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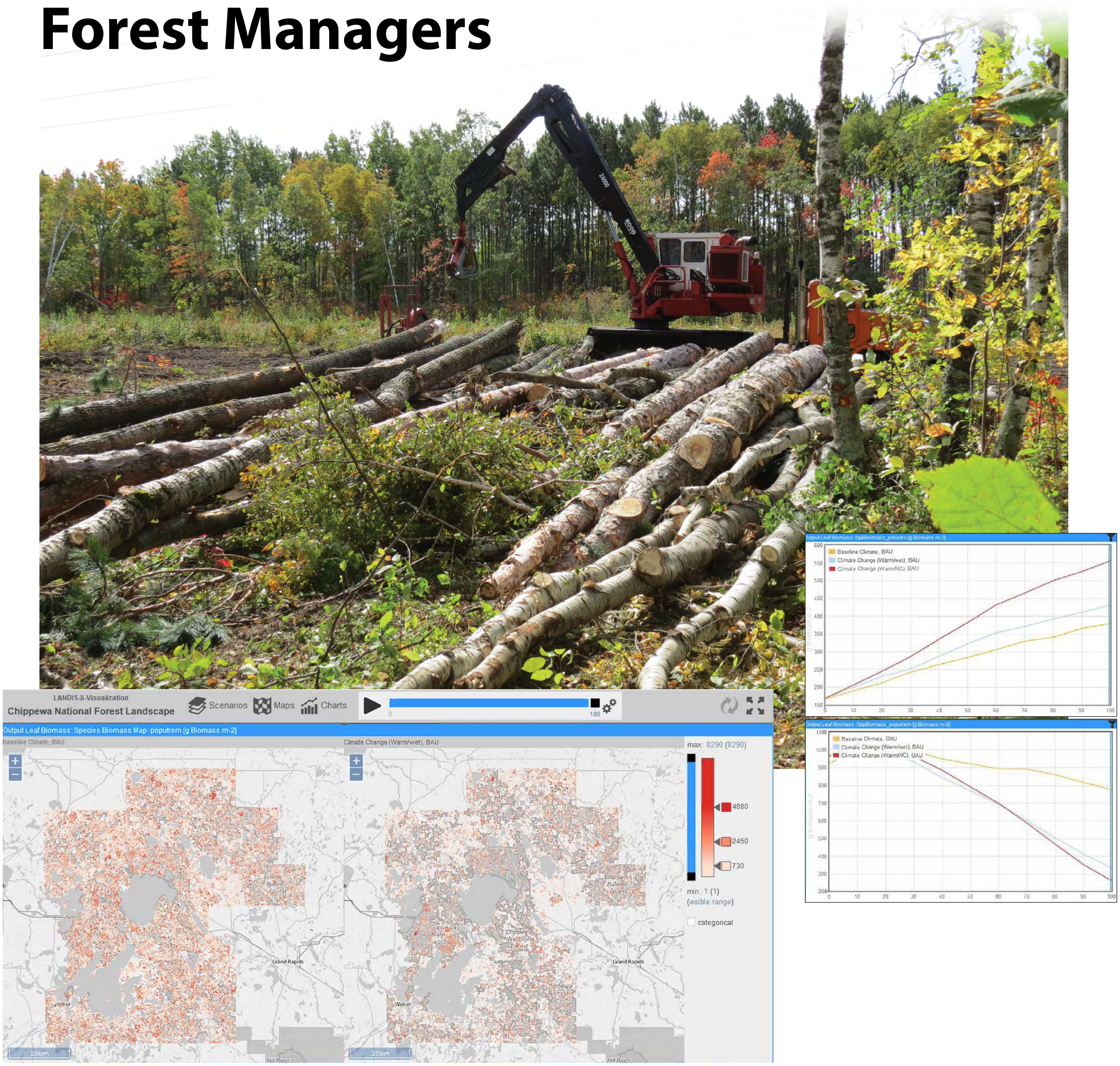
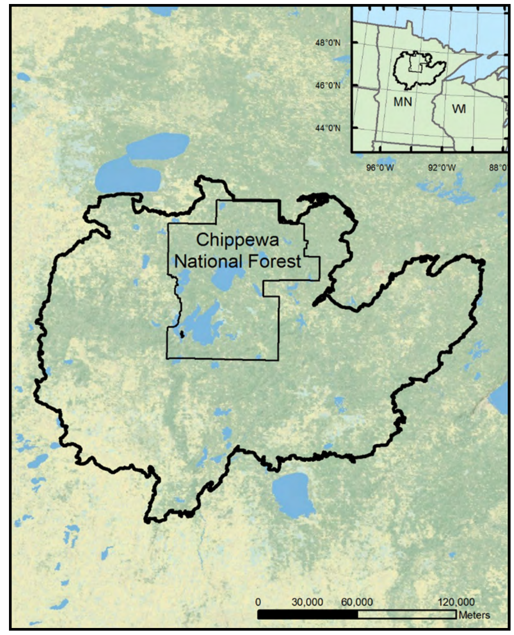
Seeing the Future Impacts of Climate Change and Forest Management: a Landscape Visualization System for Forest Managers



Forest Service Northern Research Station General Technical Report NRS-164 November 2016

Abstract

Forest managers are increasingly considering how climate change may alter forests' capacity to provide ecosystem goods and services. But identifying potential climate change effects on forests is difficult because interactions among forest growth and mortality, climate change, management, and disturbances are complex and uncertain. Although forest landscape models can account for most factors that structure forest landscapes (including climate change), the sometimes overwhelming amount of output from these models can make it hard for some managers to interpret and understand the projections. In an effort to help managers visualize and analyze model output, we developed an intuitive Web-based system: LandViz. We applied LandViz in a collaborative, iterative approach to conduct a Climate Change Vulnerability Assessment for the Chippewa National Forest in Minnesota using the LANDIS-II landscape model. LandViz enhanced managers' collaboration with model experts and increased their understanding of the tradeoffs between amounts and types of various resources in a changing climate. Managers can use the insight gained from LandViz to inform their strategic and tactical planning as they manage these tradeoffs.



Cover

Photo: Harvest after a thunderstorm severely damaged a swath of the Chippewa National Forest, Minnesota in July 2012 (photo by Chippewa National Forest). Maps and graphs: Visualizations generated by LandViz to compare effects of potential future climate scenarios on aboveground biomass of tree species on the Chippewa National Forest.

Quality Assurance

This publication conforms to the Northern Research Station's Quality Assurance Implementation Plan which requires technical and policy review for all scientific publications produced or funded by the Station. The process included a blind technical review by at least two reviewers, who were selected by the Assistant Director for Research and unknown to the author. This review policy promotes the Forest Service guiding principles of using the best scientific knowledge, striving for quality and excellence, maintaining high ethical and professional standards, and being responsible and accountable for what we do.

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Seeing the Future Impacts of Climate Change and Forest Management: a Landscape Visualization System for Forest Managers

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Top: Aerial view of the damage caused by a fast-moving thunderstorm that swept through the Chippewa National Forest on July 2, 2012. The storm affected an area 10 miles wide and 40 miles long from Cass Lake to Deer River (photo by Chippewa National Forest). Lower left: Aftermath of the storm (photo by Chippewa National Forest). Lower right: Mixed hardwood and softwood forest near Cass Lake (photo by R. Scheller, used with permission).

