Potential Future Landscape Change on the Nashwauk Uplands: An Examination of Alternative Management Scenarios Using LANDIS

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EXECUTIVE SUMMARY

Overview and Methods

The landscape simulation model LANDIS v3.6 was used to compare potential future landscape characteristics (composition and patch size) 120 years from now among ten management scenarios, for the Nashwauk Uplands subsection in northeastern Minnesota.

The scenarios included the base scenario which was designed to simulate current forest practices with regard to size and type of harvest, and scenarios that were designed to simulate cooperation among landowners (county, state, federal, and private), larger clearcut sizes than currently employed (target sizes of 60, 120 and 500 acres), variation in harvest rotation (+/- 20% compared to the current rotation), clustering clearcuts in certain parts of the landscape, increasing the use of selection and shelterwood harvests while decreasing the amount of clearcutting, and no harvest (Table 4). Wind and fire also interact with harvest and continue to influence the landscape in northeastern Minnesota, and were therefore included in the simulations.

The Nashwauk subsection has a very heterogeneous landscape of lowlands that include productive lowland forest, unproductive lowland forest, and other wetlands, alternating with uplands dominated by aspen and mixed aspen-conifer forests. Forests of red, white, and jack pine comprise a small proportion of the landscape. A long narrow ridge of uplands—the Mesabi Range—runs through the Nashwauk and supports aspen-birch forests, aspen-birch succeeding to northern hardwoods, and northern hardwood forest dominated by sugar maple.

LANDIS used a 60 m pixel size and kept track of the presence of each tree species in 10-year age classes in each pixel. After harvest or natural disturbance, young cohorts not harvested may take over (for example suppressed seedlings and saplings of shade-tolerant species such as sugar maple and balsam fir), sprouts may enter the stand (species such as aspen) and new regeneration from seed rain from older cohorts not harvested and from surrounding pixels can also create new cohorts. Disturbances of high severity (intense fires) would favor new seedlings and root sprouts, while moderate severity disturbances such as clearcutting favor a mixture of new seedlings, sprouts and release of shade-tolerant seedlings, and low severity disturbances such as selection cutting favor release of shade-tolerant species. The species of trees in each pixel thus depend on the species present before disturbance and surrounding pixels, and the type of disturbance.

The initial landscape (current conditions, including a list of species and age cohorts in which they are present for each pixel) was derived from a combination of multi-temporal Landsat satellite imagery, and Minnesota Department of Natural Resources Cooperative Stand Assessment (CSA) data for St Louis and Itasca County. At the end of 120 years of simulation, output maps were cross-classified into patches by covertype and developmental stage, including aspen-birch, upland mixed, spruce-fir, lowland conifer, and northern hardwoods in young, pole, mature and old stages of development. The patch-type maps were then analyzed by APACK, a spatial statistics program designed to calculate patch statistics from LANDIS output.

For the base scenario, a before and after comparison of landscape characteristics was made (i.e. the current landscape was compared to that simulated 120 years from now). All the other scenarios were compared to the base scenario at a common time point 120 years into the future, to see the differences that the scenarios may have on future landscape characteristics.

Main Findings

1) If the current climate continues there will be more late-successional forest types, especially spruce and fir forest in the future. The compliment to this is less aspen-birch forest (Figure 8). This was true for all the scenarios, although the change towards spruce-fir was minimized in the no harvest scenario. The no harvest scenario was dominated by natural disturbance including fire, which when superimposed on the current landscape as a starting point, led to a relatively more aspen and mixed aspen-conifer forest, and less spruce-fir than the scenarios that included harvesting.

   There are two caveats regarding this major conclusion. There is a continuous gradient from aspen-birch forests to mixed forests, to those dominated by spruce and fir. Different cover type classifications break this continuum at different places along the continuum, leading to variability in the estimated proportions of aspen, mixed and conifer forest. The methods used to classify the current cover types based on satellite imagery was unavoidably different than that used to classify the pixels to the LANDIS simulation at the end of 120 years. Also, spruce budworm could influence the distribution of balsam fir in the future and was not simulated.

   Nevertheless, the results are strong enough to indicate an important shift towards greater conifer dominance—that is more spruce and fir dominated stands and more conifers within mixed stands—across the Nashwauk landscape in the future. This result makes sense given that harvesting is a low-to-moderately severe disturbance (including clearcutting) that favors regeneration of shade-tolerant conifers, as compared to the unique sequence of disturbances—harvesting followed by slash burning—that created the current widespread distribution of the aspen-birch forest type. Gradual return of conifers is expected as time goes forward, especially as far north and east as the Nashwauk, where the climate puts conifers in a much stronger competitive position than in most of Minnesota.

2) The proportions of young versus old forest predicted for the future varied significantly among the scenarios (Figure 16). Relatively small amounts of old forest are predicted to occur in the base scenario and those scenarios where harvest rotation were shortened or lengthened without changing other aspects of forest management. Substantially more old forest is predicted in scenarios with large clearcuts, coordination among landowners, lower proportion of clearcutting, clustering, and no harvest scenarios. Much of the old forest in the no harvest scenario is in mixed forest rather than spruce and fir.

   The increase in old forests was expected for the no harvest scenario, since it is well known that natural disturbance regimes in northern conifer-dominated forests create more young and more old forest than a regulated landscape with harvesting as the dominant form of disturbance. Coordination among landowners and larger

clearcuts allowed the landscape to have larger areas of older forests because in those scenarios the model chose to harvest stands in certain concentrated areas more often while visiting other parts of the landscape less often.

3) The natural heterogeneity of the Nashwauk landscape limited the degree to which larger patches could be created by varying forest management, although there were some significant differences between the scenarios at year 120. For example, mean aspen patches were bigger in the no harvest scenario because large, fire-created aspen-birch patches remained whole into maturity (Figure 15).

There are enough small patches that the presence of large patches may be swamped by mean patch size statistics. Therefore, patch size distributions were examined, including the presence of large patches. Some scenarios produced more large patches (>50 ha) than the base scenario, and the large clearcut, coordination, clustering, and low clearcut scenarios produced more large and medium-sized patches (5-50ha) (e.g. Figures 13 and 14). Many small wetlands are interspersed with uplands on this landscape, limiting the ability to increase harvest size of contiguous upland areas except in a few areas with extensive uplands. These uplands can support large patches of forest of all forest types and ages, including aspen, spruce-fir and northern hardwoods.

Conclusion

Simulation results indicate that maintaining a large proportion of aspen-birch dominated forests will be difficult on the Nashwauk in the absence of occasional large fires. Attempting to make large clearcuts caused the model to cluster harvesting in certain parts of the landscape with contiguous stands, making the patch size characteristics similar to the scenario where clustering was artificially forced upon the landscape. The large clearcut scenarios were the most effective at creating a landscape that has some large patches and a mixture of young and old forest.

LANDIS Strengths and Limitations

The strengths included:

- The ability to account for variability in disturbance size and location by performing several duplicate runs for each scenario, so that the mean and range of potential future conditions can be assessed.
- Biological reality for effects of wind and fire disturbance that occur even on a landscape managed for timber production, and how these disturbances may impact the species of trees present
- Spatial interactions of trees on adjacent pixels, including seed dispersal from adjacent pixels, which is clearly one of the most important forces that determine successional patterns.
- Realistic differences in shade tolerance and other life-history characteristics of tree species, and simulation of the effects of species differences, such as allowing more tolerant species to invade the understory for realistic succession as the

forest ages, and estimates of which species will be able to dominate a given parcel of land over time.

The limitations of LANDIS were:

- Some important management considerations cannot be adequately simulated. Thinning simulations are risky because the removal of a cohort in an even-aged stand may result in the removal of every tree in the stand. There are no constraints on location of harvests that would be imposed by the road network in the real world, and no timber volume estimates that would allow an economic comparison among scenarios.
- The current version of the model does not allow planting, an important management strategy that could have spatial consequences.
- LANDIS is difficult to learn to run and to parameterize. It takes a few months to become familiar with and have confidence in setting up and running the model. Harvests do not automatically re-occur each decade. Instead, harvests must to be re-prescribed each decade, which results in large, complex input files and long runs (up to 9 hours each).
- Analyzing and interpreting the output is challenging. Output describing the spatial characteristics of simulated harvests are limited, making it hard for the user to determine whether desired harvest characteristics are accurately simulated. Also, metrics relating to young cohorts are very sensitive to uncertainty in establishment coefficients. It is difficult to determine whether alternative management strategies significantly affect these metrics because the effects are obscured by high error from establishment coefficients.
- The model does not simulate disease and insect infestations. Spruce budworm and tent caterpillars are important influences on succession and patch dynamics in northern Minnesota forests.

Some of these limitations, such as volume calculations and insect and disease simulations, will be addressed by newer versions of LANDIS.

INTRODUCTION

The American public is becoming increasingly concerned about how forest management practices affect landscape-scale spatial patterns (Hunter 1999, Spies and Turner 1999). Forest managers and planners are being asked to consider how current management practices will affect: 1) future habitat amounts and spatial patterns; 2) diversity of habitats and species; 3) the ability of ecosystems to adapt to climate change 4) the degree to which natural processes and spatial patterns can be restored or maintained; and 5) the amount of old-growth forest on the landscape, among others. Forest managers and planners must also be concerned about the effect of their management practices on the area and configuration of economically valuable forest types, and the effect of forest spatial patterns on the spread of insects and diseases.

To address these concerns, forest managers can employ various management strategies. By figuring out which management methods most influence the spatial pattern of forests, forest managers and planners can make more informed decisions to meet their forest pattern goals. In our study, we focused on several key management choices: coordination among landowners, clearcut sizes, clearcut clustering, and rotation ages.

Coordinated management is an approach to forest management where various landowners agree to consider the timing and pattern of each other's harvests to best meet the goals of all landowners. Public agencies may benefit from coordinated management because some agencies can have jurisdiction over another agency's land, have responsibility for wildlife that use another agency's land for habitat, have intermingled land parcels, have regulatory authority over activities near another agency's land, or have missions affected by decisions on another agency's land (Fulk et al. 1990). For example, if the state and federal ownerships wanted to create more habitat for a species that required large patches of regenerating forest on a landscape parceled into small ownership blocks they could use coordinated management to create larger harvest blocks.

On many forested landscapes, the annual area affected by clearcuts is much larger than the annual area affected by natural disturbances. Clearcut sizes can therefore have profound effects on forest spatial pattern (Li et al. 1993). Generally, larger clearcut sizes are more economical because more timber is removed at one time and fewer roads need to be built. However, larger clearcuts may have several potentially negative consequences. Exposing large areas of bare ground can result in erosion problems. Also, some species of wildlife are negatively impacted by clearcuts over 40 ha (Smith et al. 1997).

Clustering clearcuts is a system that focuses harvests in certain prime locations on the landscape. It can increase timber volume extraction while it simultaneously allows more forest area to remain in larger blocks for longer periods of time. By maintaining larger, older blocks, clustering may increase the amount of interior space and old forest on the landscape. Dynamic clearcut clustering, where the zone of clustering moves across the landscape over time, can be a cost-effective method of harvest but complicates management of static features such as recreation areas and designated old growth areas.

Static clearcut clustering avoids these problems but may be less economical because the clustered areas are effectively put in short rotation and the rest of the landscape is left in long rotation management (Gustafson 1996).

The rotation age for a given forest type is often set to the age at which the annual growth increment begins to decline. However, the rotation age usually arrives before the stand becomes old, resulting in fewer old stands on the landscape. Shortening rotations can be more economical for some tree species but can also produce landscapes dominated by younger forests. Longer rotations can be used to create more old forests and more structural diversity on the landscape.

The effects of these management choices on landscape forest spatial patterns are not fully known. However, these choices influence forest pattern at scales too large to be tackled by empirical studies. Landscape-scale forest models can serve as valuable research and planning tools by simulating the effects of management options at large spatial and temporal scales and providing information about potential future forest patterns.

In our study we used LANDIS, a spatially-explicit and stochastic model of forest landscape change, to examine the consequences of alternative management choices. We used LANDIS because it simulates large landscapes and time scales; simulates fire, wind, and harvest events; provides output describing the location and amount of acres harvested; provides detail on the spatial pattern of forest covertypes and age classes; and runs in a reasonable amount of time (He et al. 2000, Mladenoff and He 1999). LANDIS has also been used previously to study alternative management scenarios on various landscapes. Gustafson et al. (2000) used LANDIS to study timber harvesting in the Ozark Mountains. Three simple management scenarios were simulated: no harvest, clearcuts, and group selection cuts on a single management area. Shifley et al. (2000) described a second study using LANDIS to simulate alternative management scenarios in the Ozarks. Our study differed from previous studies in that we simulated three silvicultural methods (clearcuts, selection cuts, and shelterwood cuts) and varied rotation age, clearcut size, landowner coordination, and clearcut clustering.

