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Short communication

A LANDIS-II extension for incorporating land use and other disturbances

Jonathan R. Thompson [a,*], Erin Simons-Legaard [b], Kasey Legaard [b], James B. Domingo [c]

[a] Harvard Forest, Harvard University, 324 North Main St., Petersham, MA 01366, United States
[b] School of Forest Resources, University of Maine, Orono, ME 04469, United States
[c] Office of Research Computing, Notre Dame, South Bend, IN 46556, United States

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ABSTRACT

Forest landscape models (FLMs) are widely used to examine the influence of disturbances on long-term and broad-scale forest ecosystem dynamics. However, FLMs are not well-suited to simulating some types of management or disturbance regimes, including land-use change. Consequently, there are situations in which a researcher may wish to estimate the timing and location of events externally, either from a different model, empirical observations, or some other source, and then incorporate them into an FLM. We present Land Use Plus (LU+), an extension for the LANDIS-II FLM that allows users to integrate externally-developed, spatially and temporally explicit representations of land use or other disturbance into simulations. LU+ allows users to model the proximate effects of these events on forest composition and biomass, as well as subsequent dynamics, including tree establishment and the potential for future management. LU+ will significantly increase the breadth of research questions for which LANDIS-II may be appropriately used.

Software name

LU+ for LANDIS-II.

Programming language

C#.

Available at

http://www.landis-ii.org/extensions.

1. Introduction

Forest landscape models (FLMs) are valuable for simulating a range of natural and anthropogenic processes within forest ecosystems at meso-scales (generally 100–10,000 km2). There are several variants of FLMs that differ in their details, but all offer spatially explicit representations of forest dynamics, typically including details about tree species, ages, and biomass as state variables tracked within raster cells. FLMs simulate site-level processes such as tree establishment, growth, and mortality, in addition to spatially interactive processes, such as seed dispersal or contagious disturbance (e.g., wildfire or forest insect outbreaks) (Scheller and Mladenoff, 2007). Some FLMs include mechanistic representations of ecosystems processes that allow simulation of forest response to anticipated climate change, air pollution or other novel environmental conditions (De Bruijn et al., 2014). FLMs are increasingly used to estimate the relative, aggregate, and interactive impacts of several processes operating simultaneously on forest ecosystems (Thompson et al., 2011).

A key strength of FLMs is their ability to simulate the ecological interactions between succession and disturbance processes; however, existing FLMs are not well designed for simulating the spatial pattern of many important disturbances and management activities. As such, a user may wish to incorporate events whose timing and spatial distribution are determined independently from the FLM, either from another model, empirical observations, or some other source. Future land-use or land-cover change (LULCC) is a good example of a process that is frequently of interest to FLM users, but that may be better simulated with a model specifically designed for that purpose. Several approaches exist for simulating LULCC, including cellular, econometric, and agent-based algorithms

* Corresponding author.
E-mail address: jthomps@fas.harvard.edu (J.R. Thompson).

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(Brown et al., 2014). Integrating the strengths of land-cover change models (e.g. Dinamica, CLUE, SERGoM) for simulating patterns of land-use change with strengths of FLMs for simulating the ecological effects of land use on forest ecosystems is a powerful approach for understanding the impacts of LULCC on forested landscapes. While there is no reason that a LULCC model could not be fully integrated into an FLM, an approach for coupling the existing models can achieve the same results with greater parsimony.

To date, the representation of land use and land management in FLMs has been largely focused on simulating alternative silvicultural strategies (e.g. Gustafson and Crow, 1996; Radeloff et al., 2006) and their effects on aboveground live biomass (Thompson et al., 2011), biogeochemical cycling (e.g. Scheller et al., 2011), forest structure and wildlife habitat (Thompson et al., 2009), and future wildfire effects (e.g. Syphard et al., 2011). There has been comparatively little use of FLMs for examining other forest land uses, despite the fact that extensive and widespread land-cover changes are occurring in forests worldwide (Hansen et al., 2013) with significant ecological effects on the remaining forests (Foley et al., 2005). For example, in the United States exurban housing (wherein residential housing is interspersed within natural ecosystems) covers seven times the area of urban and suburban housing (Theobald, 2005). The resulting loss and fragmentation of forest cover associated with exurban housing development can have significant impacts on ecosystem functions and services (Blumstein and Thompson, 2015). Alternatively, changes in land-use policy or land ownership can result in the maintenance or even protection of forest cover, as in the case of the establishment of a conservation easement or forest preserve.