INTRODUCTION

Strategic forest management planning considers the ability of forests to provide multiple ecosystem goods and services over the long term. Forest ecosystems are heterogeneous in space and dynamic through time, being subject to highly complex interactions among succession and disturbance processes and their biotic and abiotic drivers. Strategic planning is increasingly taking into account the expected effects of climate change, with particular emphasis on how to manage landscapes to maintain ecosystem goods and services (Temperli et al. 2012). However, it is difficult to predict the novel (and uncertain) environmental conditions of the future and how a changing climate might interact with the myriad natural and anthropogenic forces that can structure forests (Gustafson 2013). Many tools and approaches have been designed to help forest managers incorporate climate change considerations into management and devise adaptation tactics (Swanston and Janowiak 2012).

The U.S. Forest Service has mandated that each national forest address climate change in both strategic (national forest-level) and tactical (project-level) management planning, and assess progress with an annual Climate Change Scorecard (U.S. Forest Service 2011b). To comply, national forests are developing plans to guide vegetation management activities intended to produce a sustained output of ecosystem goods and services as climate changes (U.S. Forest Service 2011a). Federal regulations require the use of the best available science during the planning process to identify the most likely outcomes of alternative management options. In consultation with stakeholders, managers decide on the mix of ecosystem goods and services desired for the ecosystem in question. Managers then choose the options that are expected to achieve the desired combination of goods and services. Although not governed by these regulations, industrial forest managers have an economic incentive to use the best available science to sustainably manage their forest landscapes under changing environmental conditions.

The long-term landscape outcomes of various climate and management scenarios can be projected with forecasting tools that incorporate the complex interactions among forest succession, disturbances, and their drivers (Gustafson 2013). State-of-the-art forest landscape models are powerful simulation tools that are based on current ecological science. They are a class of predictive simulators that model forest generative (establishment, development, aging) and degenerative (disturbance, senescence) processes at broad spatial and temporal scales (He 2008). Few alternatives to these models are capable of accounting for both the spatial and nonspatial biotic and abiotic interactions that structure forested ecosystems (including climate change). Forest landscape models have two particular strengths: their ability to explicitly model spatial processes, such as seed dispersal and disturbance spread, and their ability to account for interactions in both time and space, which are important determinants of future landscape composition and spatial pattern. These models are especially useful for projecting future ecosystem dynamics and objectively comparing landscape attributes under different management alternatives (Gustafson and Keane 2014).

Many managers find it difficult, however, both to run forest landscape models and to use the output to answer specialized management questions. Model parameterization is a complicated step. The volume of data generated by the models can be overwhelming, particularly when multiple climate change or management scenarios are of interest. Managers may be unable to extract the information necessary to inform their decisions—much less interpret it. Managers often lack the time or expertise to learn how to run and use forest landscape models. New approaches that facilitate improved collaboration between managers and scientists are needed. Specifically, software tools are needed to increase managers' ability to independently access model results in a way that increases their understanding of the results and facilitates more productive interactions with scientists. This paper describes our recent work to create such a tool and illustrates its relevance to forestry practice through an example of its application.

In the project described here, we 1) implement an existing framework that allows managers and scientists to collaborate in the application of a forest landscape model to a specific management problem; 2) develop a software tool that enables managers to visualize model outputs without other experts' assistance, thus better preparing them for collaboration with scientists during the decisionmaking process; and 3) describe a case study where these elements were applied on a national forest to meet specific forest management information needs.

COLLABORATIVE, ITERATIVE APPROACH

Forest managers' successful use of complex modeling technology is hampered by formidable challenges. Managers may not have modeling expertise, and even technically trained managers seldom have the time to learn and apply modeling technologies. Proper interpretation of model results requires a clear understanding of model assumptions and the limitations of the results. There must be a clear link between the decisions to be made and the information that the model delivers. Model experts can help managers develop such links and select the most appropriate model. But model experts may be unfamiliar with the specific land base that is being managed, and may therefore be poorly equipped to parameterize the model to represent local ecological or management dynamics. These challenges can be overcome only through a substantive partnership between model experts and managers. A collaborative, iterative approach (Fall et al. 2001, Gustafson et al. 2006) is a form of participatory modeling that has proven helpful when using forest landscape models in support of forest management planning (Doyon et al. 2011; Sturtevant et al. 2007, 2009a).

The conceptual framework of the collaborative, iterative approach is best represented as an interaction among model experts, decisionmakers, and local resource experts (Fig. 1). The interaction takes the form of iterative communication that is focused on applying the model to support the decisionmaking process for a particular management decision. During these stepwise interactions, the model experts, decisionmakers, and resource experts better frame the management question, refine the parameterization of the model, and gain confidence in its behavior and in the interpretation of the results. Thus, the model serves as a communication vehicle that enables all parties to conceptualize and formalize their concerns about the management decision in question. The result is equal access to information, better understanding of the management decisions to be made, improved transparency in decisionmaking, and a clear transfer of modeling technology from a research environment to a management environment (sensu Moss et al. 2014). This approach also fosters a shared understanding of the interactions among ecological and human processes, the capabilities and assumptions of the forest landscape model, the requirements for the model, and appropriate interpretation of model outputs.

A key strength of the collaborative approach is that each partner provides expertise that is critical to the success of the project. The model experts can determine the feasibility of applying existing models and may recommend building new models. They know the assumptions underlying application of a particular model, are familiar with the algorithms that drive the model, know how to estimate model parameters and develop the input data, have the technical expertise to run the model, and can guide interpretation of the results. The decisionmakers understand the management decisions that must be made, and can readily identify the information gaps that limit their ability to make defensible decisions. Without the decisionmakers' guidance, model experts may unwittingly develop sophisticated answers to irrelevant

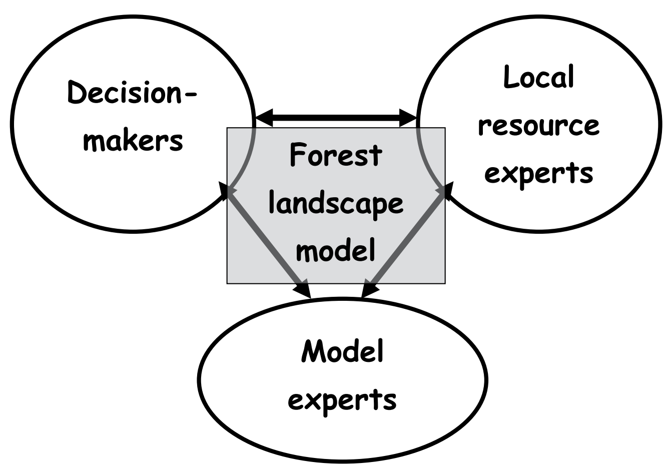

Figure 1.—A conceptual framework of the collaborative, iterative technology transfer approach. The arrows represent iterative communication. Adapted from Gustafson et al. (2006).

questions. The local resource experts make sure that the model application incorporates current knowledge about the local ecosystem, and they help the model experts estimate realistic model parameters. They can readily identify model behaviors that incorrectly simulate on-the-ground conditions. They also assist managers in developing ecologically feasible management options. This collaborative, iterative approach helps generate results that are well-informed and useful for decision support (e.g., Sturtevant et al. 2009a).

VISUALIZATION SYSTEM (LandViz)

Even with the collaborative, iterative approach, managers may struggle to integrate model results into their planning process because forest landscape models produce huge amounts of output. The sheer volume of output makes it difficult for managers to extract the pertinent results. For example, a simple simulation with 15 tree species that considers only wind and fire disturbance can produce more than 200 maps when maps of species' biomass, forest type, and disturbance location are generated for every decade of a single century. Managers or modelers may have to spend a good deal of time on data processing to synthesize data and compare landscape attributes over time for multiple scenarios. Furthermore, the technical expertise needed to conduct these analyses rarely resides within a manager's office, and providing technical support to managers on an ongoing basis is outside the mission of most researchers. Compounding the problem, simulation models usually do not provide metadata, which are information on how the data were derived and how specific datasets may be correctly used and related with other data. Yet this supporting information is necessary both to avoid interpretive and inferential errors, and to meaningfully visualize and explore the results. Thus, the barriers are very high for managers who wish to fully understand the nuances of forest dynamics as projected by a forest landscape model for alternative management or climate scenarios. Modelers can verbally describe the logical relationships between simulation output datasets. But new tools are required if these relationships are to be automatically translated into easily accessible and comparable visualizations that managers can interactively explore to answer specific questions.