We simulated forest management on the 327,540 ha Nashwauk Uplands landscape of northeastern Minnesota (Figure 1). The Nashwauk Uplands subsection is a very heterogeneous landscape within the transition zone between hardwood and boreal forests, that includes productive lowland forest with black ash (*Fraxinus nigra*) and white cedar (*Thuja occidentalis*), unproductive lowland forest of black spruce (*Picea mariana*), and other wetlands, alternating with uplands dominated by aspen (*Populus tremuloides*) and mixed aspen-conifer forests that include black spruce, white spruce (*Picea glauca*), and balsam fir (*Abies balsamea*). Forests of red, white, and jack pine (*Pinus resinosa, P. strobus, P. banksiana*) comprise a small proportion of the landscape. A long narrow ridge of uplands—the Mesabi Range—runs through the Nashwauk and supports aspen-birch (*Betula papyrifera*) forests, aspen-birch succeeding to sugar maple (*Acer saccharum*) and other hardwoods, and northern hardwood forest dominated by sugar maple. Half of the landscape is forested and forestry is currently the dominant land use. Public forests are abundant and are managed for multiple use. Aspen, the most common tree species, is

harvested for paper and waferboard products. Rivers are prevalent, and small bogs and potholes dot the landscape. Fire is important on outwash plains and to a lesser degree on moraines. Windthrow occurs throughout the landscape but has the strongest impact on the moraines (Minnesota Department of Natural Resources 2001). We chose to perform our study on the Nashwauk Uplands because of its reasonable size, mostly forested area, diversity of forest types, and diversity of landowners.

In our study, we used LANDIS to simulate ten harvest scenarios on the Nashwauk Uplands in northeastern Minnesota. We compared the results of the future landscape characteristics (composition and patch size) 120 years from the present among the scenarios, described in the Methods. The purpose of our study was to determine the potential effects of alternative management strategies on the spatial forest patterns of the Nashwauk Uplands. We had three objectives: to determine which management choices lead to larger forest patches, to determine which choices lead to more older forest, and to compare the relative distribution of spruce-fir and aspen-birch covertypes among management scenarios. This report summarizes the most important findings from the study, emphasizing seven of ten scenarios. Substantially more detail can be found in Mehta (2003).

METHODS

Development of the base scenario

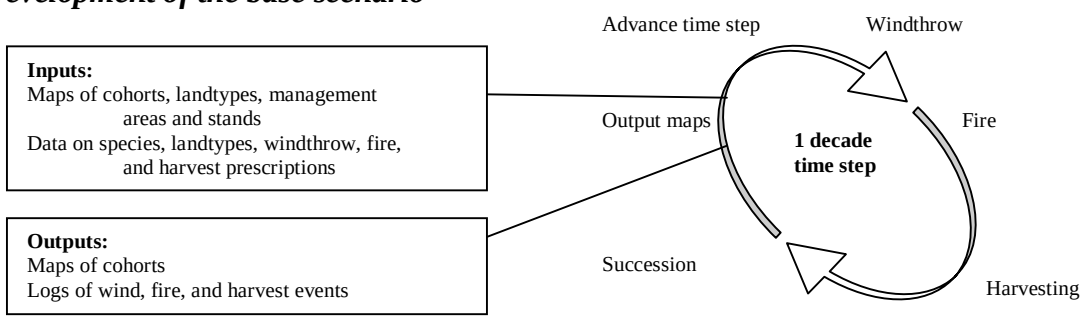

Figure 2. LANDIS overview

LANDIS requires several input maps and data files in order to run. The input maps are .gis ERDAS 7.4 raster files with 8 and 16-bit packing. These raster files store data as grids of square cells. Each cell represents a 60m x 60m area of Nashwauk Uplands and is associated with an identifier. Cell identifiers correspond to categorical data, such as landtype, management area id, or stand id. Each raster file describes a different aspect of the landscape. Raster files can be overlaid so that each cell is associated with a combination of values, one value from each file. When overlain, they create a detailed picture of the landscape at the start of the simulation.

The parameterization of LANDIS requires the creation of the following input files.

Species data inputs:
Species.gis
Species_attributes.dat
Map_attributes.dat

Disturbance data inputs:
Disturbance.dat

Landtype data inputs:
Landtype.gis
Landtype_attributes.dat

Harvest data inputs:
Management_area.gis
Stand.gis
Harvest.dat

Reclass files:
Map_index.dat
Age_index.dat

Vegetation map and data inputs

Species.gis is a map representing the initial locations of cohorts on the landscape (Figure 3). LANDIS defines a cohort as a group trees of like species and the same 10-year age class. Cells can contain more than one cohort. Each cell in species.gis contains a value that corresponds to a record in map_attributes.dat. Each record in map_attributes.dat consists of a unique fingerprint of cohorts. By linking each cell with a set of cohorts we delineate the initial cohort distribution on the landscape.

The basis of species.gis was a landuse-landcover map derived from multi-temporal Landsat satellite imagery (Wolter et al. 1995). Landsat imagery assigns a covertype to each cell. It therefore does not contain any information on coexisting species nor on the age cohorts present. We used the Landsat data to classify cells by covertype. Next, we obtained species composition and age distributions from Minnesota Department of Natural Resources' Cooperative Stand Assessment (CSA) data. These data are available for state and county owned lands throughout Minnesota and provide information on the five most common tree species in each stand. We sampled the CSA data for all of St. Louis County and Itasca County, in which the Nashwauk Uplands is contained. We recorded all the different combinations of cohorts found in all stands. This provided us with a sample of approximately 3,000 stands for which we knew species composition and age distribution. Stands were grouped into similar developmental stages based on species composition and ages according to Frelich's vegetational growth stages (Frelich 1999). The species groupings were uniquely numbered and linked directly to information contained in map_attributes.dat. After the grouping was completed, cells of a given covertype were randomly assigned a species grouping of the same covertype. For example, a cell of jack pine covertype may be assigned a species grouping containing 30 and 40-year-old aspen cohorts and 40, 50, and 60-year-old jack pine cohorts. The cell, therefore, maintains the jack pine covertype, but may also contain cohorts of other species. By our method, we were able to create species.gis with an accurate spatial distribution of covertypes but a random spatial distribution of age classes.

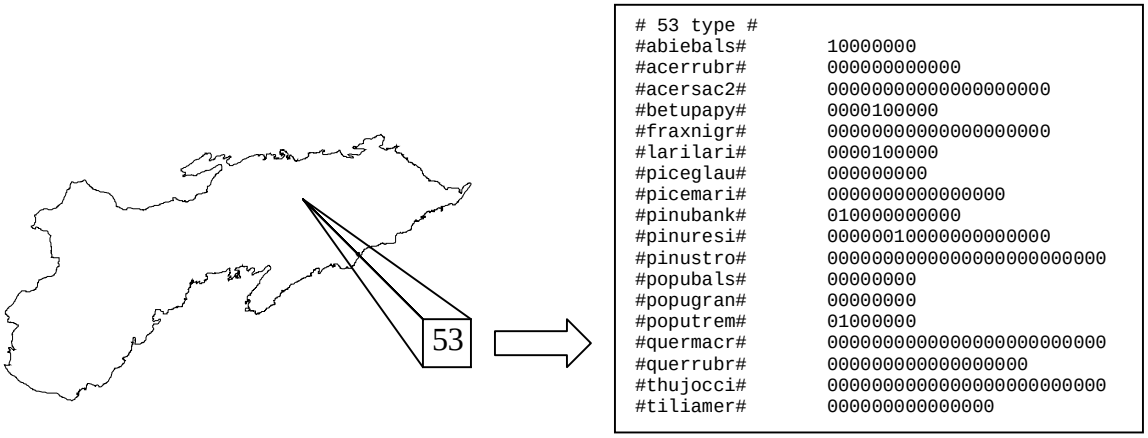

Figure 4. Associating each pixel of species.gis with an entry in map_attributes.dat.

As described above, map_attributes.dat is a file that contains a list of records (Figure A1). Each record has a unique id and a unique binary code that describes which cohorts are present and which are absent. Every cell in species.gis contains a value that corresponds to an id in map_attributes.dat (Figure 4). In this way, LANDIS is cognizant of which cohorts are present and where before the simulation begins. Map_attributes.dat was created using the final groupings of cohorts.

Species_attributes.dat contains life history information on all simulated tree species. We only included the 18 tree species that had relative frequencies greater than 2% on the landscape (Table 1). This file specifies the typical characteristics for a member of each species growing in the Nashwauk Uplands. It requires information on longevity, age at which seed production begins, relative shade tolerance, relative fire tolerance, distance beyond which 5% of seed may travel, distance beyond which .001% of seed may travel, probability of vegetatively sprouting after a fire, and age at which sprouting no longer occurs. The variation in life history characteristics between species results in different responses to landscape processes. Information for parameterizing this file was gathered from the following sources: Minnesota Tree Handbook (1986), Burns and Honkala (1990a), Burns and Honkala (1990b), Curtis (1959), Steele and Smallwood (2002), Sakai (1990), Buse and Bell (1992), and John Zasada pers. comm. (2002).

Disturbance data inputs

Disturbance.dat contains information on wind and fire disturbance characteristics (Table 2). This file requires data on minimum, mean, and maximum wind and fire sizes on the Nashwauk Uplands. It also calls for information on mean interval for windthrow. The mean interval for fire is specific to landtype and is therefore defined in landtype_attributes.dat. Disturbance events occur randomly on the landscape and can spread across all landtypes and ownership boundaries. Fire disturbances vary in severity depending on the landtype and the time since last fire or windthrow. Less severe fires remove younger cohorts. More severe fires remove all or nearly all cohorts depending on the susceptibilities of individual species. Conversely, less severe windthrows remove

mostly older cohorts, while more severe windthrows remove all cohorts regardless of species. Fire and wind can stimulate new growth by opening gaps and allowing new cohorts to establish. Fire can also stimulate vegetative sprouting in cohorts capable of doing so. There was not enough data available on fire regime characteristics in the post-settlement period to determine mean return intervals of fires. Therefore we parameterized disturbance.dat using data from pre-settlement and recent time periods for northeastern Minnesota. These data were obtained from Frelich (1998), Frelich (1999), Frelich and Lorimer (1991), Canham and Loucks (1984), and Heinselman (1996).

Landtype data inputs

A landtype is an area that has a homogeneous disturbance regime and species establishment coefficients (He et al., 2000). In landtype.gis we defined eleven landtypes (Figure 5). Five landtypes represented non-forested areas six landtypes represented forested areas. The five non-forested landtypes were lowland, bog, wetland, water, and non-forest. Included in this last category were roads, brushlands, grasslands, mines, bare ground, and urban land. These five non-forested landtypes were highly dispersed throughout the landscape. None of them were able to experience disturbances, nor were species allowed to establish on them.

The six forested landtypes included Big Rice Moraine, Whalsten Till Plain, Pike-Sandy River Sand Plain, Mesabi Range, Pengilly Till Plain, and Nashwauk Moraine. These landtypes roughly corresponded to the six landtype associations (LTAs) delineated by the Ecological Classification System (ECS) (Figure 6). LTAs are areas with unique characteristics such as glacial landforms, hydrology, soil parent material, bedrock, pre-settlement vegetation and potential vegetation (Almendinger et al. 2000). The forested landtypes also differed from each other by their disturbance regimes and species establishment coefficients. Unlike the non-forested landtypes, the forested landtypes were mostly contiguous.

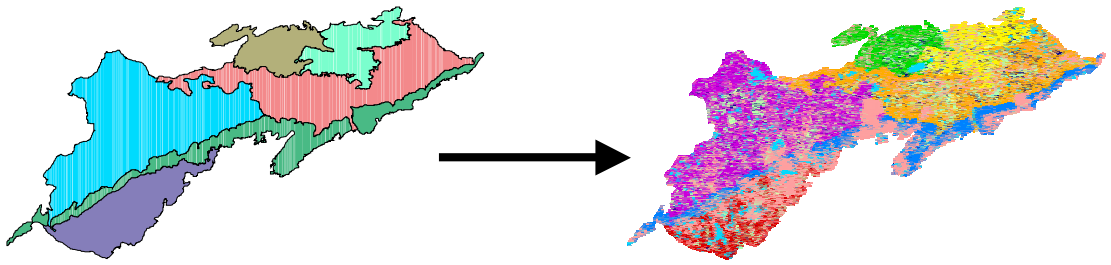

Figure 6: Creating 11 landtypes from 6 LTAs

Landtype_attributes.dat consists of data specific to each forested landtype in landtype.gis. These data include establishment probabilities for each species, mean fire return interval, time since most recent fire, time since most recent windthrow, minimum age of cohort present needed for the most shade tolerant species to establish, and relative fire severity based on time since last fire or windthrow (Table 3). The information from landtype_attributes.dat allows LANDIS to simulate fire and succession processes

differently on each forested landtype. Differences between the characteristics of landtypes result in large-scale spatial variation. The parameterization of landtype_attributes.dat was based on the same sources as used for disturbance.dat. Establishment coefficients were estimated using US Forest Service's Forest Inventory Analysis (FIA) data. All public and private plots within the Nashwauk Uplands subsection were used to calculate species establishment probabilities within each forested landtype.

