

Simulating stand-level harvest prescriptions across landscapes: LANDIS PRO harvest module design

Jacob S. Fraser, Hong S. He, Stephen R. Shifley, Wen J. Wang, and Frank R. Thompson III

Abstract: Forest landscape models (FLMs) are an important tool for assessing the long-term cumulative effects of harvest over large spatial extents. However, they have not been commonly used to guide forest management planning and on-the-ground operations. This is largely because FLMs track relatively simplistic vegetation information such as age cohort presence/absence, forest type, and biomass that are incompatible with tree density and size on which most harvest prescriptions are based. We describe and demonstrate the newly developed harvest module of the LANDIS PRO FLM, which tracks density, size, basal area, and stocking by species age cohorts for each site (cell). With this quantitative information, the module can simulate basal area controlled harvest, stocking-level controlled harvest, and group selection harvest. Through user-specified harvest year (frequency), stand ranking, and species and age preference, the new module can simulate a wide variety of harvest prescriptions such as thinning from above and below, shelterwood, clear-cutting, and group selection. We applied the LANDIS PRO harvest module to a large (17 000 km²) central hardwood forest landscape in Missouri. The simulated harvest prescriptions produced realistic stand-scale results when plotted on Gingrich stocking charts. The harvest module improves on previous versions by allowing partial treatment of individual age-classes within a cell and reporting results in metrics commonly used in stand-scale silviculture. It provides a closer link between landscape-scale simulation methods and stand-scale management.

Résumé : Les modèles de paysage forestier (MPF) sont des outils importants pour évaluer les effets cumulatifs à long terme de la récolte de bois sur de vastes superficies. Cependant, ils n'ont pas été communément utilisés comme guide pour la planification de l'aménagement forestier et les opérations sur le terrain. Cela est surtout dû au fait que les MPE font le suivi de données relativement simplistes sur la végétation, telles que l'absence ou la présence de groupes d'âge, le type forestier et la biomasse qui sont incompatibles avec la densité et la taille des arbres, données sur lesquelles sont fondées la plupart des prescriptions de récolte. Nous décrivons et illustrons le module de récolte qui vient d'être développé dans le MPF LANDIS PRO et qui fait le suivi de la densité, de la taille, de la surface terrière et de la densité relative par groupes d'âge de chaque espèce dans chaque station (cellule). Avec cette information quantitative, le module peut simuler une coupe limitée par la surface terrière, une coupe limitée par la densité relative ou une coupe de jardinage par groupe. À partir de l'année de la récolte (fréquence), du classement des peuplements, ainsi que des préférences concernant l'espèce et l'âge déterminés par l'utilisateur, le nouveau module peut simuler une vaste gamme de prescriptions de récolte, telles que l'éclaircie par le haut ou le bas, la coupe progressive, la coupe à blanc et la coupe de jardinage par groupe. Nous avons appliqué le module de récolte de LANDIS PRO à un vaste (17 000 km²) paysage de forêt feuillue centrale au Missouri. La simulation de prescriptions de récolte a produit des résultats réalistes à l'échelle du peuplement lorsqu'ils étaient représentés sur des diagrammes de densité de Gingrich. Le module de récolte constitue une amélioration par rapport aux versions précédentes parce qu'il permet le traitement partiel de classes d'âge individuelles à l'intérieur d'une cellule et la présentation des résultats à l'aide de métriques communément utilisées pour la sylviculture à l'échelle du peuplement. Il procure un lien plus étroit entre les méthodes de simulation à l'échelle du paysage et l'aménagement à l'échelle du peuplement. [Traduit par la Rédaction]

Introduction

Harvest influences forest composition and structure from fine to broad spatial scales (Papaik et al. 2010). Forest landscape models (FLMs) are an important tool for understanding the cumulative effects of harvest, since field experiments at broad scales are rarely possible (He et al. 2008). There has been remarkable progress over the past two decades in the development of FLMs to simulate forest harvesting and its effects on landscape pattern (Gustafson et al. 2000), forest composition and structure (Johnson et al. 2007), and wildlife habitats (Shifley et al. 2006). Despite the success, however, FLMs have contributed relatively little to guide forest management planning and on-the-ground operations (Shifley et al. 2009). This is largely because FLMs have relied on relatively simplistic representations of site-level processes, leading to a gap between simulated and actual harvest prescriptions (He et al. 2011).