The utility of FLMs could also be expanded by incorporating outputs from other simulation models that provide spatio-temporal depictions of natural disturbance processes for which FLMs currently lack capacity. For example, meteorological models, such as HURRECON (Boose et al., 2001), can depict the path and severity of a hurricane based on analyses of atmospheric information. By using HURRECON outputs as inputs to an FLM, researchers could develop a better understanding of the landscape-scale ecological consequences of this important disturbance. The ability to input information about historical or even hypothetical disturbance events that result in a change in forest condition (e.g., mature forest to regenerating forest) or forest conversion (e.g., mature forest to exurban development) into FLMs greatly expands their value. In addition, FLMs typically implement disturbances and management regimes with a degree of constrained stochasticity, which can be an asset or a limitation, depending on the application. Sometimes explicit control over the spatial and temporal pattern of disturbance is required.

We present an extension for the popular LANDIS-II FLM called Land Use Plus (LU+) that allows users to integrate independently-derived maps of land use or land cover change and some other disturbances. We believe this extension will significantly increase the breadth of research questions for which FLMs—more specifically, LANDIS-II—may be appropriately used.

2. Model description

The LANDIS-II modeling platform includes a core suite of libraries that parse and validate inputs and allow a selected forest succession extension to coordinate with one to many disturbances and output extensions (Scheller et al., 2007). LU+ is a disturbance extension compatible with all LANDIS-II succession extensions. Like most LANDIS-II extensions, LU+ is open source and freely available at the LANDIS-II project website: www.landis-ii.org. Download of the extension comes with a user guide and sample data.

LU+ requires users to supply a series of categorical or thematic raster map for each time step, in which map codes correspond to a land use or land cover types (e.g., managed forest land, residential development, nature preserve, hurricane severity class, etc.). Raster files must be the same grain and extent as the other LANDIS-II input maps. A change in LU+ map code for a site between two time-steps indicates a change in land use or land cover. If a change in land use also results in forest disturbance (e.g., from forest to residential development), the user describes how trees will be removed in an input text file where map codes are described. As with other extensions, the path to this text file is specified in the LANDIS-II scenario file. Formatting for the description of how trees are removed follows conventions developed for harvest prescriptions in the LANDIS-II Base and Biomass Harvest extensions (Gustafson et al., 2000). In general, users are required to identify the species, age cohorts, and percent of biomass to be removed at a site when forest disturbance occurs as a consequence of a land-use change. Similarly, this functionality can be used to simulate forest change resulting from other types of disturbance (e.g., hurricane).

Users of LU+ can also dictate certain aspects of future forests dynamics after a change in land use or land cover. For example, if the keyword "*PreventEstablishment*" is invoked for a map code, then no new tree cohorts are permitted to establish on any site with that map code (Note that once a site is flagged for *PreventEstablishment*, this may not be reversed in subsequent time steps.) Use of the *PreventEstablishment* keyword coupled with the complete removal of all species and age cohorts would effectively simulate a total conversion of forest to a non-forest land cover (e.g., urban development or agriculture). Users may simulate the removal of a specified percentage of forest biomass on a site and invoke the *PreventEstablishment* keyword to simulate a less intense land-cover conversion, such as to residential housing with tree retention in yards and along streets (sensu, Thompson et al., 2011). In this situation any remaining live cohorts would contribute to seed dispersal to adjacent forest cells, but no new cohorts would establish on the site. The keyword '*Plant*' followed by a list of species can be used within a prescription in the same manner as within the Base Harvest extension. This feature may be useful for simulating planting of specific species after a disturbance or to simulate the deliberate movement of a species to specified locations as part of a climate change adaptation experiment (Duveneck and Scheller, 2015). Finally, the '*AllowHarvest*' keyword determines if timber harvesting will be allowed in the future. When set to 'no' for a map code, all sites with that code become ineligible for timber harvesting by the Base or Biomass timber harvest extensions for the remainder of the simulation. This feature was included to allow the simulation of new protected areas, such as parks or nature reserves, which pose restrictions on harvest. When LU+ excludes sites for future harvesting, the Base and Biomass harvest extensions will recalculate the number of eligible cells within management areas to account for the newly ineligible sites.

