we simulated a permanent conversion of 3.67% per decade of NIPF forested land to a non-forest developed use (Stein et al., 2005) in 5 acre patches. This conversion is not expected to be spatially random, but is often associated with existing developments and road networks (Zhang and Nagubadi, 2005). Because our hypothetical maps did not include roads or settlements, we used the 'clustered' dispersion method in HARVEST to simulate the non-random pattern of

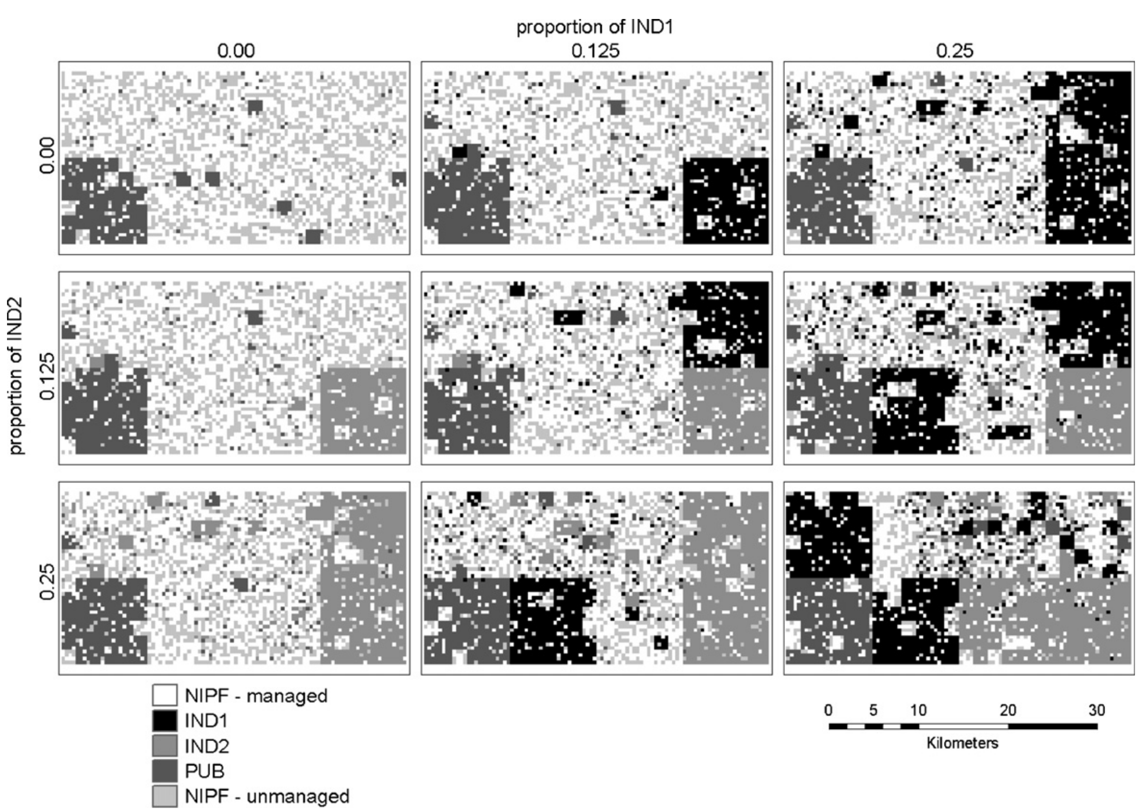

Fig. 2. One set of neutral divestiture maps. The maps were generated using a common random number sequence, varying only the proportion of each owner type. Five other replicate sets were also used in the study.

conversion to developed land uses, and converted only upland forest types (upland softwood, aspen, pine and northern hardwood).