Site-level processes in FLMs contain two distinct hierarchical processes: species level and stand level. Species-level processes simulate tree species birth (germination and establishment), vegetative reproduction, growth, and mortality. Stand-level processes simulate competition among trees for resources (such as light and nutrients) and regulate species-level processes, such as mortality caused by self-thinning (Deutschman et al. 1999). Because of computation limitations, most FLMs use either rules defined through species vital attributes (e.g., species with higher shade tolerance will replace those with lower shade tolerance) or predefined successional pathways (e.g., late-successional forest types replace early successional types within a defined timeframe) to simplify the species- and stand-level processes. Such approaches sacrifice population information (e.g., density, tree number, basal area, and stocking) with models recording primarily qualitative information such as species absence/presence in LANDIS (Mladenoff et al. 1996) or

Received 16 May 2013. Accepted 13 July 2013.

J.S. Fraser, H.S. He, and W.J. Wang, School of Natural Resources, University of Missouri, 203 ABNR Building, Columbia, MO 65201, USA.
S.R. Shifley and F.R. Thompson, III, USDA Forest Service, Northern Research Station, 202 ABNR Building, Columbia, MO 65201, USA.

Corresponding author: Jacob S. Fraser (e-mail: fraserjs@missouri.edu).

forest community types in LANDSUM (Keane et al. 2004) and SIMPPLE (Chew et al. 2004). This qualitative information is largely incompatible with tree density and size upon which most harvest prescriptions are based.

The LANDIS family of models is designed to simulate long-term (>100 years) harvest, among other disturbances, and site-level succession over large landscapes (>10⁵ ha) at variable time-step iterations (1–10 years). It has been successfully applied in over 40 countries and regions (Mladenoff 2004). In previous versions of LANDIS, each species was represented in a site (or cell) as the presence or absence of age-classes in multiples of 1–10 years. The relatively coarse data structure is difficult to link with actual silvicultural harvest prescriptions that typically specify a target residual basal area or stocking percentage, sometimes with additional constraints by species group and tree size class (Shepperd 2005).

We recently developed the LANDIS PRO FLM based on over a decade of development and testing of the original LANDIS model (Mladenoff and He 1999; Wang et al. 2013). We improved the data structure in LANDIS PRO to track the number of trees by species and age-class on each site. It is possible to estimate the corresponding basal area and stocking percentage per hectare by using a tree age to tree diameter conversion. This data structure also allows the simulated succession and disturbance processes to operate on individual trees rather than entire age cohorts.

The development of LANDIS PRO enabled the design of a new harvest module with algorithms that have the capacity to select harvest sites based on quantitative stand criteria such as stocking percentage or basal area, and to apply harvest prescriptions that may remove all or part of individual species and age cohorts. Thus, our objectives in this paper is to (1) present the design of the new harvest module, (2) apply a variety of silvicultural harvest prescriptions to a large multiownership central hardwood forest landscape in Missouri, (3) evaluate the realism of harvest simulation results at the stand scale using a standard Gingrich stand density diagram to track simulated harvest dynamics in a format that is readily understood by practicing field foresters.

Harvest module design

Overview

LANDIS PRO (version 7.0) is a new model based on previous versions (2.0–6.0). It preserves and expands the functionalities of prior LANDIS versions and introduces a more detailed data structure in the succession and harvest modules. The new data structure tracks quantitative attributes including tree age, density, size, basal area, stocking, and importance value (relative tree density plus relative basal area) by species (Wang et al. 2013). These attributes can be used to rank stands and trees for harvesting or retention based on specified basal area or stocking percentage. The quantitative attributes projected for the future can also be summarized to examine projected changes in forest structure and composition in formats that are compatible with estimates from USDA Forest Service Forest Inventory and Analysis (FIA) and other forest inventories (Dijak 2013; Wang et al. 2013). Thus, simulation results can be vetted against observed changes from repeated measurements of large-scale forest inventories and against established theories of forest stand dynamics.

The harvest module requires two maps in addition to the forest composition map and land-type (ecoregion) map required to operate the core LANDIS succession module: a management area map and a forest stand map. The management area map delineates area units within which certain specified types of harvest events are implemented. They are analogous to management areas identified in the US National Forest planning process and similar to management compartments often designated on large private forest ownerships to help schedule harvesting and other silvicultural activities. The forest stand map delineates stand boundaries. Stands identified within a management area are

smaller continuous units (e.g., 2–20 ha in extent) that are relatively homogenous with respect to species composition, size structure (the distribution of diameters for each species' age cohort), site quality, and physiography. Stands are the smallest identified treatment unit to which harvest operations are applied.

Each unique harvest treatment parameterized by the user is considered a harvest event. Users define the management area to treat, the stand ranking method, the target proportion of the management area to treat, the type of harvest, removal amount, species to harvest, and number of individuals of each species to plant. Multiple harvest events can be set to occur within a management area in one model time step. Harvest events can be set to occur during any time step, and recurring harvest events can be designed to repeat at specified intervals. Harvest events can also be set to treat selected stands in a specified initial year and then revisit the same stands and apply a subsequent specified treatment in a later year. An example is a shelterwood harvest where the overstory trees in the stand are thinned during the first step to encourage forest regeneration and then, 10–20 years later, the stand is revisited to remove the residual overstory trees.