Harvest data inputs

Management_area.gis is a map of the management areas on the landscape. Our management area map consisted of ten management areas: federal, state, county, private industrial, private/unknown, lake buffer, riparian buffer, old growth buffer, lake, and old growth (Figure 7). A management area is an area in which a single management policy is applied. Federal, state, and county management areas occurred on land owned by the federal, state, and county governments respectively. The private industrial management area consisted of large tracts of land (> 500 acres) that were owned by timber companies or other private entities. The private/unknown management area was a single management area that contained all other privately owned land (i.e., tracts less than 500 acres in size). Lake buffer, riparian buffer, and old growth buffer management areas were 60 meter wide zones around lakes, streams, and preserves respectively. These buffers were obtained from the MN DNR and correspond to current management policy guidelines. The locations of management areas were determined by intersecting several individual GIS coverages including MN DNR old growth buffers, MN GAP Analysis Project's land ownership, and a riparian coverage obtained from MN DNR. Areas or buffers representing land with protected status (i.e., state park) inherited this status regardless of any other categories. For example, a state park occurring on state land would belong to the preserve category.

Stand.gis is a map of stands present on the landscape. We delineated stands as groups of contiguous cells of a common covertype based on CSA data crosswalked with Landsat data. Stand.gis is a 16-bit file, which means that we could delineate up to 65,535 stands. Stand sizes ranged from < 1 ha to 697 ha and averaged approximately 3 ha. Stands overlapping management area boundaries were split into separate stands. For scenario 1, the total number of stands exceeded 52,000. All single pixel stands were identified and replaced using a majority-rule filter on the immediate eight-cell neighborhood (Figure A2).

Harvest.dat defines the simulated timber management practices. In the base scenario, harvest.dat summarized the current timber management practices on the Nashwauk Uplands (Figure A3). In this file, each management area is associated with a set of harvest prescriptions. We gave federal, state, county, private industrial, and private/unknown management areas each the same set of management prescriptions. The same proportion of each management area is harvested every decade. A reduced set of prescriptions is applied to riparian buffer, old growth buffer, and lake buffer management areas. No harvesting is performed in lake or preserve management areas.

Each prescription consists of specific instructions directing LANDIS on which stands to harvest, how many stands to harvest, and which cohorts to remove. A detailed description of how harvest prescriptions are simulated in LANDIS is provided in Gustafson et al. (2000).

In our harvest.dat file, each prescription corresponded to a specific harvesting method and covertype combination. Three harvesting methods were simulated, clearcuts, shelterwood cuts, and selection cuts. There were nine types of clearcut prescriptions: jack pine, red pine, spruce-fir, northern hardwood, aspen, paper birch, lowland spruce, tamarack, and lowland hardwood. We prescribed clearcuts to average 9.7 hectares in size and account for 91% of the landscape harvested each decade. Shelterwood cuts involved older stands and consisted of two entries. There were three types of shelterwood cut prescriptions: red pine, white pine, and northern hardwood. In the first shelterwood entry, stands were selected and a subset of the cohorts was removed. The second entry occurred 20 to 30 years later, depending on the covertype, and the remainder of the original subset was removed. Only 2% of the landscape harvested each decade was assigned to shelterwood cuts. Selection cuts targeted older stands and generally removed a smaller set of cohorts. There were two types of selection cuts: white pine and northern hardwood. Each decade 6% of the landscape was harvested by selection cuts.

Harvest.dat was parameterized from the following statewide harvest information sources: Timber Harvest on State Land (1997), Minnesota Forest Resources Plan (1995), Superior National Forest Land and Resource Management Plan (1986), Benzie (1977a), Benzie (1977b), Johnston (1977a), Johnston (1977b), Perala (1977), and Tubbs (1977). The prescriptions were then modified to describe the particular harvest practices on the Nashwauk Uplands based on information provided by John Zasada and Tom Crow of the North Central Forest Research Station and by Lee Frelich.

Reclassification files

Map_index.dat instructs LANDIS to create a separate map of each tree species each decade. Similarly, age_index.dat instructs LANDIS to create a map showing the spatial distribution of each cohort of each species. We set map_index.dat and age_index.dat to create maps for all cohorts of all 18 tree species included in our study.

Development of alternative scenarios

After designing the base scenario to represent current harvesting practices, we developed additional scenarios to represent alternative management options. Each alternative scenario is described in terms of how it differs from the base scenario (Table 4).

In scenario 2, we examined whether interspersion of ownership patches and the small size of ownership blocks had an effect on harvest sizes. We simulated coordinated management by merging the management areas of federal, state, county, private/industrial, and private/unknown into one large management area. We applied a

single set of harvest prescriptions to the new management area. We expected that by eliminating ownership boundaries, harvest sizes would increase. By increasing harvest sizes we expected to see increases in patch sizes, patch size variability, and a reduction in harvest costs.

For scenario 3 we looked at the effect of mean clearcut sizes on the landscape. We expected that larger mean clearcut sizes would result in larger forest patches, increased patch size variability, and lower harvesting costs. We looked at effect of increasing clearcut sizes from 24 acres to 500 acres.

Scenario 4 considered the effect of clustering clearcuts on the landscape. We located eight 2000-acre zones on the landscape with larger amounts of aspen and birch. Together these zones comprised the clustered harvests management area. We reduced the amount of clearcut harvests in the remaining management areas by 10% and added the same amount to the clustered management area. We expected that increased clustering would lead to greater patch sizes, patch size variability, and reduced costs.

In scenarios 5 and 6 we looked at the effect of rotation ages on landscape structure. By shortening rotation ages for all harvest prescriptions by 20% we expected to create more younger forests and to lower costs. By lengthening rotation ages by 20% we expected to generate more older forests and more structural diversity.

And lastly, in scenario 7 we looked at whether the effects of harvesting are distinguishable from the effects of natural disturbances on the landscape. We turned off the harvesting component of the model. We expected to see more older forest and larger patches because wind and fire events are infrequent, but large compared to harvests.

Running LANDIS

Calibration

LANDIS' wind and fire functions perform differently on landscapes of various sizes and resolutions. In order to ensure that the model performs as designed for a landscape of particular size, resolution, and disturbance regimes, LANDIS must be calibrated. LANDIS contains calibration variables that allow the modeler to adjust the variances on wind and fire sizes and mean return intervals. We calibrated LANDIS to run on the Nashwauk Uplands landscape using our estimates of wind and fire disturbance sizes and mean return intervals. We used the calibration technique described in He and Mladenoff (1999). After 15 iterations of the calibration technique we came up with error estimates for mean wind and fire sizes and mean return intervals (Table 5). On average, a wind or fire statistic will vary from the target value by the error estimate. For example, if the expected mean windthrow size is 200 ha and the error estimate for mean windthrow size is -8% then the simulation mean windthrow size will on average be 184 ha. Though the error estimates for mean windthrow interval and mean fire intervals are quite large a sensitivity analysis of LANDIS on the Nashwauk Uplands has shown that variance in fire

and wind inputs had minimal influence on landscape results compared to variation in species characteristics and management parameters (Mehta 2003). Still, the extremely large error estimates suggest that the simulation wind and fire statistics should be carefully considered.

Simulation

After calibration, all scenarios were run on the Nashwauk Uplands landscape using the same initial conditions. Runs began with the present day landscape and ended 12 decades into the future. Because LANDIS is a stochastic model we ran 10 replicates of each scenario and recorded the mean and variance of the output statistics.

Reclassification

At the end of each run, LANDIS generated output maps of the landscape. All 18 species maps were combined into one species map and species were reclassed into ten covertypes: upland mixed, lowland mixed, mixed burn, spruce-fir, aspen-birch, red and white pine, jack pine, northern hardwood, lowland conifer, and lowland hardwood. Similarly all 18 age class maps were merged into a single age class map and age classes were grouped into four developmental age classes: young (0-19), pole (20-49), mature (50-79), and old (>79). Each pixel in the covertype map was then associated with the developmental class of the dominant covertype. The result was a map of 40 forest types (Figures A4 and A5).

Though we were able to reclassify the final output maps using the method described above, we were unable to reclassify the initial landscape using the same method. The creation of the initial vegetation map (species.gis) relied on the spatial distribution of covertypes derived from satellite data. However, the satellite data did not provide information on the location of individual cohorts, so cohorts of a given species were distributed at random to pixels associated with the appropriate covertype. Thus, the initial vegetation map contained the correct spatial distribution of covertypes but not the correct spatial distribution of age classes. We obtained information about the current spatial distribution of vegetation on the Nashwauk Uplands from Host and White (2002).

Calculation

After we reclassified the landscapes we analyzed the maps using APACK, a spatial statistics program designed to calculate spatial statistics from LANDIS output (Mladenoff and DeZonia 2001) (Table 6).

<u>Landscape Statistics</u>
Mean patch size (ha): A patch is a contiguous set of pixels of a common forest type. Mean patch size is the average patch size for all forested patches on the landscape.

Perimeter-area ratio (corrected): The perimeter area ratio (corrected) statistic represents the ratio of a patch's perimeter to the perimeter of a circle with the same area, averaged across all patches. If all patches are circles then the statistic returns 1.000. The more

complex the patch shape is the greater the statistic (Mladenoff and DeZonia 2001).

Edge density (m/ha): Edge density represents the total length of edge of forest patches over the total area of the landscape (Mladenoff and DeZonia 2001).

Fractal (double log) dimension index: Fractal (double log) dimension index ranges from 1.0 to 2.0 representing the average patch fractal index. Patches with straight outlines have an index value near 1.0, while patches with irregular outlines have an index value near 2.0 (Mladenoff and DeZonia 2001).

Aggregation index: Aggregation is the number of edges between two pixels of like forest type over the maximum possible number of edges of two pixels of like type (Mladenoff and DeZonia 2001).

Contagion – relative – Li: Contagion measures the degree to which patch types are clumped into patches. Contagion – Li reports relative contagion values and ranges from 0.0 to 1.0 for maps with minimal to maximum contagion respectively (Mladenoff and DeZonia 2001).

Shannon-Weaver diversity index (SWDI): Shannon-Weaver diversity index is a measure of the richness and evenness of forest type areas on the landscape. Low diversity nears 0 (Mladenoff and DeZonia 2001).

Shannon-Weaver evenness index: Shannon-Weaver evenness index is a measure of the SWDI over the maximum possible SWDI on the landscape (Mladenoff and DeZonia 2001).

Angular second moment: Angular second moment measures landscape texture. It ranges from 0.0 for landscapes with many forest types and little clumping to 1.0 for landscapes with a single forest type (Mladenoff and DeZonia 2001).

<u>Forest Type Statistics</u>
Area (ha): Forest type area in hectares

Patch distribution: Patch size distribution and patch area distribution divided into seven bins, <1 ha, 1-5 ha, 5-10 ha, 10-25 ha, 25-50 ha, 50-500 ha, and >500 ha.

Perimeter-area ratio (corrected): Same as above but limited to forest type.

Edge density (m/ha): Same as above but limited to forest type.

Fractal dimension index: Same as above but limited to forest type.

Aggregation index: Same as above but limited to forest type.

Number of patches: Number of patches in forest type.

Significance Testing

Because information for the current landscape was obtained from a source that used a different reclassification method than ours, we were not able to make significance statements relating to landscape differences between year 0 and year 120. We were able to determine significant differences between base run results and results of the other scenarios. We used paired t-tests and the 0.05 significance level.

RESULTS

Relative amounts of spruce-fir and aspen-birch forests

Currently, 6% of Nashwauk Uplands forests are spruce-fir, and 68% are aspen-birch (Host and White 2002). The base scenario predicts that spruce-fir forests will increase to 49% and aspen-birch will decline to 13% after 120 years of current harvesting practices. All other simulated scenarios revealed similar trends (Figure 8). The no harvest scenario predicted a 34% increase in spruce-fir, the least increase among scenarios. Forest type distributions were also very similar among other scenarios, with one exception. The larger clearcut scenario had significantly more old spruce-fir forest than the base scenario (Table 7).