To this end, we developed a generic, Web-based landscape visualization system (LandViz) to view simulated landscape management scenarios (Appendix). The system has three components: 1) metadata created by the model (or manually by modelers), 2) a preprocessing system run by the modeler, and 3) a Web-based visualization tool that modelers and managers can use to visualize key outputs associated with different management or climate scenarios. The system reads the metadata, which define the relations between datasets and the scenarios to be visualized. These metadata are a bridge between the simulation output and visualization of the output. The preprocessing component analyzes the statistical distributions of values in the maps, within and across scenarios, and then assigns default settings for the visualization. Default settings determine the initial classification and color schemes, and the spatial and temporal scales appropriate for comparative viewing of maps, graphs, and time-series animations. Data are optimized for loading into a Web browser. Modelers need only run the model, run the preprocessing tool, copy the folder to a Web server, and send managers a link to access the viewer in their Web browser. Modelers can easily adapt the tool for specific audiences (e.g., the set of scenarios available and the landscape attributes that can be viewed).

The viewer was specifically designed to make it easier for managers to compare outcomes for different management and climate scenarios. With a few clicks, managers can choose from a list of climate change or management scenarios, attributes of interest (e.g., biomass of various tree species, abundance of various forest types, wildlife habitat), and maps of disturbed areas (e.g., areas disturbed by fire or insects). Maps of these attributes or disturbance events are overlaid on current geographic backgrounds (via OpenStreetMap; Haklay and Weber 2008) in side-by-side windows that are synchronized for zoom, pan, and animation (Fig. 2). Users can synchronize map color legends and add or remove breakpoints at any time. Charts (graphs) of quantitative map attributes through time can also be selected, and these are displayed in separate windows. By manipulating play and pause buttons, users can animate and freeze the maps and charts and watch the landscape and its attributes change over time.

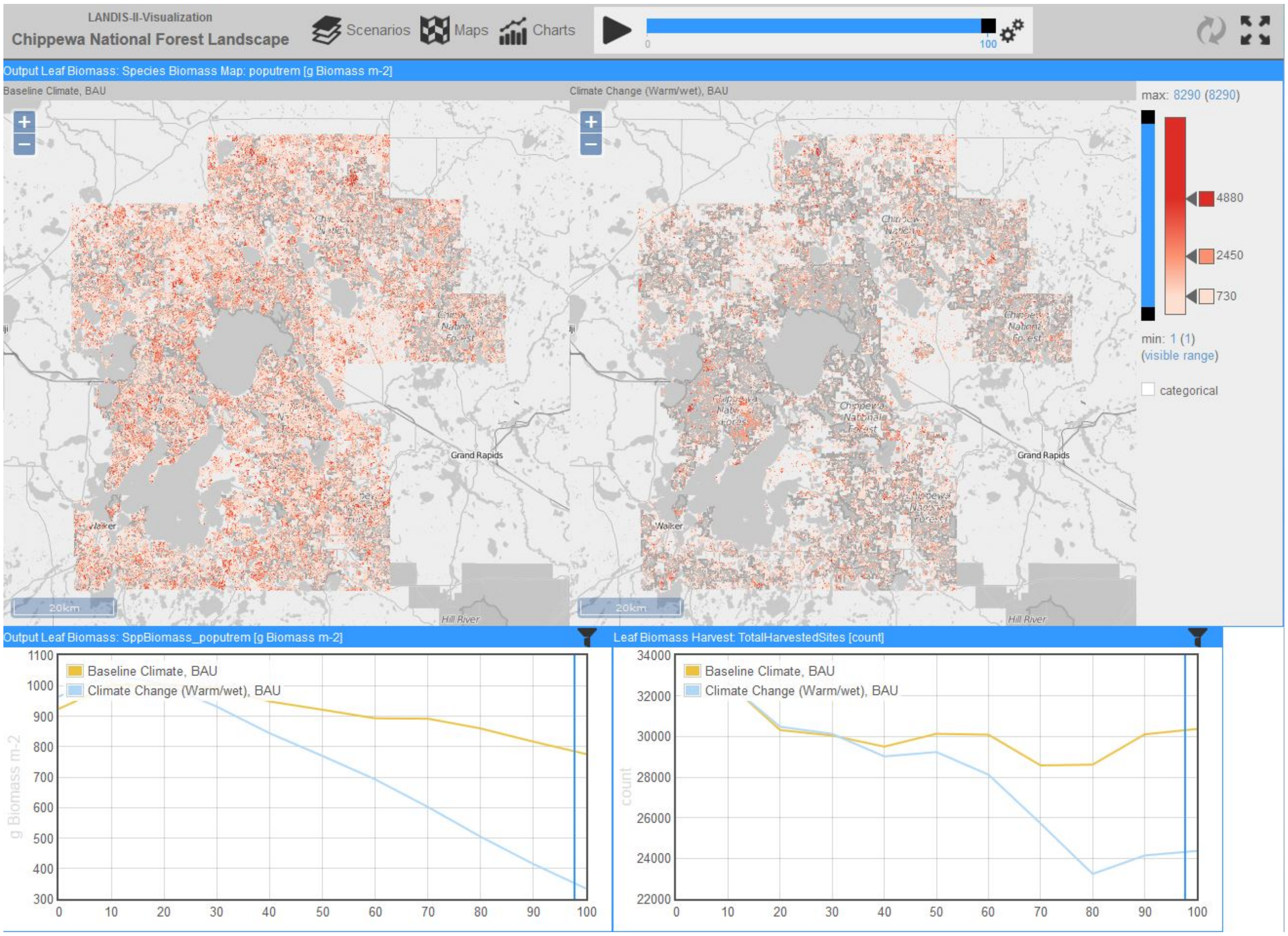

Figure 2.—Visualization of model results in LandViz. Maps show comparison of the aboveground biomass of quaking aspen, in g/m^2, at year 100, under baseline (left) and potential warm/wet future (right) climates and current management practices (BAU) on the Chippewa National Forest. Colors other than gray represent amount of biomass. Dark gray is public land or roads, medium gray is water, and light gray is the background map. Charts below the maps compare aboveground biomass of quaking aspen, in g/m^2 (left), and total projected number of 2.5-acre (1.0-ha) sites on which quaking aspen would be harvested (right), through year 100 for the same two climate scenarios.