Ranking procedures to select stands for treatment

When a harvest event is triggered within a management area, individual stands are selected for treatment based on a user-defined ranking algorithm and then the harvest treatment is applied to all forested cells in the stand, one stand at a time, until the harvest amount set by the user is satisfied (Fig. 1).

Eligibility for harvest of a given stand within a given management area is typically determined by a combination of preferences and (or) limitations based on stand age, stand basal area, stand stocking percent, tree size, or tree species. Currently, the harvest module has three ranking algorithms to determine the priority of stands for harvest. The first is a random function where eligible stands are drawn at random and treated until the desired proportional area of the management area has been treated or some other constraint terminates the process (e.g., no more stands meet minimum basal area).

The second is a basal area ranking algorithm where eligible stands are harvested in descending order starting with the stand that has the greatest stand basal area as calculated in the following equation:

$$(1) \quad BA_s = \frac{\sum BA_c}{(N \times CS^2)/10000}$$

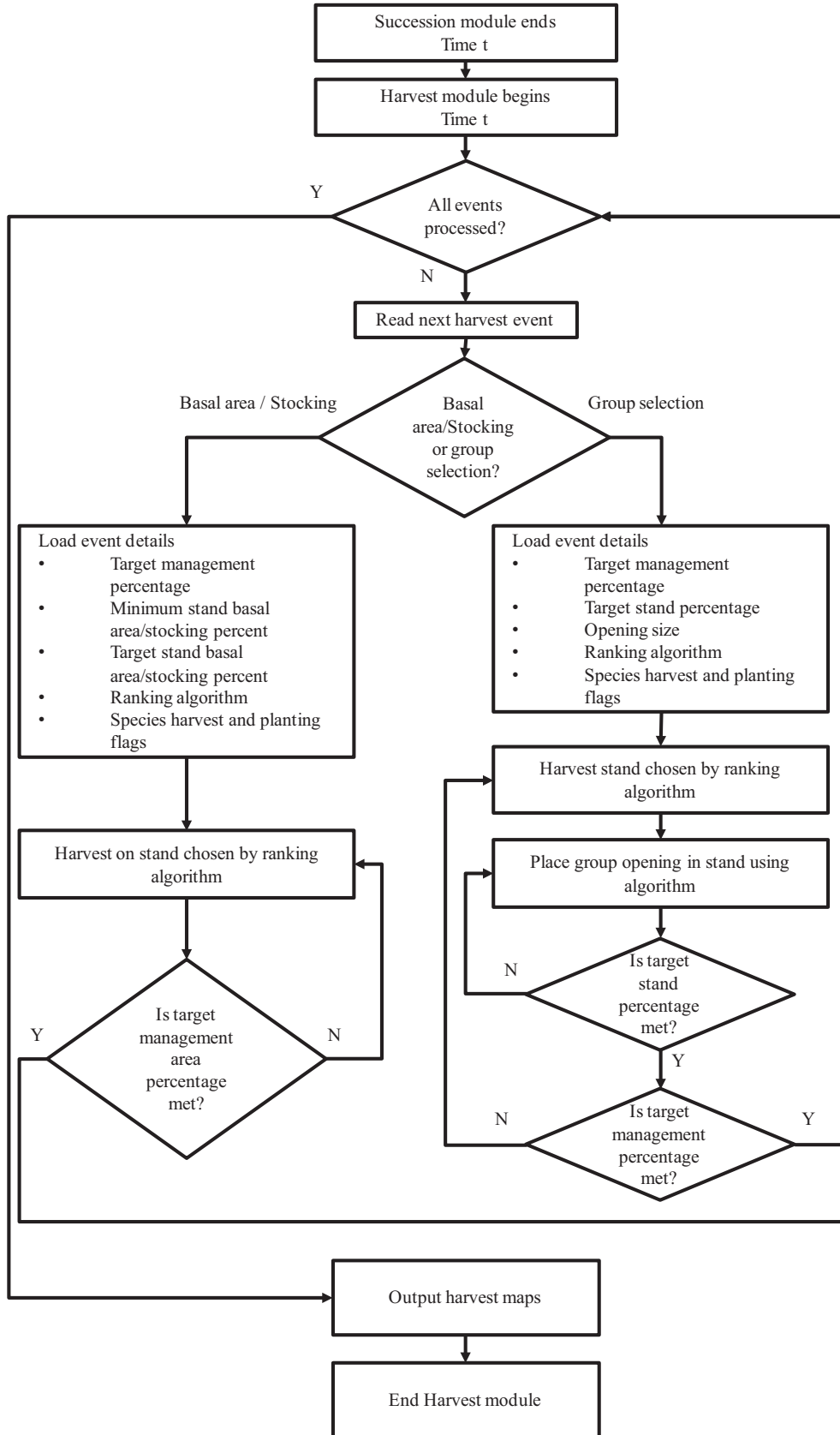
where BA_s is stand basal area in square metres per hectare, BA_c is the basal area in square metres of each cell within a stand, N is the number of cells within a stand, and CS is the cell size in metres.