Forest patch sizes

In the base scenario, our simulation results show that all forest types have patch size distributions skewed toward smaller patches, with the <5 ha size classes containing the greatest number of patches (Figure 9). Most forest types also have more forest area in smaller patches (Figure 10). Aspen-birch, spruce-fir, and northern hardwood forests are the exceptions. Aspen-birch forests had more forest area in the >500 ha patch size class than in other classes because aspen-birch forests followed fire events which on average burned over 2,500 ha at a time (Figure 11). Spruce-fir and northern hardwood forest areas were almost evenly distributed across patch size classes (Figure 12). Spruce-fir patches were numerically dominant on the landscape at 120 years. Over time, their patches merged and formed larger patches in some locations. The even distribution of northern hardwood forest patches is due to the fact that northern hardwood patches were common both as large contiguous blocks on the Mesabi Range, and as dispersed patches on the moraines.

Patch size distributions of some forest types for some scenarios strongly differed from the base scenario (e.g. Figures 13 and 14). Coordination increased the area in patches >50ha for old spruce-fir, northern hardwoods, and lowland conifer forests. The larger clearcuts scenario increased the area in patches >500ha for old spruce-fir, red and white pine, northern hardwoods, and lowland conifer forests. The clustered clearcuts scenario increased the area in patches >500ha for old spruce-fir, northern hardwoods, and lowland

conifer forests, and pole aspen-birch. The no harvest scenario produced much more forest area in mature aspen-birch patches than the base scenario. Young northern hardwood, lowland conifer, and spruce-fir types all had more forest area in >500ha patches in the shortened rotation scenario.

For the most part, mean patch sizes did not vary significantly among scenarios (Table 8). There were a few notable exceptions. The coordination scenario had a significantly larger mean old lowland conifer patch size than the base scenario. The larger clearcut scenario had a significantly larger mean old spruce-fir patch size, and a significantly smaller mean aspen-birch patch size compared to the base scenario. Mean mature aspen-birch patch size was significantly larger in the no harvest scenario (Figure 15 and Table 8).

Amount of old forest

The proportions of young versus old forest (>80 years old) varied greatly between scenarios (Figure 16). The base scenario predicted that 28% of the Nashwauk Uplands forest would be old after 120 years of current harvesting practices. The larger clearcut scenario produced the greatest amount of old forest, 62%. The shorter rotation scenario produced the least amount of old forest, 17%.

DISCUSSION

Area of aspen-birch versus spruce-fir forest

All scenarios suggest that if the current climate continues, spruce-fir forest will be more prevalent in the future. Currently, aspen-birch forests are widespread, but as spruce-fir forests expand, aspen-birch forest will shrink (Figure 8). Late-successional balsam fir and white spruce are present in the understory of aspen-birch forests on the Nashwauk Uplands, and they respond well to release when the overstory is removed during clearcut harvesting. In the no harvest scenario, where the dominant disturbance was fire, the change towards spruce-fir was minimized, and more aspen and mixed aspen-conifer forest were present at the end of the simulation. This is because fire is a high-severity disturbance that eliminates the understory of shade-tolerant species and promotes the establishment of aspen and birch (Frelich 2002).

There are two caveats regarding the major conclusion that spruce-fir forest area will increase. There is a continuous gradient from aspen-birch forests to mixed forests, to those dominated by spruce and fir. Different cover type classifications break this continuum at different places, leading to variability in the estimated proportions of aspen, mixed, and conifer forest. The methods used to classify the current cover types based on satellite imagery were unavoidably different than those used to classify the pixels in the LANDIS simulation at the end of 120 years. LANDIS classification only required 35%

relative frequency of spruce-fir to classify a pixels as spruce-fir. Satellite imagery probably required a higher threshold. Secondly, spruce budworm could influence the distribution of balsam fir in the future and was not simulated. Spruce-fir forests are highly susceptible to spruce budworm attack, and older spruce-fir forests suffer even higher mortality rates (Bergeron et al. 1995). A landscape with large, contiguous blocks of spruce-fir forest will have more infected trees because spruce budworm caterpillars can disperse by wind to neighboring conifers (Jaakko Poyry 1992). Thus, increasing spruce-fir forest area may also increase spruce-budworm attacks, which in turn may limit the future expansion of spruce-fir forest (Bergeron et al. 1995).

A third consideration is that the Forest Inventory Analysis (FIA) data for St. Louis County in northeastern Minnesota show an upward trend in the number of spruce and fir stems from 541 million in 1977 to 700 million in 2002. Most of the increase is in the small diameter stems which suggests that spruce and fir will become more abundant in the future. The increase in spruce-fir stems are consistent with our results. However, FIA data also show that white spruce covertype area decreased from 11,800 acres in 1977 to 10,140 acres in 2002. Similarly, there was a decline in balsam fir covertype area from 240,300 acres in 1977 to 223,500 in 1990 to 112,775 acres in 2002. Changes in the FIA sample plot design and forest typing algorithm between 1990 and 2001 may account for some of the discrepancy between historical trends and future predictions of total spruce-fir area. Differences between the FIA forest classification system and ours also make it difficult to asses the true magnitude of covertype change (Forest Inventory and Analysis Database 2003).

Nevertheless, the results are strong enough to indicate an important shift towards greater conifer dominance—that is, more spruce and fir dominated stands and more conifers within mixed stands—across the Nashwauk Uplands landscape in the future. The results make sense given the successional and historical patterns of spruce-fir and aspen-birch forests in northeastern Minnesota. The current high coverage of aspen-birch forests types was created by wide-scale land clearing followed by fire in the early 1900s—a very severe disturbance combination that eliminated conifers over large portions of the landscape. For the last few decades and foreseeable future, harvesting will be the dominant disturbance type, and it is usually not severe enough to eliminate understory conifers, so that conifers are in the process of reinvading the landscape.

Effects of larger clearcuts, clustering, and coordination

Coordinating harvests, increasing clearcut size targets, and clustering clearcuts all resulted in clustered harvests on the landscape. When harvests are spatially clustered, some parts of the landscape are harvested more frequently while others are harvested less frequently, resulting in more and larger patches of old forest on some portions of the landscape. Note that much of the Nashwauk landscape is broken up by small peatlands and other wetlands so that the ability of management to affect patch size is limited and only a few areas are physiognomically suitable for large disturbances that create large patches. Thus, there are enough small patches that the presence of large patches may not

be apparent when looking at mean patch size statistics (compare old spruce-fir in Table 8 with Figure 13).

However, if one looks at the proportion of forest in larger patch size classes, scenarios that resulted in clustered harvests (coordination, larger clearcuts, and clustered clearcuts) all had similar effects on forest patch sizes. Their effects on spruce-fir patch size distributions were most dramatic. The old class was the dominant age class for spruce-fir forests in these scenarios, and most forest area was in the 50-500 ha size class by the end of these scenarios. This contrasts dramatically with the base scenario, where much of the old spruce-fir area remained in the 1-5 ha size class.

There are different reasons why these three scenarios resulted in a landscape with contrasting areas of young frequently harvested and old forests. The coordination scenario results show that it is possible that clearcut sizes are limited by the small sizes of ownership blocks. By coordinating management across ownership boundaries we removed this clearcut size constraint. The model then chose larger clearcuts on parts of the landscape that had the physiognomic configuration to support large harvests. However, consolidating ownerships made several large contiguous tracts of spruce-fir, northern hardwoods, and lowland conifer available for clearcuts. These large young patches then grew to become large old patches during the later decades of the simulations. The increased clearcut size scenario had different consequences for harvest pattern. By increasing clearcut size targets, the model was forced to find areas that had physiognomic contiguity and a single ownership. There were relatively few of these tracts available, and such sites were harvested two or three times during the 120 year simulation while other areas were then not harvested and grew into older age classes. The unharvested areas were larger than in the other two scenarios and they grew into large patches of old spruce and fir during the simulation (Figure 14). In the clustered clearcuts scenario we forced the model to harvest stands in certain areas dominated by aspen-birch forest more frequently than in other parts of the landscape. Thus, all three scenarios resulted in more clustered harvests, more older forests, and larger forests patches by employing three different strategies, but the locations of the young and old patches were dependent on the strategy employed.

Variability in the amount of old forest

Relatively small amounts of old forest are predicted to occur in the base scenario and those scenarios where harvest rotation were shortened or lengthened without changing other aspects of forest management, in contrast to the scenarios that clustered harvests by coordinating among owners, attempting to create large clearcuts or forcing the model to cluster harvests. The no harvest scenario also produced greater amounts of older forest than the base scenario (Figure 16). Natural disturbances have some characteristics in common with those scenarios that predicted large amounts of older forests. They ignore ownership boundaries, tend to be large compared to current harvests, and tend to disturb some areas repeatedly, such as sandy soils that burn or ridge tops that have frequent blowdown. These characteristics of natural disturbances serve to illustrate the overall

pattern in all these results. If the total area disturbed annually is held constant, then bigger disturbances, and disturbance that are clustered in certain parts of the landscape will allow for other forest in other parts of the landscape to grow old, so there is an abundance of young forest and old forest, rather than a uniform stand age distribution that is truncated by a set rotation period. This is true whether disturbances are natural or human in origin, and is in agreement with previous analyses of landscape age distributions in boreal and near-boreal forests (Johnson 1992, Heinselman 1996, Frelich 1999, 2002).

We did expect that the longer rotation scenario would lead to more old forests than the base scenario, since rotation period was the only difference between the two. However, the results showed that though less forest was harvested, more young and less old forest was produced compared to the base scenario. This was mostly due to the delays of a few decades in harvesting the current stands to accommodate the 20 year increase in rotation period, with the result that fewer stands were able to reach 120 years of age necessary to be classified as old at the end of the 120 year simulation period. It is likely that the long rotation scenario would produce the expected result of more old forest if the simulation were run for a few hundred years.

CONCLUSIONS

Simulation Results

The LANDIS simulation results indicate that maintaining a large proportion of aspen-birch dominated forests will be difficult on the Nashwauk in the absence of occasional large fires. Much of the forest will succeed to mixed and conifer-dominated forests because harvesting is not as severe a disturbance as the intense fires that historically initiated aspen-birch forests, and shade-tolerant conifers respond well to harvesting. To maintain the current balance among aspen, birch, spruce, and fir, forest managers may have to choose other management options not studied in this paper, such as removal of conifer seedling layers at the time of harvest, or prescribed burns.

The results indicate that frequent harvest on some parts of the landscape and large harvest size are the best way to create large patches and diversity of age classes, including substantial representation of older age classes on the landscape. Coordination among landowners, larger clearcuts, and artificial clustering of clearcuts are three strategies that may help forest managers create age class diversity, although large harvests are the most effective at creating a mixture of young and old forest on a variety of forest types.

The average patch size on the Nashwauk Uplands landscape will probably always be small because of the natural heterogeneity of the landscape. However, it is possible to change the patch size distribution to create a few large patches that contain a significant proportion of land area.

Future studies of spatial landscape change at the subsection level should consider the dynamics of insect and disease outbreaks. It is known that the size, shape, and distribution of forest patches can have an effect on the extent of an outbreak. Outbreaks, in turn, affect the size, shape, and distribution of forest types (Jaakko Poyry 1992). Another major consideration to include in a follow up study is the effect of climate change on forest patterns. In the next century summer temperatures in Minnesota are predicted to increase by 7-16°F and winter temperatures are predicted to rise by 6-10°F. The growing season will be lengthened by 3-6 weeks (Union of Concerned Scientists 2003). A changing climate can alter natural disturbance frequencies, establishment abilities, and susceptibility to insects and disease. All of these factors can influence the composition and spatial patterns of forests on the landscape.

LANDIS Strengths and Limitations

The strengths included:

- The ability to account for variability in disturbance size and location by performing several duplicate runs for each scenario, so that the mean and range of potential future conditions can be assessed.
- Biological reality for effects of wind and fire disturbance that occur even on a landscape managed for timber production, and how these disturbances may impact the species of trees present
- Spatial interactions of trees on adjacent pixels, including seed dispersal from adjacent pixels, which is clearly one of the most important forces that determine successional patterns.
- Realistic differences in shade tolerance and other life-history characteristics of tree species, and simulation of the effects of species differences, such as allowing more tolerant species to invade the understory for realistic succession as the forest ages, and estimates of which species will be able to dominate a given parcel of land over time.

The limitations of LANDIS were:

- Some important management considerations cannot be adequately simulated. Thinning simulations are risky because the removal of a cohort in an even-aged stand may result in the removal of every tree in the stand. There are no constraints on location of harvests that would be imposed by the road network in the real world, and no timber volume estimates that would allow an economic comparison among scenarios.
- The current version of the model does not allow planting, an important management strategy that could have spatial consequences.
- LANDIS is difficult to learn to run and to parameterize. It takes a few months to become familiar with and have confidence in setting up and running the model. Harvests do not automatically re-occur each decade. Instead, harvests must to be re-prescribed each decade, which results in large, complex input files and long runs (up to 9 hours each).