2.5. Analysis of simulation results

Response variables were chosen based on selected indicators identified by the Montreal Process (Montreal Process Working Group, 1999). We focused on indicators of ecosystem diversity (Criterion 1.1), the productive capacity of ecosystems (Criterion 2) and recreation and tourism (Criterion 6.2). To test for the effects of ownership parcelization we regressed the mean (over 20 time steps) of response variables (described below) against p, and tested the hypotheses that indicators of forest fragmentation would increase as p increased, that forest composition would be unaffected by p, and that indicators of productive capacity and recreational access would decrease as p increased. To calibrate our results to those from a similar, real landscape, we compared response variables for the $p = 0.25$ case with those from the Menominee landscape (Gustafson et al., in press). The management of the real landscape was simulated using the same owner management parameters used in this study, but the input maps were actual ownership and stand characteristics rather than simulated ones. We analyzed the results of the divestiture experiment using two MANOVA models, which allow for global hypothesis tests of factor effects for multiple dependent variables (Johnson and Wichern, 1992). The MANOVA models used the error SSCP (residual) matrix, and the results were evaluated using Type III sums of squares. With one model we tested for spatial effects using mean (over 20 time steps) values of response variables and in the second we tested for temporal effects using the slopes of temporal trends of response variables. The classification variables were the proportion of the study area owned by each industrial owner (IND1 and IND2). Because some variables are affected primarily by the abundance of NIPF, we also estimated the variability explained solely by NIPF. This was done in a separate MANOVA analysis because NIPF and (IND1 + IND2) are deterministically related. We hypothesized that the divestiture of IND1 land would have a greater effect on the response variables than the divestiture of IND2 land because the IND1 management practices are the most different from NIPF practices.

2.6. Response variables

Response variables relevant to Montreal Process indicators were calculated using the analytical functions of HARVEST and APACK (Mladenoff and DeZonia, 2004). Indicators were calculated by forest type and by age class. 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 map into five age classes (1–15, 16–30, 31–55, 56–70, >70 years) and an uneven-aged class consisting of all northern hardwood, aspen or hemlock cells with an age >70 years, and all upland softwood cells >60 years of age. Criterion 1 (ecosystem diversity) indicators were landscape proportion of classes and measures of forest fragmentation (mean patch size, overall edge density, contagion, area of forest interior habitat (forest >150 m from an opening (age <20 years) or non-forest edge, and forest edge habitat (all non-interior forest)). Edge density is the cumulative length of edges between cells of different classes per unit area (Mladenoff and DeZonia, 2004). Contagion is an index of the likelihood that a cell is adjacent to a cell of the same class (Li and Reynolds, 1993), with higher values representing more clumped spatial distributions. Criterion 2 (productivity) indicators were the area of intensively cultured stands (all of the aspen, European larch and red pine) and wood volume extracted. HARVEST records the number of acres harvested by each owner and forest type, which we combined with yield information to estimate wood volume produced across the landscape at each time step. Because yield tables from upper Michigan were not available, we used data from Wisconsin (Hahn and Stelman, 1989). The yield tables give the cubic foot volume of all merchantable trees (by forest type) in 10-year age classes based on state-wide inventory data. Because European larch yield tables were not available, we used red pine yield data because these species have similar growth rates. Linear interpolation was used for ages between the 10-year increments. Because partial harvests were simulated by lowering the age of a stand (where age is a surrogate for stand development, Gustafson et al., in press), we calculated the wood volume extracted as the proportion of the merchantable volume removed by a partial cut. For example, if owners described a partial harvest of northern hardwood as analogous to returning a 70-year-old stand to a 55-year-old condition, we "harvested" a percentage of the yield based on this age difference. If Y is yield per acre, this example would give $Y(70 - 15)/70$, which is then multiplied by the number of acres of northern hardwood harvested. In one case (IND1 cedar), the partial cut removed all the cedar, leaving a lowland conifer stand without changing the age. In this case, we assumed that 60% of the volume was removed. Criterion 6 (recreation and tourism) indicators were total area and mean patch size of land in public or industrial ownership, which are measures of land open to the public for recreation. We used an eight-neighbor rule to delineate habitat patches, where cells adjacent on either an edge or a diagonal are part of the patch. We used a four-neighbor rule for ownership patches, which assumes that cells touching only on the diagonal are not effectively connected for recreational purposes.