The third algorithm ranks stands by calculating the Gingrich stand-stocking percentage, which is a measure of the growing space occupied by trees within a stand relative to the maximum limit and is calculated using the following formula (Gingrich 1967):

$$(2) \quad S = C_1 N_t + C_2 \sum D + C_3 \sum D^2$$

where S is the stand-stocking percentage; C_1 , C_2 , and C_3 are the regression coefficients for a model estimating individual tree area given a specific tree density and size distribution in various forest types; N_t is the number of trees per hectare for the stand; D is the individual tree diameter (cm/ha), and D^2 is the squared individual tree diameter (cm²/ha). For this study area we used the values –0.00507, 0.01698, and 0.00317 for the coefficients C_1 , C_2 , and C_3 , respectively, which is consistent with published research pertaining to upland oak and hickory forests in the region (Gingrich

Fig. 1. Flow-chart of the LANDIS PRO 7.0 harvest module process for each management area.



Can. J. For. Res. Downloaded from www.nrcresearchpress.com by UNIV OF MISSOURI - COLUMBIA on 10/08/13
For personal use only.

Table 1. Harvest module parameters for simulating common forest management prescriptions.

Harvest type	Removal order	Target basal area (m ² /ha)	Percentage of target stocking (%)	Mean group size (cells)	Group size SD (cells)	Percentage of stand area treated (%)
Clear-cut	Largest first	0.0	—	—	—	—
Thinning from above	Largest first	17.0	—	—	—	—
Thinning from below	Smallest first	17.0	—	—	—	—
Shelterwood	Smallest first	—	50.0	—	—	—
Group selection	—	—	—	2	1	20.0

1967). The Gingrich stocking equation is a widely used method for simultaneously examining the change in BA, the number of trees, the quadratic mean stand diameter, and the stocking percentage following the harvest of a stand. Stands are harvested in descending order starting with the highest stand stocking percentage.

Basal area controlled harvest

In the BA-controlled harvest, trees are removed from a stand until a user-defined target residual basal area is reached. Users can set a minimum stand basal area that the stand must be greater than to be eligible for harvest. The harvest algorithm can remove trees in ascending order of size starting with the smallest size classes (e.g., mimicking thinning from below or shelterwood harvesting) or in descending order starting with the largest size classes (mimicking thinning from above). If the target residual BA is at or near zero, the treatment corresponds to a clearcut. To determine the amount of cutting that needs to occur on each cell, the program takes the difference between the current BA_s and the target BA_s. This difference is multiplied by each cell's BA relative to the total BA_s to calculate the amount of basal area to be removed for that cell.

At the cell level, the program tracks the number of individual trees in each age-class. Using either a default curve or user-defined values, the age of each species is converted to a diameter (Loewenstein et al. 2000). This diameter is used to calculate a BA for each age-class for each species. To decrease processing time, the program then divides the total set of age-classes for each species into four equally sized groups. Since species longevity vary, the group sizes will vary between species. The BA per age-class group is calculated and the groups are harvested for each species until the BA in the age group would exceed the remaining target harvest amount. This triggers an iterative process where the program will then enter each age group and harvest individual trees until the remaining harvest target is met.

When combined with species-specific harvest constraints, this harvest method can simulate a range of commonly used forest harvest practices including clear-cut, shelterwood, and selection harvests as well as various thinning methods.

Stocking level controlled harvest

The second type of harvest event is controlled by stand-stocking levels. The user can define a minimum stocking level that stands must exceed to be eligible for harvest. This method operates similarly to the BA-controlled harvest, but uses the previously described Gingrich (1967) stand density stocking percentage rather than BA to control harvest amounts.

Group selection harvest

The third type of harvest event is group selection. It is designed to harvest small groups of trees to create canopy openings within a stand. Canopy openings can vary in size depending on the silvicultural objectives; 0.1–1.0 ha is typical. Starting with the user-specified year, the program uses the specified ranking algorithm to select specific stands within a management area for treatment. Within a stand, group opening harvests are clusters of cells where all tree species that are otherwise eligible for harvest are removed. The size of each group opening is drawn from a normal probability distribution for which the user specifies the mean number of

cells and standard deviation. The minimum group opening size is one cell, therefore, the spatial resolution of the cells used to represent the landscape must be considered when parameterizing the model for harvest. For example, the area covered by a single 10 m cell is roughly the area occupied by a mature hardwood tree in the US Midwest (Johnson et al. 2002). Consequently, for a landscape represented at a 10 m resolution, a group selection harvest that clears a single cell (100 m²) approximates individual tree harvesting. Larger cell sizes result in larger minimum sizes for group selection harvest openings.