- Analyzing and interpreting the output is challenging. Output describing the spatial characteristics of simulated harvests are limited, making it hard for the user to determine whether desired harvest characteristics are accurately simulated. Also, metrics relating to young cohorts are very sensitive to uncertainty in establishment coefficients. It is difficult to determine whether alternative management strategies significantly affect these metrics because the effects are obscured by high error from establishment coefficients.
- The model does not simulate disease and insect infestations. Spruce budworm and tent caterpillars are important influences on succession and patch dynamics in northern Minnesota forests.

Some of these limitations, such as volume calculations and insect and disease simulations, will be addressed by newer versions of LANDIS.

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Table 1. Species characteristics

Species	longevity	age of reproductive maturity	shade tolerance rank	fire tolerance rank	effective dispersal distance (m)	max dispersal distance (m)	probability of vegetative reproduction after fire	age at which parent tree can sprout
Abies balsamea	80	25	5	1	50	160	0	0
Acer rubrum	120	28	3	2	-1	-1	0.5	60
Acer saccharum	200	40	5	2	100	-1	0.25	40
Betula papyrifera	100	15	2	2	60	75	1	100
Fraxinus nigra	200	40	2	2	-1	-1	0	100
Larix laricina	100	40	1	1	40	60	0	0
Picea glauca	90	30	4	1	40	60	0	0
Picea mariana	160	30	4	1	79	200	0	0
Pinus banksiana	120	10	1	3	20	40	0	0
Pinus resinosa	200	35	2	5	12	275	0	0
Pinus strobus	250	50	3	5	60	210	0	0
Populus balsamifera	80	10	1	3	-1	-1	1	80
Populus grandidentata	80	10	1	3	1	-1	1	80
Populus tremuloides	80	15	1	2	-1	-1	1	80
Quercus macrocarpa	250	35	2	5	5	10	0.75	80
Quercus rubra	180	50	3	3	10	15	0.75	80
Thuja occidentalis	250	30	5	2	20	60	0	0
Tilia americana	150	15	4	2	46	150	0.25	100

Table 2. Natural disturbances simulated on the Nashwauk Uplands landscape.

	Wind	**Fire**
Minimum disturbance size	5 ha	259 ha
Maximum disturbance size	3,785 ha	112,406 ha
Mean disturbance size	97 ha	9,324 ha
Mean return interval	1,500 years	(see table 3)

Table 3. Establishment coefficients and other landscape level attributes by landtype.

	Whalsten Till Plain	Pike-Sandy River Sand Plain	Big Rice Moraine	Nashwauk Moraine	Mesabi Range	Pengilly Till Plain	lowland	bog	wetland	non-forest	water
Abies balsamea	0.8085	0.6306	0.7879	0.6226	0.5091	0.3947	0	0	0	0	0
Acer rubrum	0.2128	0.2613	0.3636	0.2767	0.6545	0.2632	0	0	0	0	0
Acer saccharum	0	0.009	0	0.0692	0.4182	0.1053	0	0	0	0	0
Betula papyrifera	0.7447	0.5135	0.6667	0.5975	0.8545	0.5	0	0	0	0	0
Fraxinus nigra	0.1064	0.1081	0.1515	0.1824	0.1091	0.1579	0	0	0	0	0
Larix laricina	0.1915	0.2342	0.2424	0.1447	0	0.1316	0	0	0	0	0
Picea glauca	0.2128	0.1712	0.2121	0.239	0.2909	0.0526	0	0	0	0	0
Picea mariana	0.3404	0.3694	0.3636	0.2767	0.0909	0.1316	0	0	0	0	0
Pinus banksiana	0.1489	0.3243	0.2121	0.1384	0.0909	0	0	0	0	0	0
Pinus resinosa	0.1277	0.2252	0.1212	0.0692	0.0545	0.0526	0	0	0	0	0
Pinus strobus	0.1702	0.0721	0.1212	0.0126	0.0727	0.0526	0	0	0	0	0
Populus balsamifera	0.0851	0.1261	0.0606	0.2579	0.2182	0.2632	0	0	0	0	0
Populus grandidentata	0.0638	0.045	0.0303	0.0629	0.1091	0.1053	0	0	0	0	0
Populus tremuloides	0.7234	0.6847	0.7273	0.7421	0.8	0.8684	0	0	0	0	0
Quercus macrocarpa	0	0	0	0.013	0.013	0.0175	0	0	0	0	0
Quercus rubra	0	0.009	0	0.0189	0.2	0.0263	0	0	0	0	0
Thuja occidentalis	0.3191	0.1081	0.1212	0.0818	0.0364	0.0263	0	0	0	0	0
Tilia americana	0	0	0.0303	0.0377	0.2727	0.0789	0	0	0	0	0
minimum age of cohorts present before shade tolerant 5 species's establishment	60	60	20	40	60	50	0	0	0	0	0
mean fire return interval	70	70	225	150	2000	70	0	0	0	0	0
last windthrow disturbance	750	750	750	750	750	750	0	0	0	0	0
last fire disturbance	35	35	113	75	1000	35	0	0	0	0	0

Table 4. Alternative management scenarios.

Scenario	Goals	Description	Modification of input data
1 base		Current management practices	Target clearcut size = 24 acres, 10% of landscape harvested per decade
2 coord	Increase patch size, Increase patch size variability, Reduce costs	Increase coordination between landowners	Merge federal, state, county, private/industrial, and private/unknown management areas
3 cc_500	Increase patch size, Increase patch size variability, Reduce costs	Increase target clearcut size[1]	Increase target clearcut size from 24 acres to 500 acres (202 ha)
4 cluster	Increase patch size, Increase patch size variability, Reduce costs	Increase clustering of clearcuts	Add new management area consisting of eight ~2000 acre (~810 ha) patches on the landscape that have over 30% aspen and birch cover. Decrease clearcutting by 10% outside of these patches. Add the balance of the clearcuts to the new management area so that the total clearcut area on the landscape remains constant.
5 rot_short	Increase patch size, Increase patch size variability, Reduce costs, Increase productivity	Shorten rotation age	Shorten rotation age by 20%
6 rot_long	Increase patch size, Increase patch size variability, Reduce costs, Increase age class diversity	Lengthen rotation age	Lengthen rotation age by 20%
7 no_harv	Natural disturbances only	No harvest	No harvest

[1] Target size is the mean clearcut size that the model attempts to achieve. The natural heterogeneity of the landscape and land use patterns limit the ability of the model to meet target clearcut sizes.

Table 5. Calibration results

Calibration parameter	**Error estimate**
Mean size wind	-8%
Mean interval wind	-236%
Mean size fire	-1%
Mean interval fire - Whalsten Till Plain	-57%
Mean interval fire - Pike-Sandy River Sand Plain	-221%
Mean interval fire - Big Rice Moraine	+30%
Mean interval fire - Nashwauk Moraine	-159%
Mean interval fire - Mesabi Range	+52%
Mean interval fire - Pengilly Till Plain	-4756%

Table 6: Definitions of landscape and class metrics used in analysis (Mladenoff and DeZonia 2001).

Landscape Metrics	
Mean Patch Size	Area of landscape / number of patches (ha)
Edge Density	Total perimeter / total landscape area (m/ha)
Shannon-Weaver Diversity Index	$-\sum(p(i) \times \ln(p(i))$ where p = probability and i = class
Shannon-Weaver Evenness Index	$\frac{\text{Measured diversity}}{\text{Max possible diversity}}$ where measured diversity is SWDI, and max diversity is ln(# of classes present)
Contagion (relative-Li)	$1.0 - \left(\frac{-\sum\sum(t(i,j) \times \ln(t(i,j)))}{2 \times \ln(\text{\# of classes present})} \right)$ where t is an adjacency matrix and i and j represent total classes
Angular 2nd Moment	$\sum\sum(t(i,j)^2)$ where t is an adjacency matrix and i and j represent total classes
Aggregation Index	$\frac{\text{total adjacent edges of landscape with itself}}{\text{max adjacent edges of landscape with itself}}$
Class Metrics	
Relative Area	% of landscape in class
Mean Patch Size	Area of class / number of patches in class (ha)
Perimeter Area Ratio (Corrected)	Average of $\frac{\text{patch perimeter}}{(\text{area} \times 4\pi)\text{^}1/2}$
Fractal Index	2 x log-log regression of patch areas vs. patch perimeters
Edge Density	$\frac{\text{total perimeter of class}}{\text{total study area}}$ (m/ha)
Aggregation	$\frac{\text{total adjacent edges of class with itself}}{\text{max adjacent edges of class with itself}}$

Table 7. Forest type area in hectares for six covertypes at year 120. Highlighted cells represent forest type areas that significantly differed from base scenario values. RW = red and white pine, SF = spruce-fir, AB = aspen-birch, NH = northern hardwoods, LC = lowland conifer, UM = upland mixed.

	base	coord	cc_500	cluster	rot_short	rot_long	no_harv
RW-young	2471	2177	1612	1992	4812	2597	1216
RW-pole	3	5	3	6	8	6	4
RW-mature	3	4	1	5	2	3	0
RW-old	6419	6788	9731	5656	4321	5441	6344
SF-young	27104	23800	11023	22028	42481	43152	18654
SF-pole	12256	7661	6454	7156	17865	11426	1887
SF-mature	28381	19645	7923	21531	9391	12797	23144
SF-old	11839	21199	47963	21995	10921	10528	11025
AB-young	10371	8922	10194	10254	10757	9555	7411
AB-pole	6863	12037	7244	10339	8645	4555	5954
AB-mature	3006	3432	2440	4051	3324	3524	6793
AB-old	1369	1689	2541	1299	432	1090	1157
NH-young	6176	5570	3119	6022	11072	8134	2607
NH-pole	1185	1396	1816	1634	1531	1172	266
NH-mature	828	1254	1050	1343	853	1047	833
NH-old	7532	8919	11490	9836	3960	4911	7515
LC-young	1218	1347	971	1012	3072	1208	981
LC-pole	171	471	206	276	415	102	16
LC-mature	472	438	345	342	304	231	11
LC-old	4729	9052	7145	7296	2884	5453	16903
UM-young	13893	9349	5369	9452	17594	24795	19753
UM-pole	20	33	26	59	28	34	20
UM-mature	18	29	30	57	27	35	77
UM-old	13258	14147	20926	15785	4747	8212	27161

Table 8. Mean forest patch sizes in hectares. Highlighted cells represent mean patch sizes that significantly differed from base scenario values. RW = red and white pine, SF = spruce-fir, AB = aspen-birch, NH = northern hardwoods, LC = lowland conifer, UM = upland mixed.

	base	coord	cc_500	cluster	rot_short	rot_long	no_harv
RW-young	0.78	0.74	0.60	0.68	1.09	0.90	0.87
RW-pole	0.43	0.44	0.32	0.51	0.55	0.63	0.38
RW-mature	0.45	0.45	0.17	0.49	0.48	0.38	0.18
RW-old	1.26	1.26	1.49	1.16	1.14	1.18	1.46
SF-young	2.55	2.44	1.67	2.36	3.28	3.08	1.92
SF-pole	2.61	2.51	2.60	2.33	2.97	2.59	1.68
SF-mature	3.18	2.69	2.62	2.56	2.51	2.49	2.91
SF-old	2.14	2.41	3.91	2.23	1.59	1.77	1.54
AB-young	5.38	4.69	5.05	4.14	4.88	6.75	7.39
AB-pole	5.38	6.11	4.49	5.82	5.96	3.93	9.35
AB-mature	5.00	4.25	3.32	4.15	3.48	3.77	18.28
AB-old	1.00	0.96	1.34	0.88	0.46	0.72	1.04
NH-young	2.49	2.31	2.42	2.51	3.27	2.93	1.44
NH-pole	2.03	1.87	2.50	2.30	1.86	2.11	1.49
NH-mature	1.61	2.27	1.84	1.89	1.52	1.83	3.09
NH-old	2.68	2.90	3.51	3.05	2.06	2.23	2.70
LC-young	1.46	1.32	1.46	1.28	2.44	1.52	1.10
LC-pole	1.12	1.30	1.16	1.21	1.28	1.15	0.60
LC-mature	1.88	1.66	1.64	1.56	1.63	1.53	0.79
LC-old	1.38	2.45	1.54	1.80	1.20	1.38	1.89
UM-young	1.61	1.08	0.71	1.29	1.64	2.03	1.87
UM-pole	0.77	0.86	0.76	0.78	0.80	0.80	0.73
UM-mature	0.88	0.88	0.85	0.94	0.76	0.82	0.93
UM-old	1.50	1.47	1.82	1.54	1.06	1.23	2.52