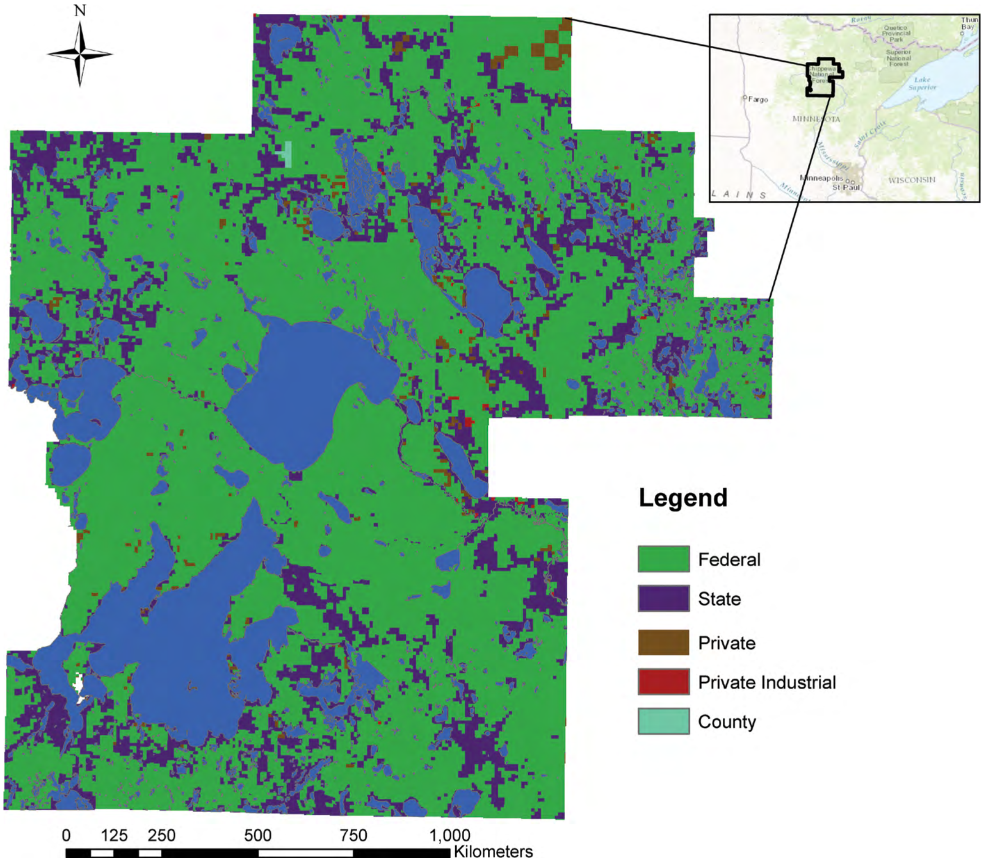

Figure 3.—Ownership pattern within the Chippewa National Forest boundary (map by M. Lucash).

CASE STUDY: CLIMATE CHANGE VULNERABILITY ASSESSMENT FOR THE CHIPPEWA NATIONAL FOREST

The Chippewa National Forest (CNF) is a 266,726-ha (659,000-acre) national forest in north-central Minnesota managed by the U.S. Forest Service. The CNF is interspersed with lands managed by the Minnesota Department of Natural Resources (MN-DNR), the Leech Lake Band of the Ojibwe Nation, and many nonindustrial private forest landowners, as well as UPM Blandin industrial forest land (Fig. 3). The current CNF Forest Management Plan (U.S. Forest Service 2004) reflects an ecosystem management philosophy that seeks to shift the relative abundance of ecological communities closer to their range of natural variability (Grumbine 1994). It is silent, however, on how to plan for climate change, and under its current management direction the ecosystem goods and services that the public desires may not persist in the face of changing conditions. Accordingly, CNF managers are beginning to incorporate climate change considerations into their current management activities, and are developing methods to predict climate impacts on the CNF in preparation for the next revision of the plan.

We applied the collaborative, iterative approach to conduct forest landscape modeling to support a Climate Change Vulnerability Assessment for the CNF that will help the Forest meet its responsibilities under the Climate Change Scorecard (U.S. Forest Service 2011b). We used the Northwoods Climate Change Response Framework (NCCRF) (Handler et al. 2014a, 2014b; U.S. Forest Service 2012), which helps national forests, state and local agencies, private and industrial landowners, and conservation organizations assess the vulnerability of different forest types to climate change to guide future management decisions. A variety of modeling approaches—forest landscape models, ecosystem-level models of productivity, species distribution models—are compared to discern where there is greatest agreement (and disagreement) about climate change effects on forest types. A recently completed regional assessment using the NCCRF for northern Minnesota (Handler et al. 2014a) suggests that some of the forest species valued by stakeholders in the region will decline under climate change.

Modeling for the Climate Change Vulnerability Assessment for the CNF was conducted by an informal team of researchers (model experts) from the U.S. Forest Service, Northern Research Station; managers from the CNF; and local resource experts from the CNF, the MN-DNR, and academia. We used the LANDIS-II forest landscape model (Scheller et al. 2007) to simulate climate change impacts because it was one of the models used in the NCCRF's vulnerability assessments in Minnesota (Handler et al. 2014a) and in Wisconsin and Michigan (Janowiak et al. 2014). A particular strength of LANDIS-II is its ability to generate easy-to-compare outputs for alternative management and climate scenarios. For analytical purposes, the model can output an almost unlimited variety of future forest characteristics at user-defined temporal and spatial scales, and these outputs may be further processed to estimate landscape conditions (e.g., wildlife habitat) at scales that are relevant to forest management.

LANDIS-II simulates individual tree species' establishment, growth, competition, and senescence, and disturbances such as wildfire, wind events, insect outbreaks, and timber harvesting at large spatial (>100,000 ha, or >250,000 acres) and long temporal (centuries) scales on a grid of spatially interacting cells. For the simulations described here, we used LANDIS-II v6.0 with the Century Succession extension v.4.0.2 (Scheller et al. 2011) to simulate forest establishment, growth, and competition. In the model, aboveground and belowground live and dead biomass and age of cohorts are tracked for each cell, along with detritus accumulation, soil processes, and carbon and nitrogen cycling. The following extensions were used: the Biomass Harvest extension (Gustafson et al. 2000) to simulate timber harvesting, the Dynamic Fire and Fuel System v2.0.5 extension (Sturtevant et al. 2009b) to simulate wildfire, the Base Wind v2.1.2 extension to simulate wind disturbance, and BDA v3.0 extension (Sturtevant et al. 2004) to simulate jack pine (*Pinus banksiana* L.) mortality from jack pine budworm (*Choristoneura pinus*). The Century Succession and disturbance extensions independently act on individual cohorts within cells, so together they simulate forest dynamics that are under the combined influences of succession, disturbance, and forest management processes. We simulated 100 years into the future using a 10-year time step, beginning at 2010, a time period consistent with the length of climate change projections.

Model inputs and procedures are described in detail in Lucash et al. (in review), but we briefly outline them here. Initial forest conditions were derived for each ownership type by using actual forest stand data when available (e.g., CNF, MN-DNR) and otherwise imputing conditions by using U.S. Forest Service Forest Inventory and Analysis data (Handler et al. 2014a) at a cell resolution of 4 ha (10 acres). Species-specific vital attributes for the succession extension were derived from the literature and the local resource experts. The landscape was subdivided into 25 ecoregions (areas of homogeneous soils and climate). Five climate scenarios (including baseline) representing combinations of temperature and precipitation trends were used as inputs to produce a wide range of climate futures. The following monthly climate projections (CMIP5; Intergovernmental Panel on Climate Change 2013) were downloaded from the U.S. Geological Survey's online climate data portal (U.S. Geological Survey 2016): the University of Idaho Gridded Surface Meteorological Dataset (baseline), CanESM2-45 RCP 4.5 (warm/dry scenario), ACCESS1_0 RCP 4.5 (hot/wet), GFDL-ESM2M RCP 8.5 (warm/wet), and MIROC ESM RCP 8.5 (hot/dry). Forest management prescriptions representing the current practices of each landowner were developed in consultation with managers and resource experts, and applied within the boundaries for each ownership. We collaborated with local resource experts to estimate model parameters for natural disturbance using published and unpublished empirical data.