Simulated harvest openings are placed within a stand until the cumulative area of harvest openings in the stand reaches the proportion of the total stand area specified by the user for treatment. The placement of openings is controlled by an algorithm that will attempt to distribute them throughout the stand with no opening adjacent to another, even in neighboring stands, although an opening may be placed adjacent to another if it is necessary to meet the target stand treatment proportion. The harvest algorithm will then move on to the next stand determined by the priority ranking algorithm and continue until the cumulative area of treated stands reaches the user-specified proportion of the management area to be treated. When a stand is treated with group selection harvest, the entire area of the stand is used to calculate the proportion of the management area that has been treated, not just the cells where the group harvests occur.

Case study

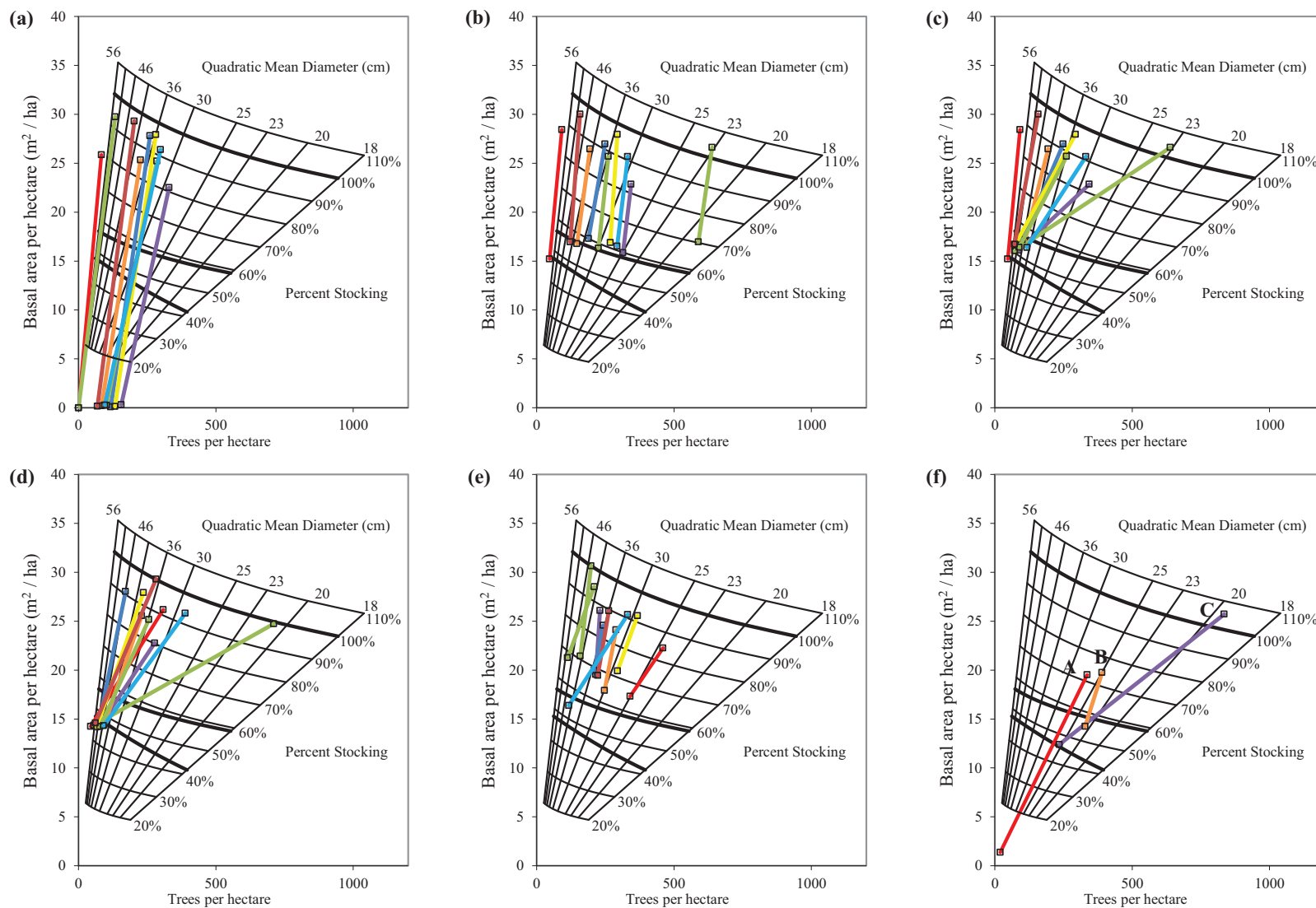
Study area

To demonstrate the effects of the harvest module, we selected a large forest landscape in southern Missouri. The study area is comprised of 17 600 km² of forested area in the Ozark Highlands ecological section in Missouri. Common tree species in this area include white oak (*Quercus alba* L.), post oak (*Quercus stellata* Wangenh.), black oak (*Quercus velutina* Lam.), hickory (*Carya* spp.), sugar maple (*Acer saccharum* Marsh.), and shortleaf pine (*Pinus echinata* Mill.). Based on FIA reports of tree density and biomass amounts, we chose to simulate seven species: a white oak group, a black oak group, a hickory group, eastern redcedar (*Juniperus virginiana* L.), shortleaf pine, sugar maple, and an elm group (*Ulmus* spp.).

Model simulations

The initial landscape and species age–diameter relationships were parameterized using FIA inventory data with the methodology described in Wang et al. (2013) and the simulation was run for 150 years at a 5 year time step. The harvest module was parameterized to apply five common management practices; clear-cutting, thinning from above, thinning from below, shelterwood harvest, and group selection harvest (Table 1) to over 65 500 stands across the landscape. The conditions simulated for the youngest age cohort often included large numbers of small diameter trees and vegetative sprouts, and those conditions usually changed rapidly within the next simulated time step. In common inventory practices, these small trees are usually excluded when estimating stocking percentage and BA, therefore, the youngest age cohort (1–5 years) for each species was left out when calculating these metrics (Kabrick et al. 2002).

Fig. 2. Gingrich stocking chart showing the change in stand density, basal area, quadratic mean diameter, and stocking percentage before and after harvest for 45 randomly selected stands with nine treated under each of five different harvest scenarios: clearcut (a), thinning from above (b), thinning from below (c), shelterwood (d), and group selection (e). The plots displayed in (f) are pre- and post-harvest stocking levels from two published studies conducted within the area simulated in this paper. Line A shows stocking before and after a clear-cut and line B shows the results of an intermediate thinning (Kabrlick et al. 2002). Line C shows the effects of a thinning that was conducted to leave vigorous individuals in the overstory (McMurry et al. 2007).