3. Results

3.1. Parcelization experiment

The relationship between most response variables and ownership parcelization (p) was consistent with our hypotheses. We hypothesized that forest composition would be unaffected by p. Forest composition (defined either by age class or forest type) was not significantly related to p ($\alpha = 0.01$) for any age class or forest type. We hypothesized that indicators of forest fragmentation would increase with p. Decreasing patch size indicates increased fragmentation, and patch size did

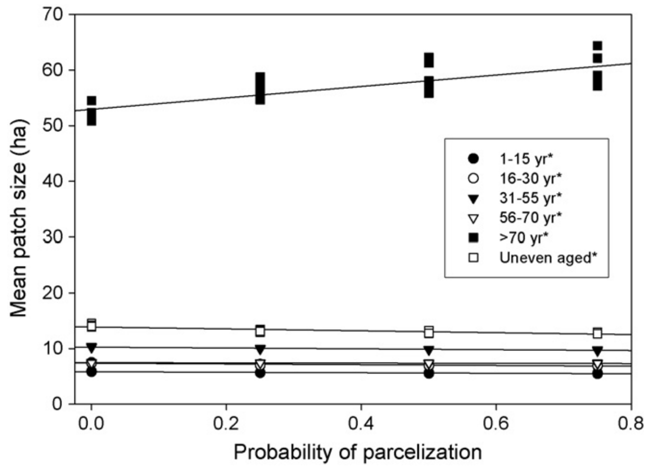

Fig. 3. Relationship of patch size (defined by age class) to the probability of ownership parcelization (p). All six replicates are shown and lines represent the fitted linear regression model. Slopes significantly different than zero ($\alpha = 0.01$) are indicated by an asterisk.

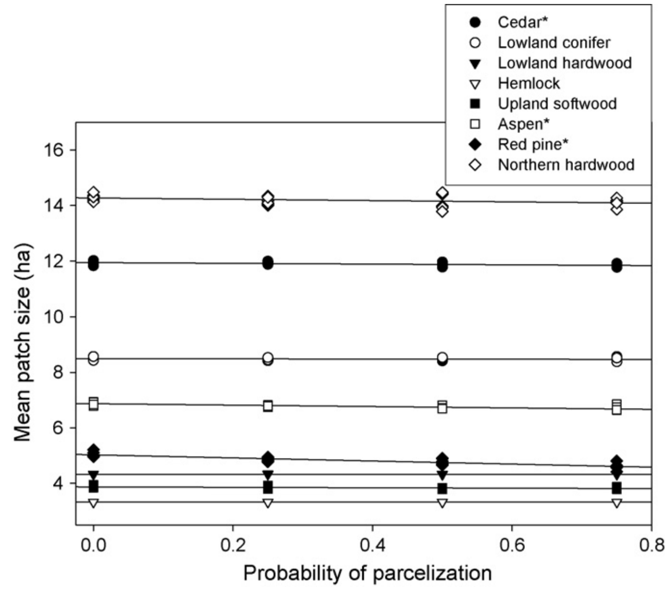

Fig. 4. Relationship of patch size (defined by forest type) to the probability of ownership parcelization (p). All six replicates are shown and lines represent the fitted linear regression model. Slopes significantly different than zero ($\alpha = 0.01$) are indicated by an asterisk.

decrease with p for all but one age class and for three forest types (Figs. 3 and 4). Contrary to our hypothesis, patch size increased significantly with p for the >70 year age class. Consistent with our hypothesis, edge density of age classes and forest types increased as a function of p, although the slope was less for edge density of forest types (Table 2). Similarly, contagion of age classes and forest types decreased as a function of p, although the slope was less for contagion of forest types (Table 2). The amount of forest interior habitat also decreased with p and forest edge habitat increased (Table 2). We hypothesized that productive capacity would decrease with p. Although the area of intensively cultured stands and the volume of wood extracted were negatively related to p, the relationships were not significant (Table 2). We hypothesized that indicators of recreational access would decrease as p increased. The total area of recreational land was invariant, but the mean patch size of recreational land decreased as a step function of p (Fig. 5, linear slope estimated in Table 2). Mean patch size of recreational land on the $p = 0.0$ landscapes was an order of magnitude larger than on the $p > 0.0$ landscapes because patches conformed to township boundaries. It should be noted that most relationships represented as a linear slope in Table 2 were slightly non-linear, with a very modest flattening of slope at the highest values of p. Patch size of recreational land was the only variable that was markedly non-linear.