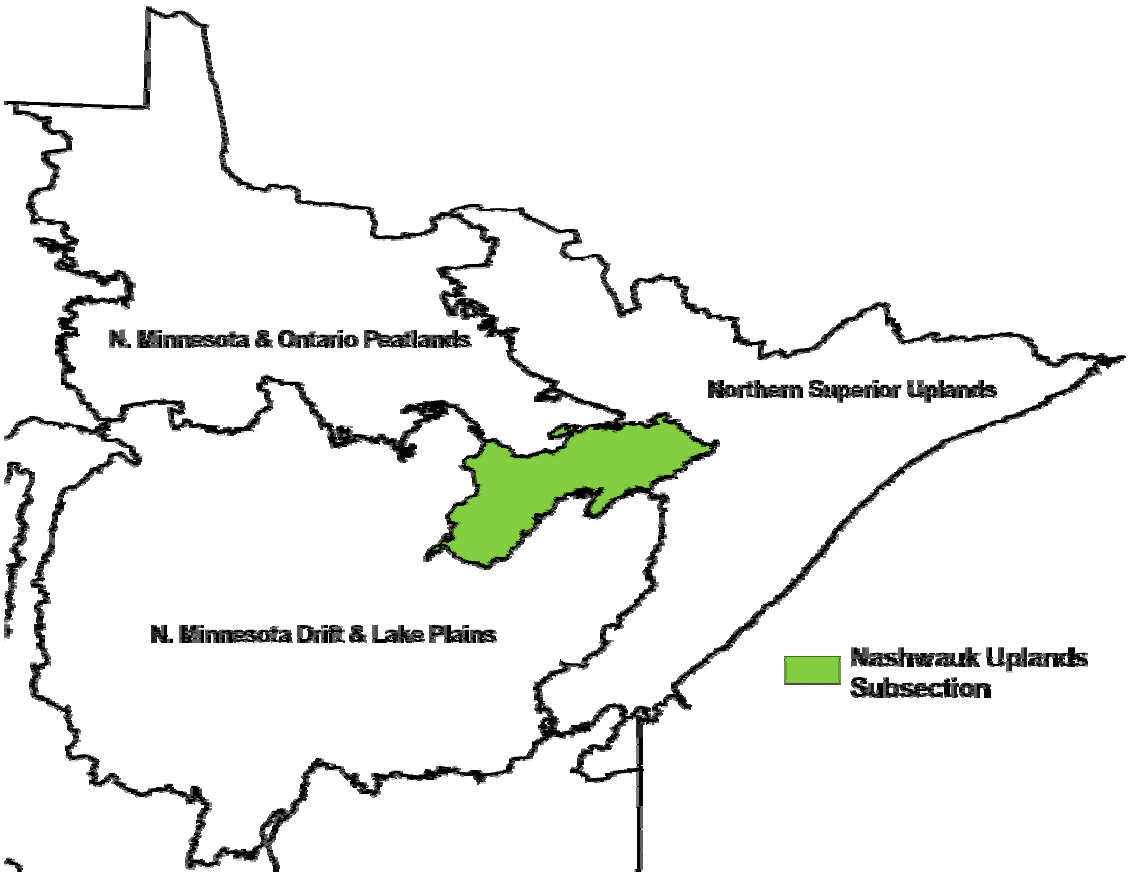

Figure 1. Location of the Nashwauk Uplands subsection in northeastern Minnesota

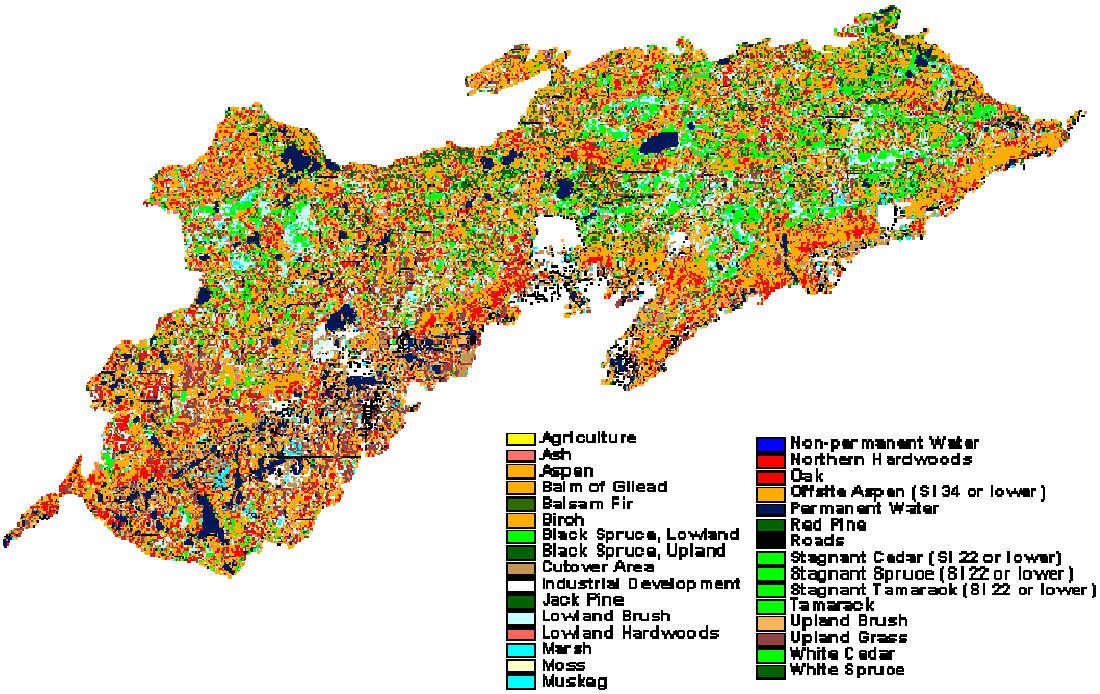

Figure 3. Current vegetation map used as input for all harvest scenarios of LANDIS simulations in the Nashwauk Uplands.

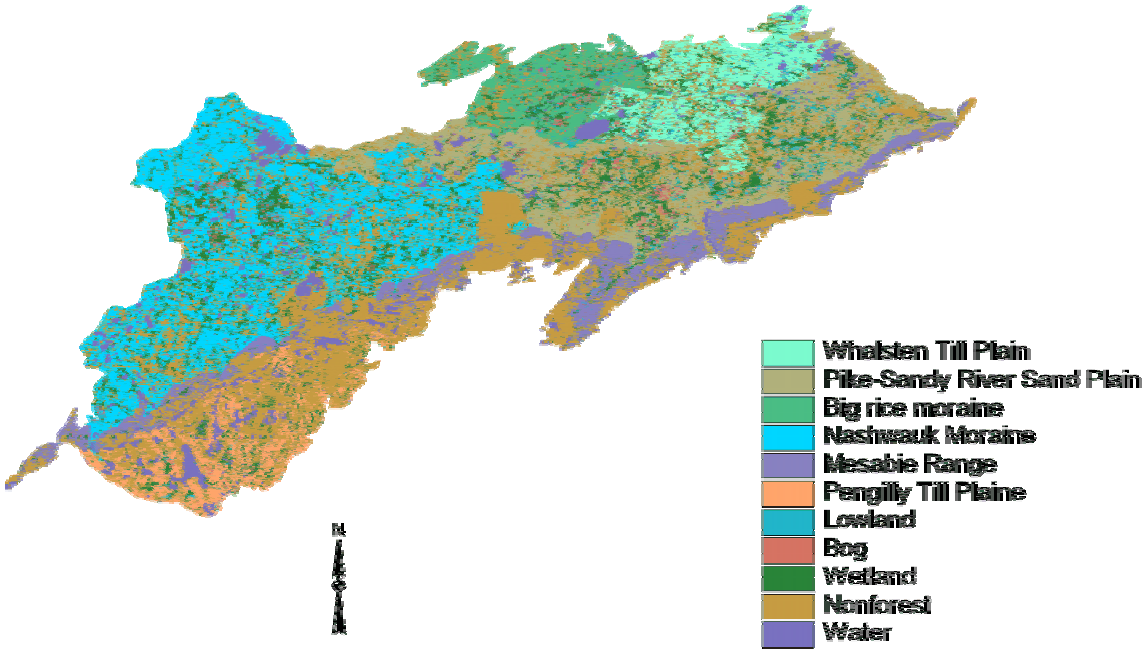

Figure 5. Landtype map for all harvest scenarios in Nashwauk Uplands

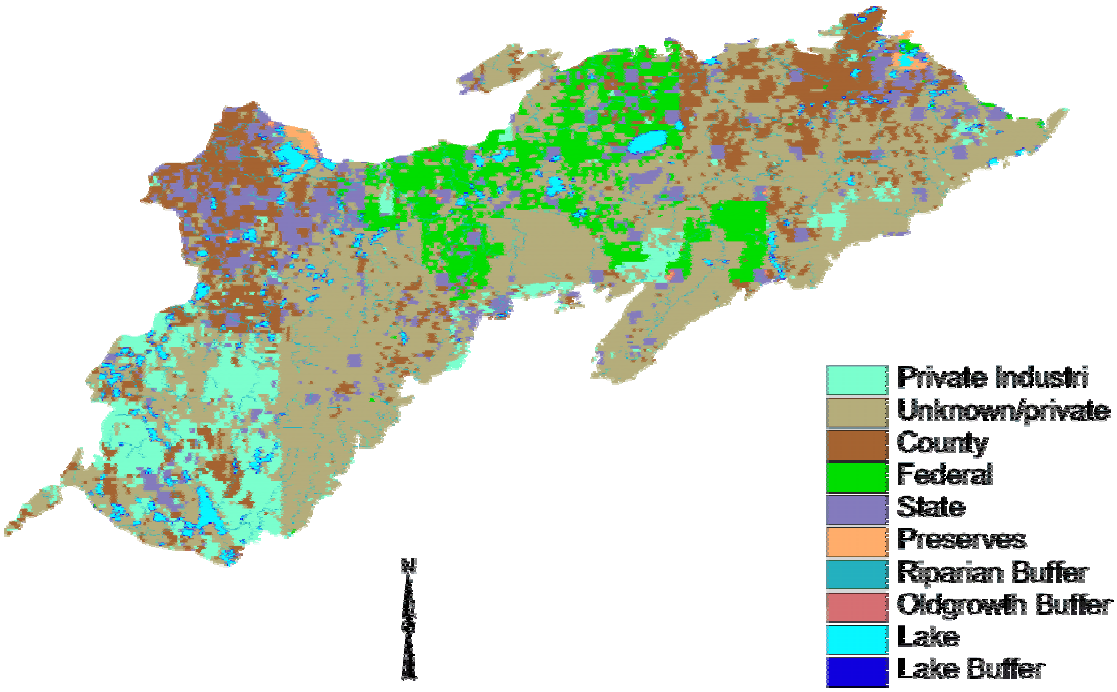

Figure 7. Default management area map for LANDIS simulations in the Nashwauk Uplands.

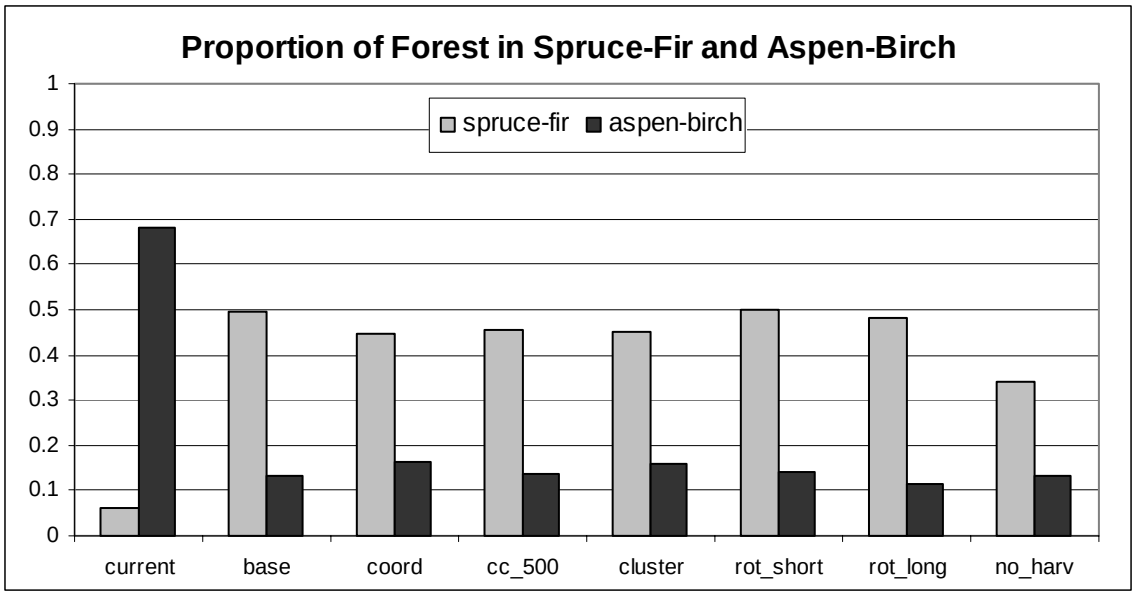

Figure 8. Proportion of forest area predicted in spruce-fir and aspen-birch covertypes among the scenarios. The current scenario porportion is based on Landsat imagery classification by Host and White (2002). All simulated scenarios predict an increase in spruce-fir and a decrease in aspen-birch forest area.