Evaluation of model predictions

We selected nine stands at random from the landscape for each of the simulated management practices to examine the effects at the stand scale. We used a Gingrich stocking diagram to illustrate harvest effects on BA, number of trees, quadratic mean diameter, and stocking percentage for each stand.

To build the Gingrich stocking diagrams showing harvest effects of individual stands, we created a GIS mask layer with stand boundaries. We examined the stands by running a zonal statistics function in ArcGIS on the BA and tree number maps output by the model to extract the total BA and number of trees present in each diameter class in the stands before and after the harvest event. These values were plotted using a Gingrich stocking chart Excel template (Larsen 2012). To assess the realism of the stand-level effects that each simulated prescription had, we plotted the pre- and post-harvest average stocking levels from three different published harvest studies conducted within the boundaries of our study area for comparison. The first was a clearcut and the second was an intermediate release thinning. Both were performed as part of the Missouri Ozark Forest Ecosystem Project (MOFEP) (Kabrick et al. 2002). The third was a fuel reduction thinning that favored vigorous individuals in the overstory (McMurry et al. 2007).

Results and discussions

The nine stands examined under the clear-cut simulation went from an 80%–95% stocking to a level just above zero following harvest (Fig. 2a). When compared against observed stocking levels of stands harvested under a clear-cut prescription (Fig. 2f, line A), the simulated stands followed a similar trend (Kabrick et al. 2002). In the thinning-from-above scenario, each of the nine stands dropped approximately 30% in stocking and the quadratic mean diameter decreased after harvest (Fig. 2b). This was in agreement with observed stocking levels from an intermediate release thinning (Fig. 2f, line B) (Kabrick et al. 2002). In the thinning-from-below scenario, each stand decreased 30%–50% in stocking, the quadratic mean diameter increased, and the trees per acre decreased sharply after harvest (Fig. 2c). The same behavior was observed in a fuel-reduction thinning that targeted smaller individuals in the stand (Fig. 2f, line C) (McMurry et al. 2007). The shelterwood harvest simulation shows that the trees per acre decreased in each stand and the stocking levels declined to about 40%, with a residual BA of approximately 14 m²/ha (Fig. 2d). Publications state that light to moderate shelterwood treatments have residual BAs ranging from 7.3 to 17.7 m²/ha after thinning from below (Dey and Parker 1996) or 40% to 50% residual stocking percentage (Schlesinger 1993). In the group selection scenario, stocking dropped 20%, and the quadratic mean diameter remained the same in most stands after harvest (Fig. 2e).