3.2. Divestiture experiment

NIPF had the dominant influence on the mean values of variables (Table 3) because it was the dominant land owner. The effects of variation in abundance of an industrial owner on specific variables did indeed vary by owner. When the effect on a variable of an owner's management practices was different from the other two owners (as seen in the signs in Table 3), the abundance of that owner explained the most variability in that variable, although there were exceptions. In cases where this does not hold, the sign given for the owner that explains the least of the variation was usually only marginally significant. Consistent with our expectation, IND1 tended to have more impact on the response variables than IND2. In most cases the

Table 2
Estimates of regression parameters for the parcelization experiment (Response variables were regressed on p (probability of ownership parcelization). t-Values test the hypothesis that the slope equals 0.0. Slopes for individual forest types and age classes were not significantly different from zero)

Response variable	Slope	S.E.	R^2	t	$Pr > \|t\|$
Edge density (all age classes) (m/ha)	0.197	0.019	0.82	10.14	<0.0001
Edge density (cover types) (m/ha)	0.051	0.008	0.63	6.35	<0.0001
Contagion (age classes)	−0.004	0.0005	0.71	−7.64	<0.0001
Contagion (cover types)	0.0002	0.0004	0.00	0.47	0.6410
Forest interior (ha)	−2313.23	180.54	0.88	−12.81	<0.0001
Forest edge (ha)	2295.32	175.46	0.88	13.08	<0.0001
Area of plantations (ha)	−0.072	0.039	0.10	−1.86	0.0765
Volume of wood extracted (m^3)	−745.4	3086.8	0.00	−0.24	0.8114
Area of recreational land (ha)	0.0	0.0	N/A	N/A	N/A
Patch size of recreational land (ha)	−25373	5159.5	0.50	−4.92	<0.0001

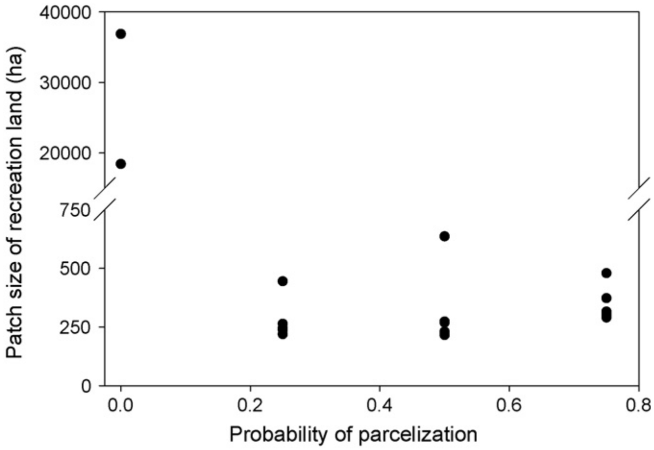

Fig. 5. Relationship of patch size of recreational land to the probability of ownership parcelization (p). All six replicates are shown. Values >20,000 ha represent the combined area of two adjacent townships.

effect of the two industrial owners was opposite to that of the NIPF owners, but there were exceptions. For example, the IND1 owner converts northern hardwood to other types while IND2 and NIPF tend to add northern hardwood. This contrast allows IND1 to exert the dominant effect on this variable (66%). IND2 exerts the dominant influence on the contagion of cover types by converting other types to the northern hardwood matrix. The even-aged cutting techniques of IND1 increase the amount and size of 1–15 year age class patches, reduce the amount and size of >70 year age class patches and reduce forest interior. The large proportion of unmanaged stands on NIPF lands would suggest that increasing the proportion of NIPF would not increase measures of fragmentation. However, examination of the signs in Table 3 shows that the NIPF owners increase some measures of fragmentation of cover types (e.g., proportion of developed, edge density, contagion of cover types) because of the conversion to developed land use that occurs there. Of the industrial owners, IND1 had the most effect on area of intensive culture, but IND2 had the most effect on volume of wood extracted. NIPF was inversely related to the volume of wood extracted and the amount of recreational land (Table 3), and wood volume harvested was reduced by 55% when all industrial land was divested.