Currently, LU+ does not allow the user to explicitly specify the fate of dead wood. Cohorts killed by the extension are simply removed from the list of live cohorts on the site. This could be a limitation for users wishing to track the fate of dead wood or its effects on C cycling within the CENTURY succession extension. Dead wood does not affect any other processes in any existing LANDIS-II disturbance extensions.

3. Case study

As an example application of LU+, we modeled 50 years of forest landscape change within a 3700 km^2 area of central Massachusetts, USA (Fig. 1). The simulations projected a linear continuation of the rate and spatial pattern of recent trends in forest land use, including

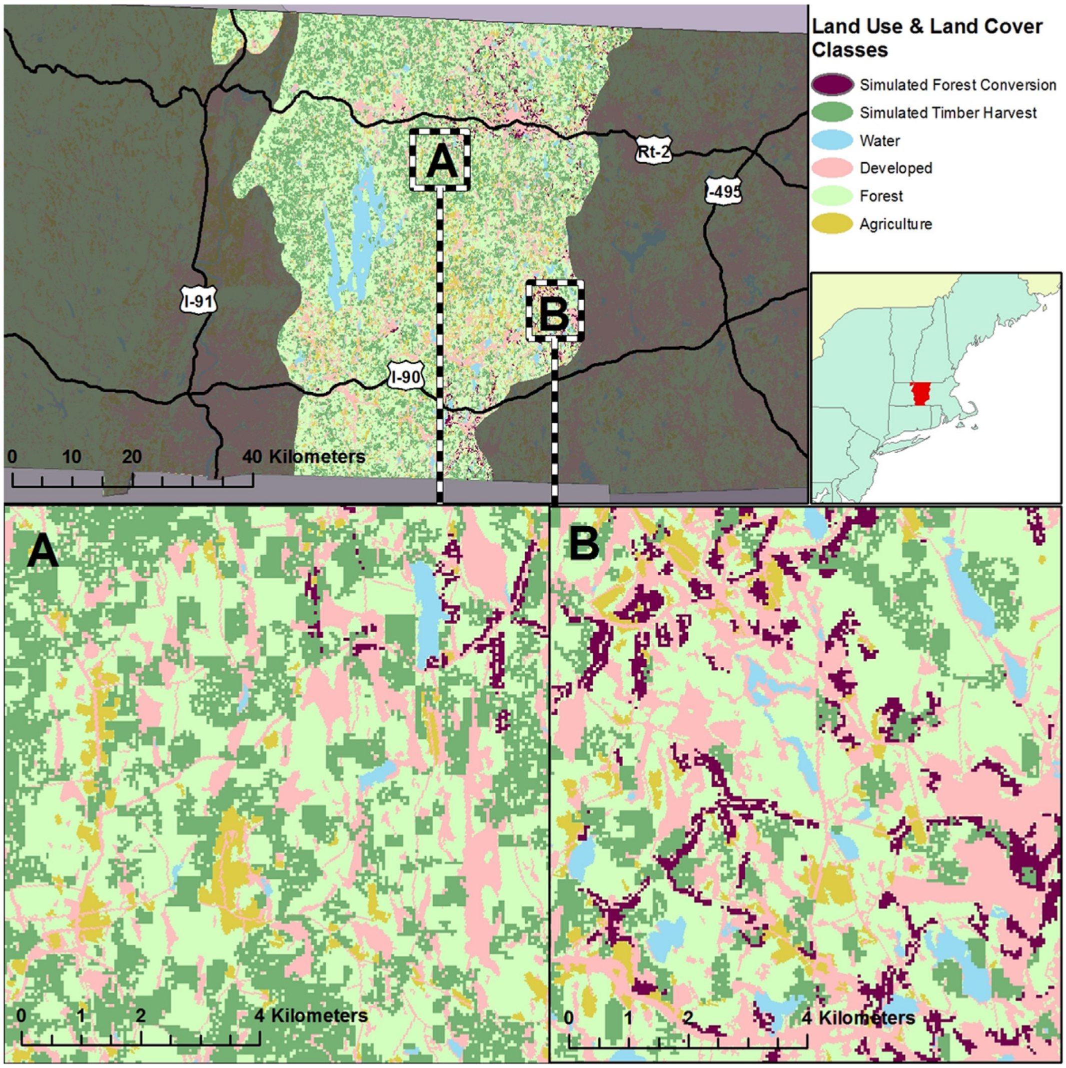

Fig. 1. Simulated forest land uses over fifty years in central Massachusetts, USA. Dark green areas show all areas harvested at least once within the simulation. Dark red areas show accumulated areas of forest conversion to developed uses. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