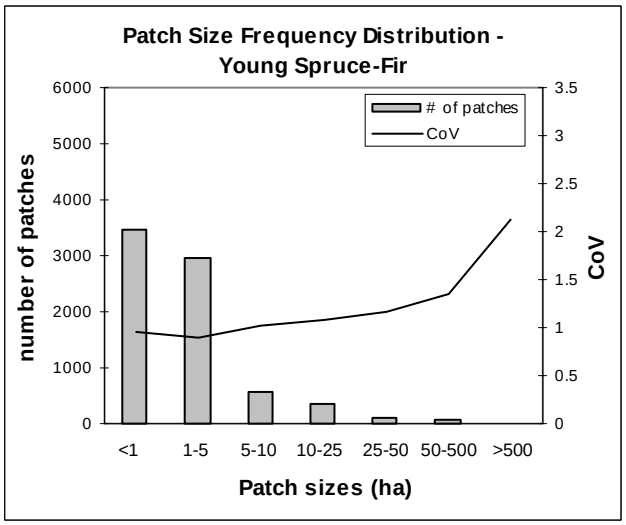

Figure 9. Example of a typical patch size frequency distribution and coefficient of variation, young spruce-fir.

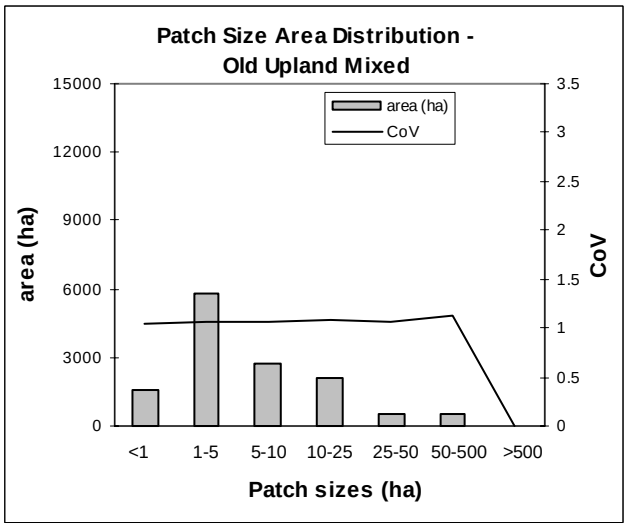

Figure 10. Example of a typical patch size-area distribution and coefficient of variation, old upland mixed forest.

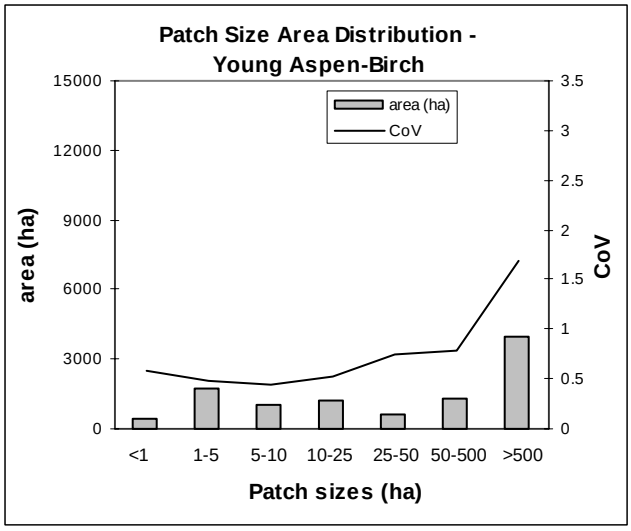

Figure 11. Distribution and coefficient of variation of young aspen-birch forest area among patch size classes. In all scenarios the distribution of aspen-birch forest area peaked in the large size classes.

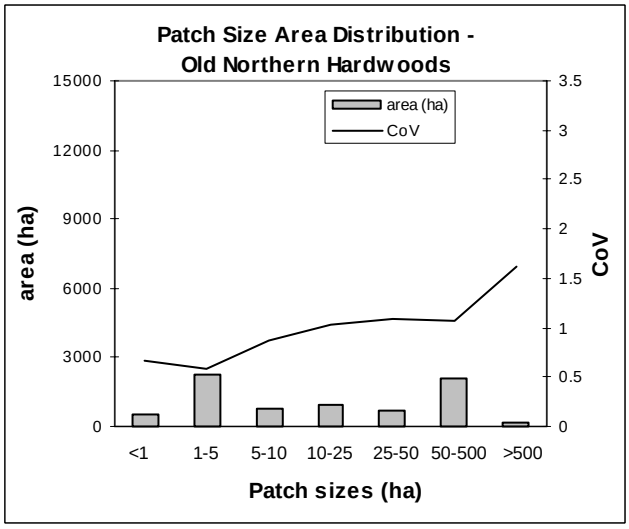

Figure 12. Distribution and coefficient of variation of old northern hardwood area among patch size classes. In all scenarios northern hardwood and spruce-fir forests had an even distribution of area allocated across patch size classes.

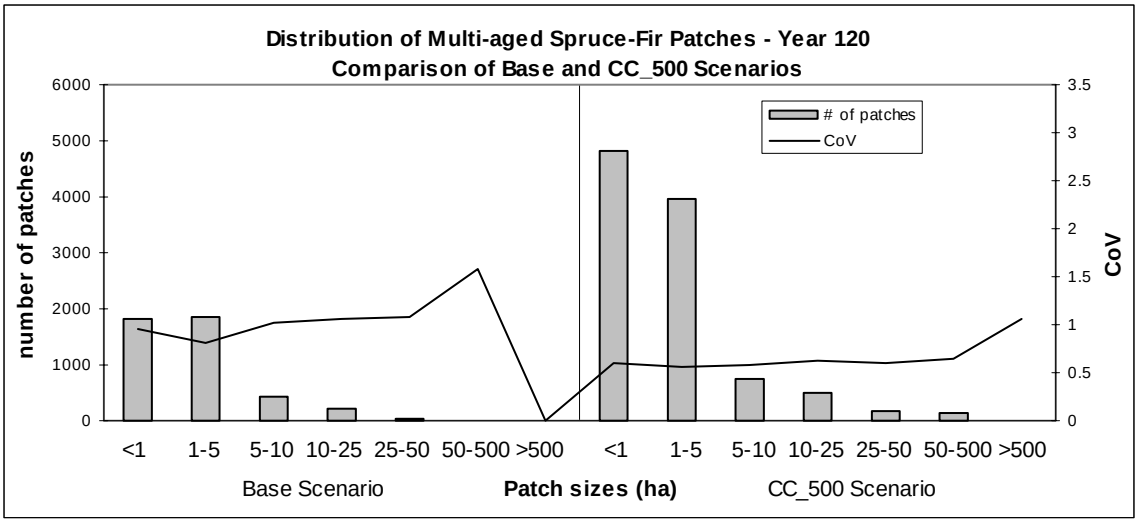

Figure 13. Frequency distribution of old spruce-fir patches across 7 size classes and the coefficient of variation of patch sizes within size classes. The patch size distribution is more skewed towards smaller patches in the scenario with 500 acre target clearcut sizes (cc_500), than in the base scenario.

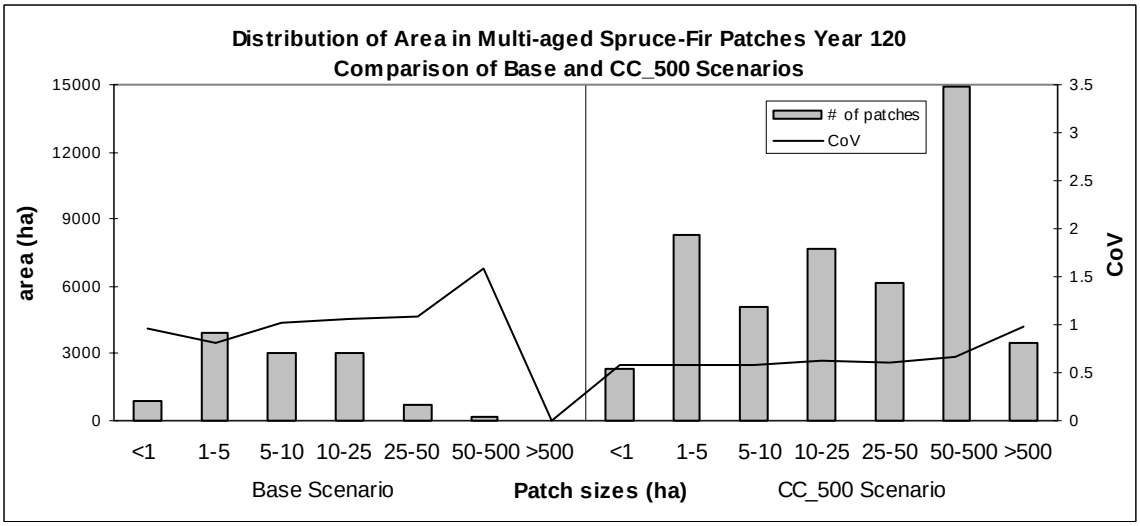

Figure 14. Distribution of old spruce-fir area across 7 patch size classes and the coefficient of variation of area in each size classes. The area distribution is more skewed towards larger patches in the scenario with 500 acre target clearcut sizes (cc_500), than in the base scenario.

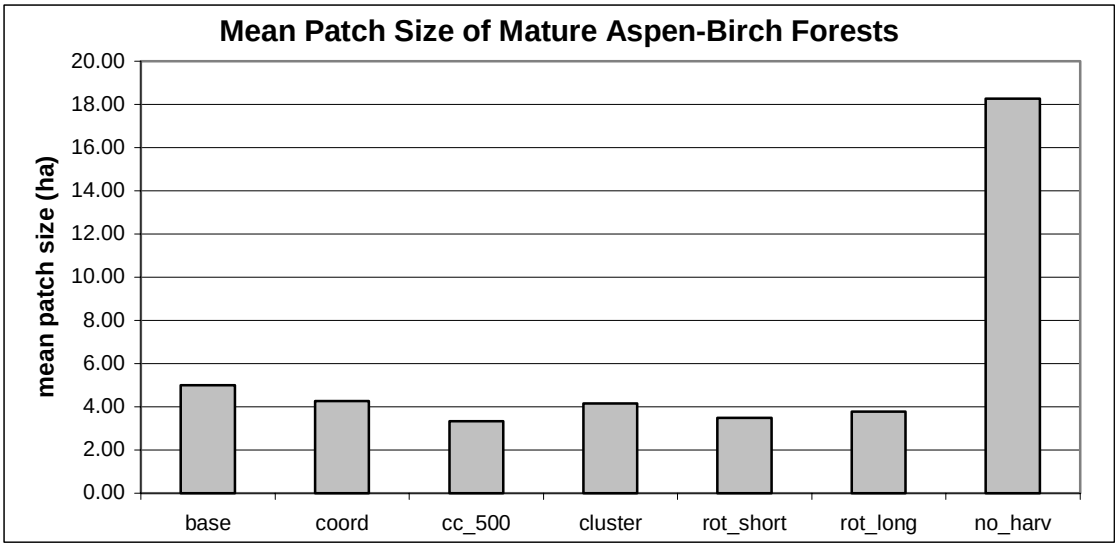

Figure 15. Mean patch size of mature aspen-birch forests by scenario.