The proportion of the study area owned by the industrial owners explained at least 80% of the variation in the temporal trend (slope through time) of all but one response variable as indicated by R^2 values (Table 4). Here also, the effects of variation in abundance of an industrial owner on specific variables varied by owner. NIPF again had the dominant effect on the temporal trend of most variables. IND1 had the dominant effect on trends of the youngest and oldest age classes because of its emphasis on even-aged cutting techniques. IND2 had the dominant effect on trends in the abundance of northern hardwood and contagion of cover types because of its conversion of some stands to the northern hardwood type. NIPF also had an important negative effect on the trend for contagion of cover types because of its conversion of forest to development. The sign for the effect of owners was sometimes counter-intuitive. For example, although IND1 was the primary generator of the 1–15 year age class, it was negatively related to the size of patches of this class. This was caused by greater variability in this variable for IND1 compared to NIPF, which happened to result in a greater negative slope for IND1. Similarly, although nearly half of NIPF land is unmanaged, NIPF shows positive trends for most measures of fragmentation (edge density, contagion of cover types, interior/edge), while the industrial owners have opposite trends. This is the result of

Table 3
Relative effect of the extent of the study area owned by the industrial owners (IND1 and IND2) on the spatial effects (mean value) of response variables (Values given are the percent of the total MANOVA Type III sums of squares explained by each level of the class variable (proportion of the study area owned by the two industrial owners). Boldface values are significant ($\alpha = 0.0001$). The sign columns represent whether the mean values increased or decreased as the proportion of the study area owned by the owner increased. NIPF estimates were calculated in a separate MANOVA with proportion of the study area owned by NIPF owners as the class variable)

Response variable	IND1 (%)	IND2 (%)	NIPF (%)	R^2	IND1 sign	IND2 sign	NIPF sign
Proportion of 1–15 year age class	**58.5**	**41.2**	**99.1**	1.00	+	+	−
Proportion of >70 year age class	**92.2**	7.5	**76.2**	1.00	−	−	+
Proportion of uneven-aged class	**61.5**	**38.2**	**98.4**	1.00	−	−	+
Proportion of northern hardwood type	**66.2**	**32.5**	3.1	0.99	−	+	NS
Proportion of urban type	**50.1**	**49.8**	**99.9**	1.00	−	−	+
Mean size of 1–15 year age class patches	**56.2**	**43.6**	**99.4**	1.00	+	+	−
Mean size of >70 year age class patches	**88.4**	**10.7**	**80.3**	0.99	−	−	+
Mean size of uneven-aged patches	**57.8**	**42.1**	**99.3**	1.0	−	−	+
Mean size of all cover type patches	**40.9**	**58.1**	**99.0**	0.99	+	+	−
Edge density (all age classes)	**36.1**	**63.4**	**97.6**	0.99	−	−	+
Edge density (cover types)	**46.6**	**53.3**	**99.8**	1.00	−	−	+
Contagion (age classes)	**64.0**	**14.7**	**70.3**	0.79	−	−	+
Contagion (cover types)	1.1	**96.5**	**54.6**	0.98	NS	+	−
Forest interior	**93.8**	1.9	**61.2**	0.96	−	NS	+
Forest edge	**89.5**	0.6	**52.9**	0.90	+	NS	−
Area of intensive culture	**82.0**	**17.8**	**88.2**	1.00	+	+	−
Volume of wood extracted	**36.6**	**63.2**	**98.0**	1.00	+	+	−
Area of recreational land	**50.0**	**50.0**	**100.0**	1.00	+	+	−
Patch size of recreational land	10.7	10.9	**39.3**	0.22	NS	NS	−

Table 4
Relative effect of the extent of the study area owned by the industrial owners (IND1 and IND2) on the temporal trends (slope through time) of response variables (Values given are the percent of the total MANOVA Type III sums of squares explained by each level of the class variable (proportion of the study area owned by the two industrial owners). Boldface values are significant ($\alpha = 0.0001$). The sign columns represent whether the slope values increased or decreased as the proportion of the study area owned by the owner increased. NIPF estimates were calculated in a separate MANOVA with proportion of the study area owned by NIPF owners as the class variable. Public access variables did not change through time and are not shown)