timber harvest and forest conversion. We used the LANDIS-II Biomass Succession 3.0 extension to simulate forest growth and succession, the LANDIS-II Biomass Harvest 3.0 extension to simulate timber harvest, and the LANDIS-II LU+ 1.0 extension to simulate patterns of forest conversion to developed uses. The simulations used a 50 m grain size and ten year time steps. Details regarding the parameterization of tree attributes and the timber harvest regime can be found in Thompson et al., (2011). We first simulated the rate and pattern of forest conversion using the Dinamica Ego cellular automata model (Soares-Filho et al., 2002, 2013), calibrated based on the observed changes in development between 2001 and 2011 within the National Land Cover Database (Jin et al., 2013). We then used the five decadal land-cover change output maps from Dinamica as inputs to LU+ in order to simulate the extent and pattern of conversion of forest land to residential and commercial uses. To show the individual and aggregate effects of the two land uses (forest harvesting and forest conversion), we conducted four separate simulations: (1) forest growth only with no land uses, (2) forest growth with timber harvest, (3) forest growth with forest conversion, and (3) forest growth with timber harvest and forest conversion (see Fig. 2).

Within the resulting simulations, timber harvest occurred on 2100 ha yr^{-1} in patches ranging from 8 to 20 ha and removes primarily older (>80 yrs) cohorts of merchantable tree species (e.g. *Quercus rubra*, *Pinus strobus*, and *Acer saccharum*). Most harvests occur in areas of low road density (McDonald et al., 2006; Thompson et al., 2011). Forest conversion occurs on 120 ha yr^{-1} in patches ranging from 0.25 ha to 7 ha and removes 100% of all forest biomass regardless of species. Most conversion occurs near town centers and within 250 m of roads (Thompson and Plisinski unpublished data). Unlike harvest, forest conversion in this simulation stipulates that no future tree establishment can occur on the site. Over the 50 year simulation more than five times more biomass was removed via harvest than by conversion, on average 1,60,000 Mg yr^{-1} versus 31,000 Mg yr^{-1}, respectively. After fifty years, the simulation with timber harvest had 2.9% (2.42 Tg), less live aboveground biomass than the simulation with forest growth only. The simulation with forest conversion had 2.0% (1.67 Tg) less biomass than the forest growth only simulation; and the simulation that included both land uses had 4.9% (4.07 Tg) less biomass. Note that timber harvest removed more than five times more biomass than forest conversion while reducing live biomass by just 1.5 times; this reflects the permanent loss of productivity associated with forest conversion. This example showcases some of the

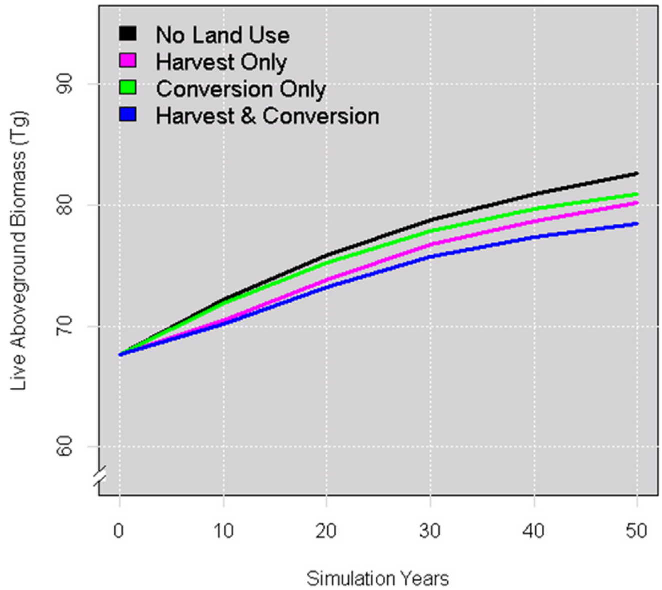

Fig. 2. Changes in total aboveground live biomass within alternative land-use scenarios in central Massachusetts, USA.

functionality of LU+ while also highlighting the trade-offs between extent, intensity, and permanence of different land-use disturbances in terms of long-term biomass dynamics and large spatial scales.

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