We held face-to-face meetings to build a mutual understanding of the conceptual framework of the LANDIS-II model, collaboratively develop model inputs, develop heuristic management scenarios, and produce specifications for the visualization system. The process was iterative, so meetings were held at about 6-month intervals, with details worked out collaboratively between meetings by phone and email.

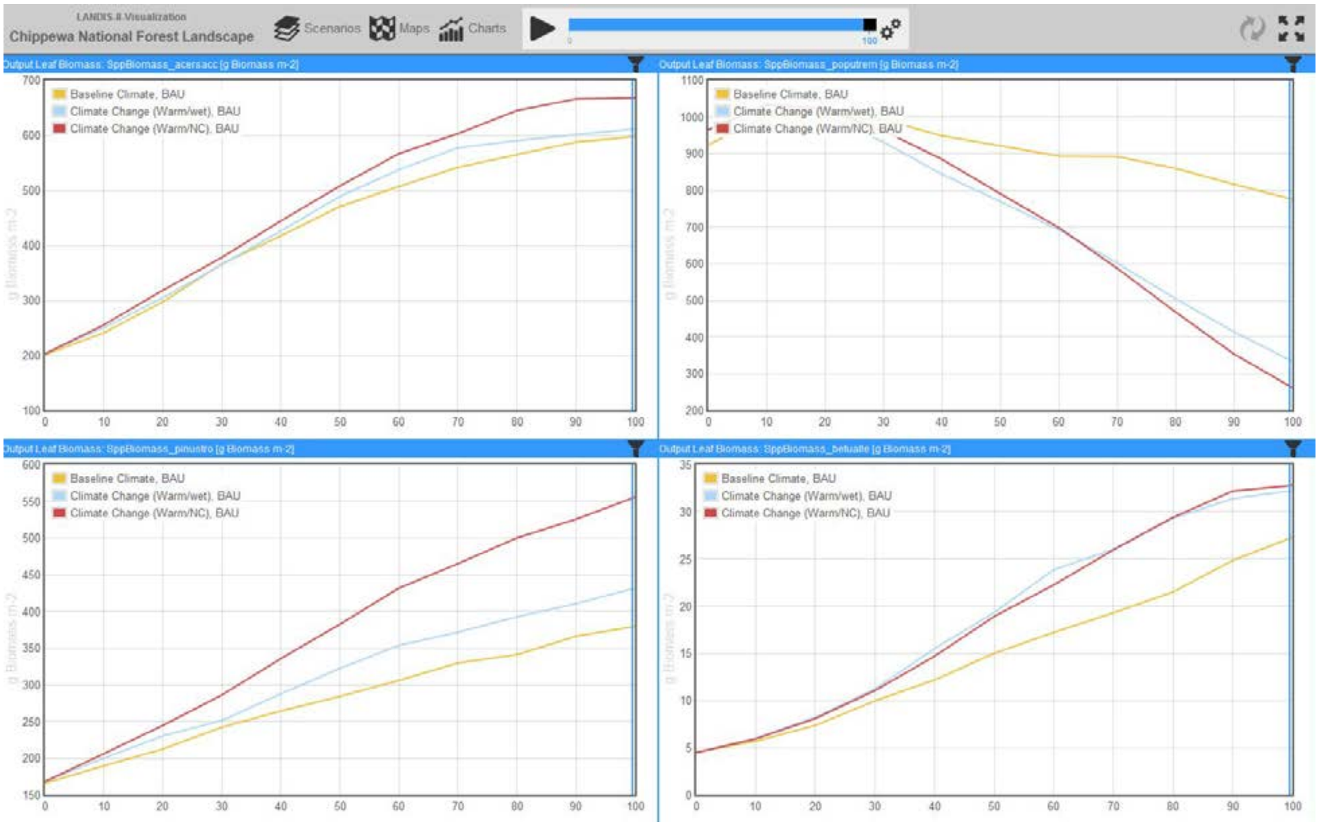

Figure 4.—Charts comparing the projected effect of various climates and current management practices (BAU) on the aboveground biomass of sugar maple (*Acer saccharum* Marsh.; upper left), quaking aspen (*Populus tremuloides* Michx.; upper right), eastern white pine (*Pinus strobus* L., lower left), and yellow birch (*Betula alleghaniensis* Britt.; lower right), in g/m^2, on the Chippewa National Forest, through year 100.

At each meeting, progress was presented to the team and adjustments were made based on feedback by managers, resource experts, and model experts. The team developed several scenarios for simulation and analysis. Here we present outputs from a baseline "business as usual" (BAU) management scenario for illustrative purposes. When this scenario was simulated with and without climate change, the consequences of not considering climate change in management strategies could be evaluated. To best illustrate the visualization capabilities of the new LandViz tool, we present results for selected species for which climate change produced relatively divergent outcomes.

Chippewa National Forest managers currently use LandViz to explore model output to understand how the scenarios affect the simulated dynamics of specific forest characteristics. Use of LandViz allows them to engage in ongoing collaborative interactions with scientists on a much deeper and more insightful level. For example, managers wondering how the abundance of quaking aspen (*Populus tremuloides* Michx.) might be affected by future climate and disturbance regimes can quickly view maps of projected aspen biomass over 100 years under present and future climate and then graph how biomass varies over time (Fig. 2). They will see a projected decline in aspen, which may prompt a question about which species will be gaining in biomass as aspen declines. Managers can quickly create graphs of the biomass of other species through time for each climate scenario (Fig. 4). The insights from this exercise may result in creative interactions with scientists to develop novel management approaches that can be initially tested with the forest landscape model.

In another example, an interdisciplinary team working on an environmental analysis for a future vegetation management project could examine how various species are projected to fare within a specific Ranger District. Because the CNF has experienced several recent major windthrow events, the team might also use LandViz to view the maps of wind disturbance events across the