Response variable	Temporal trend	IND1 (%)	IND2 (%)	NIPF (%)	R^2	IND1 sign	IND2 sign	NIPF sign
Proportion of 1–15 year age class	−	**61.4**	**15.7**	9.9	0.77	+	−	NS
Proportion of >70 year age class	+	**87.7**	**11.9**	**82.2**	1.00	−	−	+
Proportion of uneven-aged class	+	**53.6**	**46.0**	**99.6**	1.00	−	−	+
Proportion of northern hardwood type	−	1.5	**89.9**	**57.5**	0.91	NS	+	−
Proportion of urban type	+	**50.1**	**49.8**	**99.9**	1.00	−	−	+
Mean size of 1–15 year age class patches	+	**55.9**	**34.6**	**98.4**	0.90	−	−	+
Mean size of >70 year age class patches	+	**83.0**	**15.3**	**84.8**	0.98	−	−	+
Mean size of uneven-aged patches	+	**44.6**	**54.0**	**99.3**	0.99	−	−	+
Mean size of all cover type patches	−	**50.2**	**46.9**	**99.1**	0.97	+	+	−
Edge density (all age classes)	+	**31.9**	**67.3**	**96.0**	0.99	−	−	+
Edge density (cover types)	+	**48.4**	**51.5**	**99.8**	1.00	−	−	+
Contagion (age classes)	+	**68.6**	**23.3**	**86.3**	0.92	−	−	+
Contagion (cover types)	−	6.2	**78.0**	**72.1**	0.84	NS	−	−
Forest interior	−	**44.8**	**54.7**	**99.3**	0.99	+	+	−
Forest edge	+	**45.5**	**53.8**	**99.1**	0.99	−	−	+
Area of intensive culture	−	**62.0**	**37.6**	**98.0**	1.00	+	+	−
Volume of wood extracted	+	**17.6**	**81.6**	**87.2**	0.99	+	+	−

the continual conversion to developed land use that occurs on NIPF land. These permanent fragmenting effects overwhelm less fragmenting temporal trends produced by the practices of the industrial owners (compare signs of NIPF to IND1 and IND2). Because the ownership maps did not vary through time, the temporal effects of owner abundance on recreational land were not analyzed.

3.3. Comparison with a real landscape

The comparison of response variables between the neutral model landscapes and the real industrial forest landscape of Menominee County, Michigan showed that forest composition (age and type) was quite similar, but that measures of fragmentation were sometimes quite different (Table 5). Mean patch size was consistently larger on the neutral landscapes primarily because they are composed of stands on a regular grid, and it is easier for large patches to form by diagonal connections among stands. The differences in edge density are related to the differences in patch size, with larger patches having a lower area-to-edge ratio that results in a lower edge density. Contagion is lower on the neutral landscapes because stands are smaller than on the real landscape. The behavior of the contagion index is different than patch size because contagion considers adjacency on cell edges only, not diagonals (Riitters et al., 1996). Wood volume extracted was higher on the

Table 5
Comparison of mean values through time (standard error in parentheses) of measures of spatial pattern in neutral model landscapes ($p = 0.25$) and a real industrial forest landscape in Menominee Co., Michigan (Gustafson et al., in press)

Response variable	$p = 0.25$	Real landscape
Proportion of 1–15 year age class	0.05 (0.0005)	0.08 (0.0003)
Proportion of >70 year age class	0.37 (0.0008)	0.28 (0.0002)
Proportion of uneven-aged class	0.20 (0.0007)	0.24 (0.0007)
Proportion of northern hardwood type	0.26 (0.0004)	0.26 (0.0004)
Mean size of 1–15 year age class patches (ha)	5.7 (0.02)	6.4 (0.08)
Mean size of >70 year age class patches (ha)	58.6 (2.56)	9.3 (0.03)
Mean size of uneven-aged patches (ha)	12.9 (0.22)	5.0 (0.01)
Mean size of all cover type patches (ha)	10.5 (0.01)	3.3 (0.003)
Edge density (all age classes) (m/ha)	12.1 (0.03)	22.2 (0.008)
Edge density (cover types) (m/ha)	12.9 (0.004)	20.4 (0.006)
Contagion (age classes)	0.36 (0.0008)	0.52 (0.00006)
Contagion (cover types)	0.39 (0.0007)	0.62 (0.00009)
Mean distance to a forest edge (m)[a]	317.8 (2.04)	122.1 (0.34)
Proportion of intensive culture (ha)	0.19 (0.0004)	0.26 (0.0006)
Mean volume of wood extracted (m^3/ha)	17.1 (0.07)	25.9 (0.03)
Mean size of recreational land patches (ha)	269.4 (35.89)	6906.6 (N/A)