The new LANDIS PRO harvest module takes advantage of a more detailed quantitative data structure representing the forest stand age structure, size structure, and species composition. Relative to earlier LANDIS versions, it allows users to more precisely model harvest prescriptions at the stand scale by specifying residual BA, residual stocking percentage, group opening sizes, and constraints on species to be included or excluded. We used these quantitative tree- and stand-scale data in the new harvest module to prioritize stands for harvest and implement a wide range of harvest prescriptions. The previous version of the LANDIS harvest module (Gustafson et al. 2000) could output maps showing the type of harvest performed as well as the time of the last harvest event for each cell. This version carries over those capabilities and, in addition, outputs maps that report the amount of BA harvested for each species in each cell.

Examination of the harvest scenarios at the stand scale revealed realistic changes in forest BA, number of trees, and quadratic mean diameter for several harvest treatments. This was an important step in model verification. The clear-cut method reduced the stands to the specified BA amount. Since the removal began with

the largest trees, the quadratic mean diameter of the stands decreased. The comparison between the thinning from below versus the thinning from above produced expected results. Both prescriptions had the same target BA value, but one started removal with the smallest trees and the other with the largest trees. Where the removal was from above the number of trees in the stand did not decrease as much as with removal from below, since fewer trees needed to be cut to reach the target BA. The quadratic mean diameter of the stands decreased when thinned from above and increased when thinned from below. The shelterwood method performed in a similar manner to thinning from below, but the amount of BA removed was greater. The group selection method had little effect on the quadratic mean diameters of the stands and had varying amounts of removal, since the cells within each stand were chosen at random. The results from the clearcut, thinning from above, and thinning from below produced results in agreement with published pre- and post-harvest stocking levels using similar harvest prescriptions.

The new harvest module in LANDIS PRO can benefit forest management research and planning by providing a tool that is able to simulate forest harvest treatments based on parameters that are commonly used in forest management plans (Johnson et al. 2002). This design improves on previous versions by allowing partial treatment of individual age-classes within a cell and reporting results in metrics commonly used in stand-scale silviculture (Johnson et al. 2002). It provides a closer link between landscape-scale simulation methods and stand-scale management. Furthermore, because LANDIS PRO can be applied at large spatial extents (~10⁸ ha) it provides a tool to examine effects of harvest, disturbance, and succession at scales relevant to contemporary forest management issues addressing sustainability, bio diversity, and climate change.

Acknowledgement

We thank Qia Wang for the LANDIS PRO coding and William Dijak for general technical support. The project was funded by the USDA Forest Service, Northern Research Station and University of Missouri Mission Enhancement Program.

References

- Chew, J., Stalling, C., and Moeller, K. 2004. Integrating knowledge for simulating vegetation change at landscape scales. *West. J. Appl. For.* **19**: 102–108.
- Deutschman, D., Levin, S., and Pacala, S. 1999. Error propagation in a forest succession model: the role of fine-scale heterogeneity in light. *Ecology*, **80**: 1927–1943. doi:10.1890/0012-9658(1999)080[1927:EPIAFS]2.0.CO;2.
- Dey, D., and Parker, W. 1996. Regeneration of red oak (*Quercus rubra* L.) using shelterwood systems: ecophysiology, silviculture and management recommendations. Ontario Forest Research Institute Paper No. 126, Sault Ste. Marie, Ontario.
- Dijak, W. 2013. Landscape Builder: software for the creation of initial landscapes for LANDIS from FIA data. *Comput. Ecol. Software*, **3**: 17–25. doi:10.0000/issn-2220-721x-compucecol-2013-v3-0003.
- Gingrich, S.F. 1967. Measuring and evaluating stocking and stand density in upland hardwood forests in the central states. *For. Sci.* **13**: 38–53.
- Gustafson, E.J., Shifley, S.R., Mladenoff, D.J., Nimerfro, K.K., and He, H.S. 2000. Spatial simulation of forest succession and timber harvesting using LANDIS. *Can. J. For. Res.* **30**(1): 32–43. doi:10.1139/x99-188.
- He, H.S., Keane, R.E., and Iverson, L.R. 2008. Forest landscape models, a tool for understanding the effect of the large-scale and long-term landscape processes. *For. Ecol. Manage.* **254**: 371–374. doi:10.1016/j.foreco.2007.09.069.
- He, H.S., Yang, J., Shifley, S.R., and Thompson, F.R. 2011. Challenges of forest landscape modeling — Simulating large landscapes and validating results. *Landscape Urban Planning*, **100**: 400–402. doi:10.1016/j.landurbplan.2011.02.019.
- Johnson, P.S., Shifley, S.R., and Rogers, R. 2002. The ecology and silviculture of oaks. 2nd ed. CAB, Wallingford. doi:10.1079%2F9780851995700.0000.
- Johnson, K.N., Bettinger, P., Kline, J.D., Spies, T.A., Lennette, M., Lettman, G., Garber-Yonts, B., and Larsen, T. 2007. Simulating forest structure, timber production, and socioeconomic effects in a multi-owner province. *Ecol. Appl.* **17**: 34–47. doi:10.1890/1051-0761(2007)017[0034:SFSTPA]2.0.CO;2. PMID:17479833.
- Kabrick, J.M., Jensen, R.G., Shifley, S.R., and Larsen, D.R. 2002. Woody vegetation following even-aged, uneven-aged, and no-harvest treatments on the Missouri Ozark Forest Ecosystem Project Sites. In 2nd Missouri Ozark Forest Ecosystem Project Symposium. pp. 84–101.
- Keane, R.E., Cary, G.J., Davies, I.D., Flannigan, M.D., Gardner, R.H., Lavorel, S.,