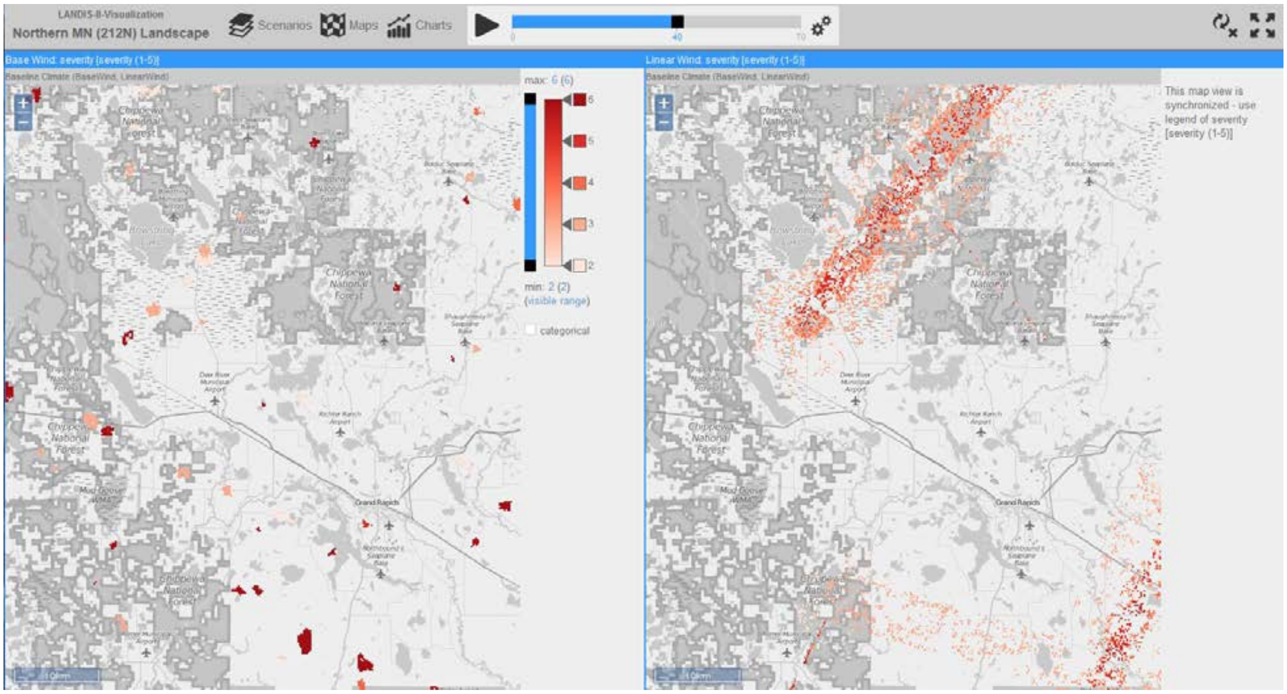

Figure 5.—Visualization of the location and intensity of wind disturbances between years 30 and 40 for microbursts (left) and linear wind events such as derechos and tornadoes (right) on the Chippewa National Forest. Colors other than gray represent relative intensity of wind events. Dark gray is public land or roads, medium gray is water, and light gray is the background map.

CNF for each climate scenario and analyze the impact of those simulated events on forest composition and biomass (Fig. 5).

As a final example, one of the goals of the current CNF Plan involves increasing the percentage area of conifers on the landscape. Achieving this goal could be very expensive, involving site preparation, planting or seeding or a combination, and control of competing vegetation and damage by animals. Model outputs will help CNF managers determine which coniferous species would be wiser investments, given that some species may fare poorly in a changing climate. For example, objectives in several CNF landscapes include increasing jack pine, eastern white pine (*P. strobus* L.), red pine (*P. resinosa* Ait.), white spruce (*Picea glauca* (Moench) Voss), and balsam fir (*Abies balsamea* L.). In some locations, eastern white pine has not been favored because of concerns about browsing by deer (*Odocoileus virginiana*) and susceptibility to blister rust (*Cronartium ribicola* J.C. Fisch). But if white pine is projected to do better under future climate than other currently favored species—which may not fare as well in the future (e.g., jack pine)—then managers may be persuaded to revise their tactics.

Such model projections can also be used to evaluate the consequences of climate change on conifer-dependent birds, which make up one-third of bird species on the CNF (Fig. 6).

We envision that LANDIS-II outputs and LandViz will be routinely used to inform planning at both tactical and strategic levels. Outputs can inform timber harvest practices that encourage some species and discourage others, depending on key climatic influences. Because LandViz shows the spatial interaction of climate effects, ecoregion, and management across the landscape, tactical practices can be spatially targeted. We must note that cell-level projections of landscape models are highly uncertain, but general trends and spatial patterns at landscape scales can be relied upon when answering project-level questions. Analysis teams can use LandViz interactively to collectively view model outputs and explore management issues within a common framework. Perhaps most importantly, LandViz allows for transparent analysis of the influences of climate change and management and enables each stakeholder to evaluate tradeoffs associated with alternative management and climate scenarios on a common footing.

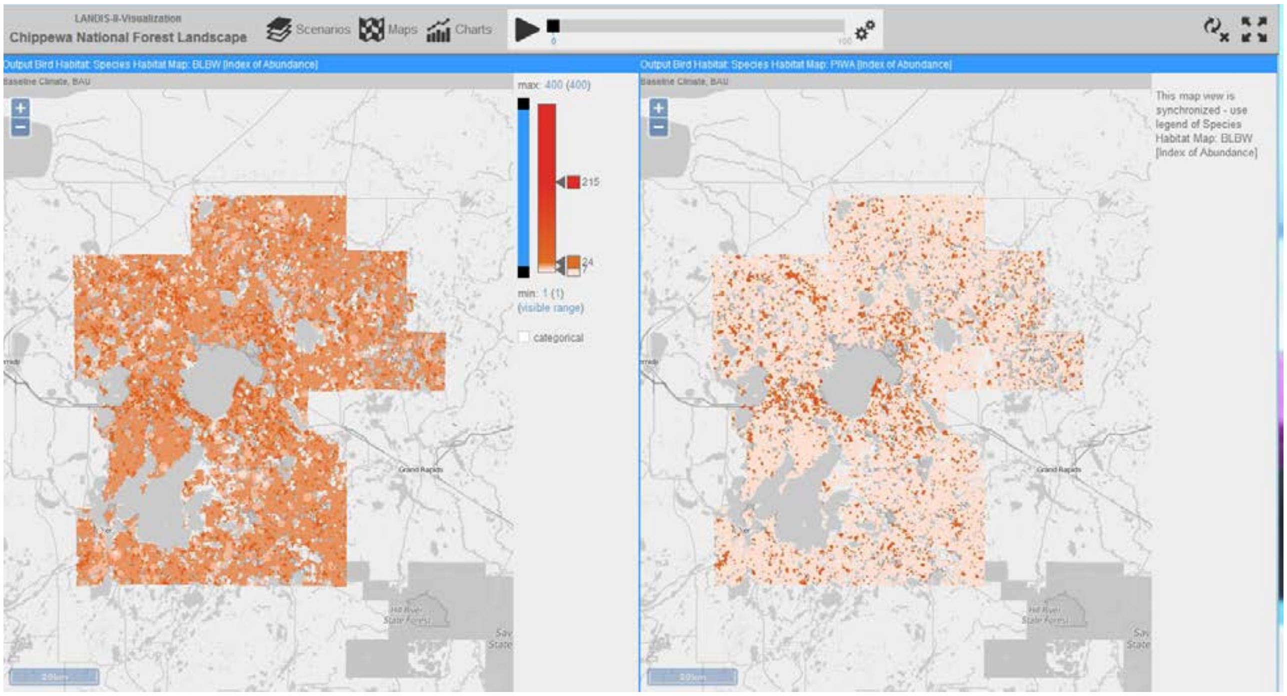

Figure 6.—Visualization of relative habitat quality for Blackburnian warbler (*Setophaga fusca*; left) and pine warbler (*S. pinus*; right) on the Chippewa National Forest under the baseline (current) climate scenario and current management practices (BAU) at year 100. Colors other than gray represent relative habitat quality. Dark gray is public land or roads, medium gray is water, and light gray is the background map.

Strategic planners for the CNF anticipate our approach will be extremely useful during the next revision of their management plan because 1) LANDIS-II is well-suited to project the outcome of alternative management scenarios while accounting for other factors that structure forested landscapes, 2) the CNF planners were involved in the modeling process and therefore guided the questions to be addressed, and 3) LandViz makes the outputs readily accessible to a wide audience, from local experts to stakeholders. Model outputs can be used to quantify the effects of alternatives on forest age, species composition, and overall landscape pattern, including wildlife habitat. Pairing forest landscape models with visualization tools will allow managers to become even more sophisticated partners in collaborations with scientists to support planning efforts.

LandViz is also an effective communication tool for managers, partners, stakeholders, and the public. Results from our LANDIS-II Climate Change Vulnerability Assessment were recently shared with a regional landscape committee of the Minnesota Forest Resource Council. This committee is responsible for revising a landscape plan for north-central Minnesota that considers potential climate change impacts. Committee members represent a variety of organizations and ownerships, including the MN-DNR, the U.S. Forest Service, five county land departments, three soil and water conservation districts, conservation organizations such as The Nature Conservancy, the forest products industry, Minnesota Indian Affairs Council, universities, and nonindustrial private forest landowners. A key benefit of visualizing model results is that committee members were encouraged to think more explicitly about climate change and the viability of current management strategies into the future from an "all-lands" perspective across ownerships. They are now more likely to explore other tools for climate change analysis and to develop management options for comparison. We saw that LandViz catalyzed a process by which partners and stakeholders began to better appreciate what a future under climate change may look like in terms of forest dynamics and forestry practice.