[a] The average distance of all forested cells to the nearest opening (forest age <20 years) or non-forest edge. This interior index (GISfrag, Ripple et al., 1991) is comparable between landscapes of different extents.

real landscape because the proportion of land under intensive culture was higher and the real landscape contained some fast-growing exotic species (European larch) that were not simulated on the neutral model landscapes. Although the proportion of land having recreational access was virtually identical between the real and neutral landscapes (not shown), the mean size of patches of recreational land was much smaller on the neutral landscapes because they contain many more patches that are smaller than those found on real landscapes. These comparisons revealed that the behavior of the response variables on the neutral landscapes was sometimes different from those seen on a real landscape, but the reasons for the differences can be interpreted. This gives us added confidence that our experimental results are applicable to the management of real landscapes.

4. Discussion

Our experiments reveal the general expected response of forested landscapes to ownership parcelization and divestiture. Forest composition and measures of productivity are not much affected by parcelization, but measures of fragmentation and recreational access are. Divestiture may result in changes to existing management strategies, and the effect of those changes will depend on the magnitude of the difference between the management objectives of the previous and new owners. The most significant changes result when some forested land is converted to developed uses. Real landscapes will show a unique response to parcelization and divestiture related to existing patterns of road networks, physical features and ownership patterns, but the general trends should be similar.

We limited parcel size to $\geq$16 ha and assumed that land use was not related to parcel size, to study the parcelization of industrial forest landscapes. Parcels may become much smaller in non-industrial landscapes, and harvest rates and land use may be significantly different on small parcels. For example, parcels $<$16 ha have much lower harvest rates and are more likely to be converted to residential land use (Butler and Leatherberry, 2004). Therefore, our parcelization results should not be extrapolated to landscapes with fine-scale parcelization ($<$16 ha).

Some of the temporal trends in response variables we observed may be artifacts of initial age class distributions, which for some forest types caused increases in area harvested in later time steps because not all stands were old enough in early time steps. This was clearly seen in wood volume estimates, and it likely affected other measures also. However, our initial age distributions were based on those of a real landscape, and most real landscapes do not have perfectly even age distributions. Thus, our results can be viewed as realistic, if not normative.

Our results clearly show that parcelization of ownership increases the fragmentation of forests. The seriousness of this increase in fragmentation is less clear. For example, the amount of forest interior and overall patch size each decreased about 5% when p was changed from 0.0 to 0.75. Measures of edge density and contagion changed even less. Quantifying the ecological effects of such changes would be fertile ground for other research, and would provide insight into the urgency for policy actions that might be considered to reduce parcelization. Parcelization also appears to have a major impact on recreational access. The mean size of recreational patches declined more than an order of magnitude when p was changed from 0.0 to 0.25. However, across levels of p that are consistent with real landscapes (i.e., $p \geq 0.25$), the effect of p was minimal (Fig. 5).

Divestiture has significant effects on composition and fragmentation of age classes and forest types that depend on which owner is divesting. Industrial owners tend to increase fragmentation by their cutting activities (Table 3), but the openings they create are ephemeral, and the landscape-wide amount of fragmentation remains relatively constant through time. However, when the new owner(s) of divested lands convert them to developed uses, the openings created are not ephemeral. In our experiments, we simulated development of 3.7% per decade on NIPF land, which is consistent with current estimates for the US (Stein et al., 2005). This rate of development was sufficient to cause significantly increasing rates of fragmentation (Table 4), and the ecological consequences may become quite severe over time (e.g., Radeloff et al., 2005). Because fragmentation by development is chronic and permanent, our results suggest that this is a much greater threat to ecological sustainability than even highly intensive forest management (e.g., IND1).

Our experiments provide a first approximation of the fundamental relationships between forest parcelization and divestiture, and indicators of forest sustainability. The design of the experiments held constant many factors that may co-vary with parcelization and divestiture, and are therefore in that sense, unrealistic. However, because the experiments are not confounded by these covariates, the trends seen in our results can be attributed to the main effects of parcelization and divestiture. Our results show that divestiture potentially has more serious consequences for forest sustainability than parcelization, primarily because of the possibility of conversion to non-forest land uses. We modeled the spatial location of land use conversion very crudely. Because of the importance of this factor, future studies should incorporate more sophisticated models of this process.

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