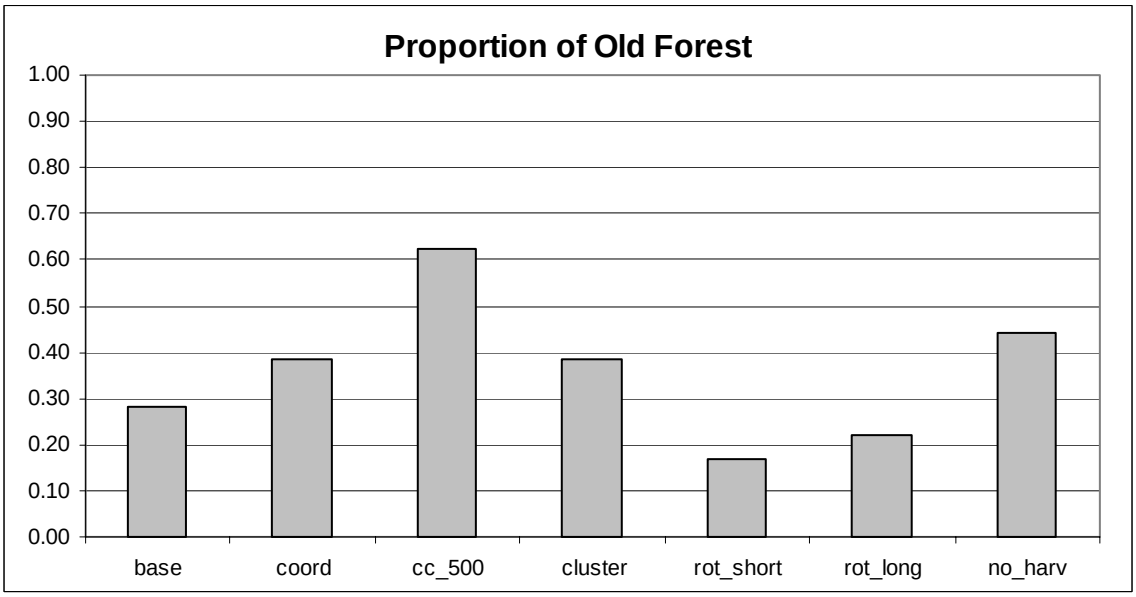

Figure 16. Proportion of forest predicted in old stage of development among the scenarios.

APPENDIX

```
# 65 type #
#abiebals#  1     00100100
#acerrubr#  1     000000000100
#acersac2#  1     00000000000000000000
#betupapy#  1     0000000000
#fraxnigr#  1     00000000000000000000
#larilari#  1     0000000000
#piceglau#  1     100100100
#picemari#  1     0000010010000000
#pinubank#  1     000000000000
#pinuresi#  1     00000000000000000000
#pinustro#  1     000000000000000000000000
#popubals#  1     00000000
#popugran#  1     00000000
#poputrem#  1     00000010
#quermacr#  1     000000000000000000000000
#querrubr#  1     000000000000000000
#thujocci#  1     000000010000000000000000
#tiliamer#  1     000000000000000
```

Figure A1: Example of 1 record in map_attributes.dat showing the presence of 10 cohorts of 6 species for all pixels in species.gis labeled 65.

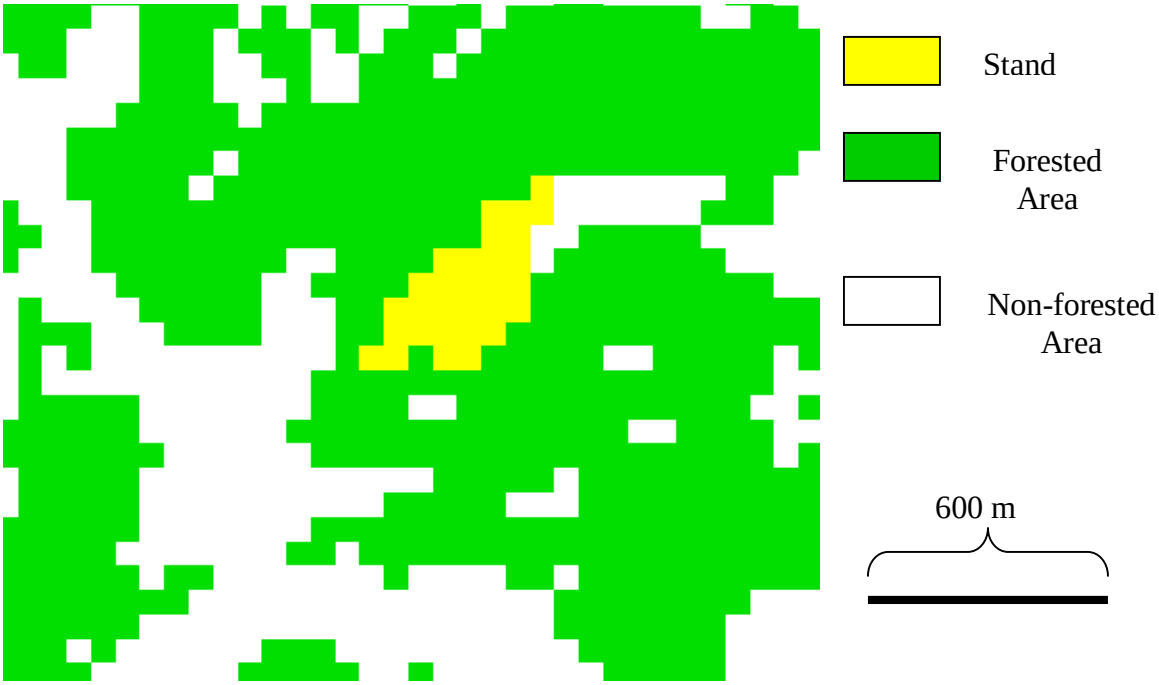

Figure A2. Example of forest stand delineation used in all LANDIS simulations of the Nashwauk Uplands. Over 53,000 stands were identified for scenario 1, but only one is depicted here.

```
4                   # Harvest regime 4 - One-entry, stand-spreading #
aspen-clearcut      # Event label #
5                   # Management area id #
30                  # Minimum stand age (in years) #
3                   # Economic Ranking algorithm #
1                   # Entry decade #
1271                # Target number of pixels to cut #
27                  # Mean number of pixels included in each harvest #
2                   # Standard deviation (of harvest size distribution) #

# aspen clearcut #
#abiebals# 00011111
#acerrubr# 000111111100
#acersac2# 00011111110000000000
#betupapy# 0001110000
#fraxnigr# 00011111110000000000
#larilari# 0000000000
#piceglau# 000111111
#picemari# 0000000000000000
#pinubank# 000000000000
#pinuresi# 00000000000000000000
#pinustro# 000000000000000000000000
#popubals# 00111111
#popugran# 00111111
#poputrem# 00111111
#quermacr# 000111111100000000000000
#querrubr# 000111111100000000
#thujocci# 000000000000000000000000
#tiliamer# 000111111100000

# economic ranks aspen clearcut - rank, maturity #
#abiebals#    1 40
#acerrubr#    1 120
#acersac2#    1 120
#betupapy#    1 70
#fraxnigr#    1 50
#larilari#    1 80
#piceglau#    1 40
#picemari#    1 60
#pinubank#    1 50
#pinuresi#    1 90
#pinustro#    1 120
#popubals#    75 10
#popugran#    75 30
#poputrem#    75 30
#quermacr#    1 120
#querrubr#    1 120
#thujocci#    1 110
#tiliamer#    1 120
```

Figure A3: Example of a harvest prescription

Steps to defining coverytpe

a) Select a pixel
b) Define the neighborhood around the pixel (include the pixel)
c) Count the number of pixels in the neighborhood that each of 18 species occurred on [$Count_{species_i}$]
d) Sum the counts across all 18 species to get a total count [$Count_{total} = Count_{species_i}$]
e) Divide individual species counts by the total count to give the relative frequency for each species [$RF_{species_i} = Count_{species_i} / Count_{total}$]
f) Define new variables that are combinations of relative frequencies for species groups:
    1) $RW = RF_{red_pine} + RF_{white_pine}$
    2) $JP = RF_{jack_pine} + RF_{burr_oak}$
    3) $SF = RF_{white_spruce} + RF_{balsam_fir}$
    4) $AB = RF_{trembling_aspen} + RF_{balsam_poplar} + RF_{bigtoothed_aspen} + RF_{paper_birch}$
    5) $NH = RF_{sugar_maple} + RF_{basswood} + RF_{red_oak} + RF_{red_maple}$
    6) $LC = RF_{white_cedar} + RF_{black_spruce} + RF_{tamarack}$
    7) $LH = RF_{black_ash} + RF_{red_maple}$
    8) LOWL = LC + LH
    9) UPL = RW + JP + SF + AB + NH
    10) LMIX = LC/LH
    11) UMIX = (RW + JP + SF)/(AB + NH)
    12) MB = AB / SF
    13) RF_{max} = variable 1-7 with greatest RF
g) Define covertypes using the decision tree (Figure 1) to evaluate neighborhoods

Steps to defining age

a) For each species*age, use the following thresholds to define age categories
    a. 0-19 y Young
    b. 20-49 y Pole
    c. 50-79 y Mature
    d. > 79 y Old
b) For covertypes RW, JP, SF, AB, MB, NH, LC, and LH, define neighborhood age as the age category with highest relative frequency using only the species that are characteristic of the covertype (e.g. use only Red Pine and White Pine ages to define age of a RW neighborhood).
c) For covertypes UM and LM, define neighborhood age as the age category with the highest relative frequency using all species.

Figure A4: Covertype and age class definitions

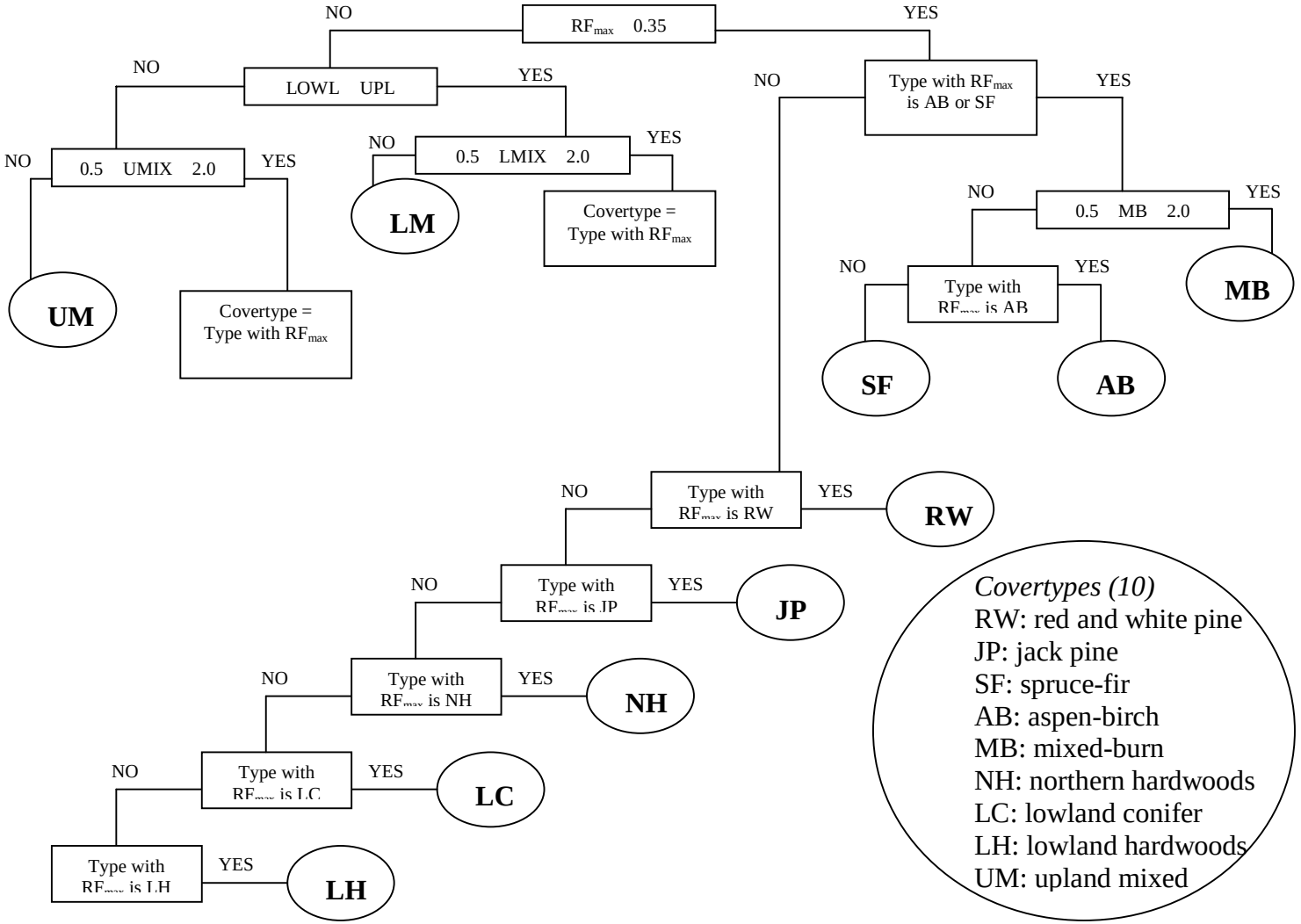

Figure A5. Decision tree for defining pixel covertype using the frequency of species in the neighborhood.