- Lenihan, J.M., Li, C., and Rupp, T.S. 2004. A classification of landscape fire succession models: spatial simulations of fire and vegetation dynamics. *Ecol. Model.* **179**: 3–27. doi:10.1016/j.ecolmodel.2004.03.015.
- Larsen, D.R. 2012. Stand stocking. Available from <http://oak.snr.missouri.edu/nr3110/topics/gingrich.html> [accessed 1 April 2012].
- Loewenstein, E.F., Johnson, P.S., and Garrett, H.E. 2000. Age and diameter structure of a managed uneven-aged oak forest. *Can. J. For. Res.* **30**(7): 1060–1070. doi:10.1139/x00-036.
- McMurry, E.R., Muzika, R.-M., Loewenstein, E.F., Grabner, K.W., and Hartman, G. 2007. Initial effects of prescribed burning and thinning on plant communities in the Southeast Missouri ozarks. *In* 15th Central Hardwood Forest Conference. pp. 241–249.
- Mladenoff, D.J. 2004. LANDIS and forest landscape models. *Ecol. Model.* **180**: 7–19. doi:10.1016/j.ecolmodel.2004.03.016.
- Mladenoff, D.J., and He, H.S. 1999. Design, behavior and application of LANDIS, an object-oriented model of forest landscape disturbance and succession. *In* Spatial modeling of forest landscape change: approaches and applications. Edited by D.J. Mladenoff and W.L. Baker. Cambridge University Press, Cambridge, UK. pp. 125–162.
- Mladenoff, D.J., Host, G.E., Boeder, J., and Crow, T.R. 1996. LANDIS: a spatial model of forest landscape disturbance, succession, and management. *In* GIS and environmental modeling: progress and research issues. Edited by M.F. Goodchild, L.T. Steyaert, B.O. Parks, C. Johnston, D. Maidment, M. Crane, and S. Glendinning. John Wiley & Sons, New York. pp. 175–180.
- Papaik, M.J., Fall, A., Sturtevant, B., Kneeshaw, D., Messier, C., Fortin, M.-J., and Simon, N. 2010. Forest processes from stands to landscapes: exploring model forecast uncertainties using cross-scale model comparison. *Can. J. For. Res.* **40**(12): 2345–2359. doi:10.1139/X10-186.
- Schlesinger, R. 1993. Oak regeneration potential increased by shelterwood treatments. *North. J. Appl. For.* **10**: 149–153.
- Shepperd, W. 2005. SDI-Flex: a new technique of allocating growing stock for developing treatment prescriptions in uneven-aged forest stands. *In* Restoring Fire-Adapted Ecosystems: Proceedings of the 2005 National Silviculture Workshop. USDA For. Serv. Pacific Southwest Research Station, Albany, Calif. Gen. Tech. Rep. pp. 171–180.
- Shifley, S.R., Thompson, F.R., Dijak, W.D., Larson, M.A., and Millsbaugh, J.J. 2006. Simulated effects of forest management alternatives on landscape structure and habitat suitability in the Midwestern United States. *For. Ecol. Manage.* **229**: 361–377. doi:10.1016/j.foreco.2006.04.030.
- Shifley, S.R., Rittenhouse, C.D., and Millsbaugh, J.J. 2009. Validation of landscape-scale decision support models that predict vegetation and wildlife dynamics. *In* Models for planning wildlife conservation in large landscapes. Edited by J.J. Millsbaugh and F.R. Thompson. Elsevier Science, San Diego. pp. 415–448. doi:10.1016%2FB978-0-12-373631-4.00016-2.
- Wang, W.J., He, H.S., Spetich, M.A., Shifley, S.R., Thompson, F.R., III, Larsen, D.R., Fraser, J.S., and Yang, J. 2013. A large-scale forest landscape model incorporating multi-scale processes and utilizing forest inventory data. *Ecosphere*, **4**(9): art106. doi:10.1890/ES13-00040.1.