CONCLUSIONS

One of the greatest benefits of LandViz for managers is its ability to paint a picture of the realm of future possibilities. The ability to visualize how climate and various management scenarios may change a landscape through time is very powerful and compelling. Managers have complex stories to tell about the work that they are contemplating for a forested ecosystem or landscape. Being able to show various alternative futures facilitates clearer communication and focuses attention and dialogue on goods, services, and habitat values that matter to stakeholders. It helps make the case for the critical need to manage in the context of change, rather than just attempting to maintain the status quo. For tactical planning, LandViz helps managers decide where and how to invest time, energy, and financial resources to most efficiently and effectively achieve functional ecosystems—and perhaps more importantly, to identify where efforts to resist change are likely to be futile. Strategic planning involves managing the tradeoffs between amounts and types of various resources, and we expect that models paired with visualization will increase understanding of these tradeoffs in a changing climate. The most important benefit of visualization tools designed for managers may be the level of independence that they give managers. Tools such as LandViz support exploration and reflection, which in turn strengthen the value of managers' collaboration with scientists. Such independence is difficult to achieve with forest landscape models because of their complexity. But it is essential if managers are to understand model outputs enough to apply them in routine strategic and tactical planning.

Although LandViz has powerful potential to enhance manager–scientist collaboration, it is important to note that is not a "silver-bullet" decision-support tool. It has no optimization capabilities, it does not make management recommendations, it does not compute levels of uncertainty, and it is limited to the scenarios defined in advance. Nevertheless, its ability to help managers to directly explore outputs from a forest landscape model increases their understanding of how alternative scenarios affect specific forest characteristics and dynamics and provides valuable insight for decision support that is difficult to obtain elsewhere. It is also important to recognize that LANDIS-II projections have limitations as well. LANDIS-II is designed to simulate the effect of each ecological process on vegetation independently, which allows the vegetation outcome to emerge as an interaction of the processes. This is a robust approach for novel combinations of processes and environmental conditions (e.g., climate change). However, values used for input maps and estimated model parameters do have a degree of uncertainty. There are also competing scientific views about how some ecological processes operate, and LANDIS-II was constructed by making assumptions about which view is correct. Therefore this model accurately computes outputs based on the inputs and its formalization of ecological theory, but the output must be interpreted in terms of these various sources of uncertainty (Xu et al. 2004). LANDIS-II predicts expected behavior given the inputs, but cannot predict what specifically will happen in the future (Thompson et al. 2012).

We believe that the collaborative, iterative modeling approach coupled with targeted visualization (e.g., LandViz) has potential to benefit not only U.S. Forest Service managers but also managers in other agencies and organizations responsible for large forest landholdings. The combination of collaborative, iterative modeling and visualization can assist land managers in harnessing the powerful predictive capabilities of forest landscape models. All land management organizations face similar issues related to climate change and strategic planning that must be addressed at the scale of ecosystems and landscapes, and forest landscape models are arguably the most comprehensive and integrative predictive tools available to answer management questions at that scale. A collaborative, iterative approach lowers the barriers to the use of forest landscape models by forest managers and increases their confidence in model outputs.

If the collaborative, iterative approach for applications of forest landscape models is widely adopted to support management decisions, the demand for modeling expertise could quickly outpace the supply. However, our experience suggests that model developers need not serve as the model experts. Instead, entrepreneurial model experts with experience in applications of forest landscape models (e.g., former postdoctoral scientists) could provide contractual modeling services as the demand for such services increases.

LandViz allows managers to extract information from model outputs independently of the model experts. This capability is expected to greatly increase the accessibility and usefulness of model results. Thus, we expect managers to be more likely to use the model outputs for decision support. Further, LandViz was designed for flexibility. It is a general platform that links to a time-series of maps and tabular data contained within a predictable hierarchical folder structure via metadata. Any spatial model that projects change over time and produces such data could be linked to LandViz to display its outputs. Regardless of the model used, decisionmakers can benefit from the ability to visualize how management options will change landscape dynamics through time as they consider options for providing future ecosystem goods and services.

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APPENDIX
LandViz Development and Details

1. LandViz: System Requirements and Objectives

Our goal was to develop a generic Web-based system for geovisual analysis of forest landscape simulation scenarios. Therefore we developed LandViz, a configurable, extendable data visualization system for LANDIS-II forest simulation output. The system is intended to facilitate communication between forest scientists and forest managers. It serves these two user groups' different needs for data exploration and analysis by affording temporal and multi-map side-by-side comparison across scenarios. Key features of the system are out-of-the box Web deployment, customization of data access and functionality for different user groups, easy integration of modules in a generic architecture, data-driven default map symbolization, and interactive on-the-fly reclassification, filtering, and highlighting in maps and diagrams across space, time, and scenarios.

Based on our experience working with the forest managers of the Chippewa National Forest, we identified the following five software requirements for a visualization system that would facilitate the exchange of information between forest researchers (who parameterize and run landscape change models) and stakeholders (who use simulation data to inform management decisions and policy choices). Requirements are listed in order of importance.

(1) Ease of use: The software should not require any familiarity with geographic information systems, Web programming, cartographic design, or complicated software installation. The approach should allow users to concentrate solely on analyzing simulation output data.

(2) Customization: Stakeholders are interested only in specific model output datasets. The system should allow customized dataset access and visualization based on specific needs. Typically stakeholders need access to only a small fraction of the total outputs generated by a landscape model; additional data detract from their focus and can cause cognitive overload (Bunch and Lloyd 2006).

(3) Scenario comparison: The comparison of multiple scenarios is essential. The visualizations should be tailored to this requirement by automatically synchronizing data and visual elements (e.g., color ramps) across scenarios.

(4) Web-enabled: Data transfer, storage, and organization contribute to the overall data bottleneck. Therefore the system should store data remotely and provide a unified interface to model outputs and tools for scenario comparison. In addition, the system should be suitably reactive to user inputs with minimal load times and fast refresh rates.

(5) Extensibility and generic system architecture: The software should be designed with a modular and generic architecture that is not limited to a single model or model configuration, but allows the visualization of any landscape simulation model output.

We developed a system to meet these requirements. LandViz has a generic software architecture, initially designed to display LANDIS-II model output (Scheller et al. 2007). Although approaches for visualizing LANDIS-II simulation output exist (Birt et al. 2009, Jenny et al. 2014), they do not facilitate manager–scientist communication and do not readily enable side-by-side comparison of scenarios.

2. Implementation of LandViz

The software requirements outlined earlier were implemented as follows:

2.1. Ease of Use

We removed as many steps as possible between tool activation by an end user, such as a forest manager, and meaningful engagement with the data. Therefore it was imperative that the requested menus, maps, and tables load with reasonable default settings and without user input. Creating such preferences for visualization required additional metadata about the model output, which would otherwise be cumbersome for the model user to collect.

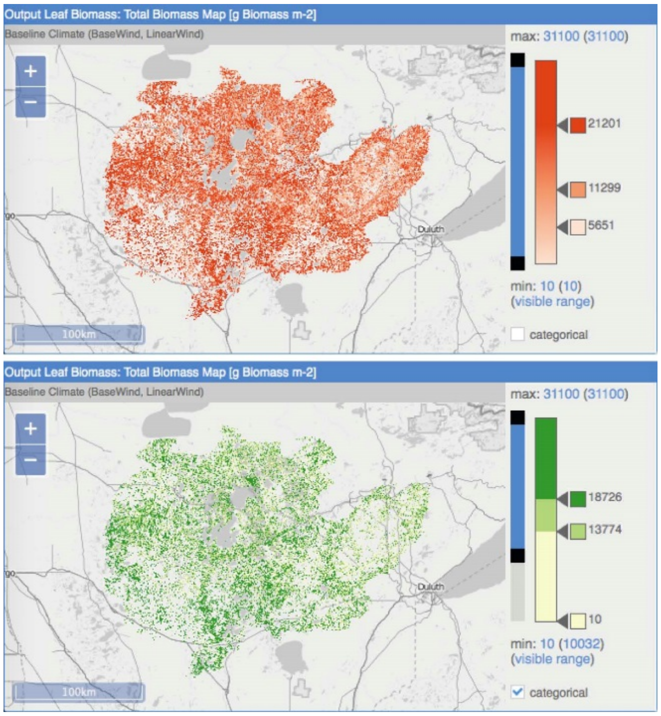

Figure 7.—Map tiles (see Figure 2) resymbolized in the Web application using the customizable classification tools powered by WebGL.

Therefore LandViz includes a preprocessing component, a Python command-line script using GDAL (Geospatial Data Abstraction Library; http://gdal.org/) and NumPy (http://www.numpy.org/) that extracts this meta-information from model outputs automatically. Using XML metadata files (provided by the LANDIS-II model for each output map or table), the script populates a data model used for the visualization process. It runs analyses on the temporal map outputs and stores additional statistics like data type (e.g., nominal, ordinal), data range, and a measure of central tendency over the whole time period.

Using these statistics, a default classification for visualization is generated for every time-series map. Separate distinct colors are used for qualitative data values; two map classification modes are provided for quantitative data: classified and unclassified. Classified data result in symbolization with distinct class boundaries (Fig. 7, lower image); unclassified data are represented with a gradient color ramp (Fig. 7, upper image). Unclassified maps are particularly useful for animations and comparison tasks over time, which made them very suitable for use in LandViz. According to an empirical survey, users perceive unclassified map animations as smoother and slower; those surveyed indicated that unclassified data tend to show change better than classified data (Harrower 2007).

Similarly, menus of options are automatically populated with the list of scenarios and model outputs associated with a given project and stakeholder group. The same XML metadata files used to record data types also record variable names and units; these are used to construct intuitive menu lists with associated units.

2.2. Customization

LandViz can be customized for a particular project and stakeholder group by running the preprocessing component that creates a ready-to-deploy Web application. Scenario and data selections are made by editing an XML template file. The scientists who run the model can create interactive Web sites with visualizations geared for different audiences; they can highlight different parameters or scenarios without any background knowledge of Web programming.

This customizable XML template specifies metadata about the scenarios and their outputs as well as configuration information for the automatic generation of the Web application's visualization and user interface (see following). This information is the bridge between the landscape change model (LANDIS-II) and LandViz.

End users can easily modify the default map symbolization to make certain characteristics or details of a dataset more apparent. For this reason, the map legends (Fig. 8d) can be interactively adapted: users can edit the number of classes, change class breaks and colors, and restrict the data range, which acts like a filtering function.

The color gradient defined by the user through manipulating the interactive legend is converted to a texture. The texture is then made accessible to the self-developed WebGL fragment shader on the client graphics processing unit (see Section 2.4) to assign a color to each raster value in the map. Line charts and maps are synchronized for animation. When a user is animating over time, maps are exchanged at each time step and a vertical line moves over the chart to indicate the chart values corresponding to this time step. Users

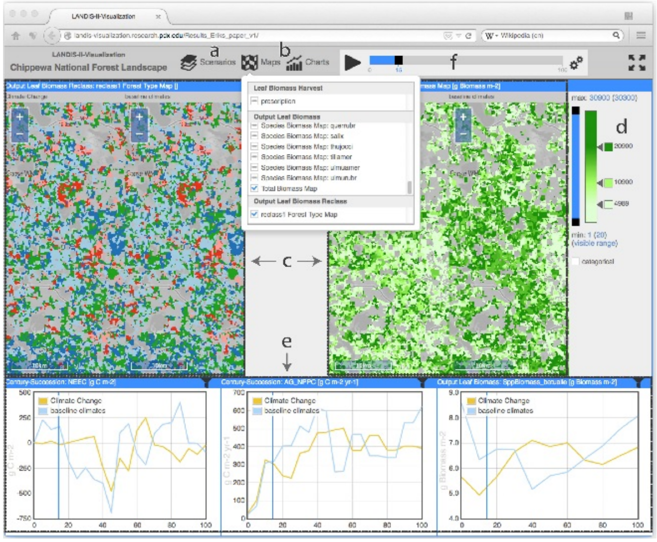

Figure 8.—Web client interface showing (a, b) selection menus, (c) maps, (d) filter and interactive legend, (e) charts, and (f) temporal navigation.

can easily make temporal and spatial connections between datasets. For example, if a chart indicates a sharp drop in biomass of a forest at a certain point in time, the user may pay special attention to the map of fires at that time step. Using map and playback controls (Fig. 8f), users can jump to certain points in simulation time, change animation speed, and zoom and pan in the maps during animation.

2.3. Scenario Comparison

After accessing LandViz, the end user selects a simulation scenario for exploration or two scenarios for comparison using a drop-down menu (Fig. 8a). Two additional drop-down menus provide a selection of map and diagram parameters for display (Fig. 8b). The user-interface allows for a maximum of four open map windows (Fig. 8c); thus, two parameters can be shown as maps for a two-scenario comparison or up to four maps for exploring a single scenario. Side-by-side comparison instead of overlay was chosen to allow for temporal side-by-side animation and to better discern differences between maps with parameters symbolized by using multiple classes. Interactive zooming and panning in one map window is applied to all displayed maps to facilitate comparison between parameters and scenarios.

To compare scenarios across time and space, maps need to be standardized by colors and data range across scenarios. Class breaks and ranges used for symbolization of a parameter are calculated based on the range of all displayed parameter sets over space and time. When a scenario is added, the symbolization is automatically adjusted to allow valid comparison.

The Web-based visualization client can also display tabular data over time as line charts (Fig. 8e). A single chart can show datasets from different scenarios; a maximum of four charts, each with multiple parameters, can be viewed at the same time. When the user is comparing scenarios, selecting a specific parameter automatically leads to the addition of the datasets of both scenarios. Depending on the data, the user can filter line charts by predefined landscape classes. Flot (http://www.flotcharts.org/), a plotting library that builds on the jQuery JavaScript library, was used to implement the line charts.

2.4. Web-enabled with Rapid Response Rate

The LandViz preprocessing component creates a customized, ready-to-use Web application with graphical user-interface that runs in the end user's Web browser. Access through a browser is especially useful for organizations that require security clearance for local software installation; security clearance is not required to use the LandViz visualization client. The Web visualization can easily be made accessible to the end user by providing the corresponding URL.

The Web-based visualization client is an HTML5/JavaScript application that uses the jQuery framework, a popular client-side JavaScript library, to implement the logical application structure and interface elements. It uses OpenLayers 3 (OpenGIS Web map tile service implementation standard; http://www.opengeospatial.org/standards/wmts), a free and open-source Web mapping framework, to load map tiles and display them in the client's map view using WebGL for hardware accelerated rendering. WebGL (Web Graphics Library) is a JavaScript API for rendering two-dimensional and three-dimensional graphics (WebGL – OpenGL ES 2.0 for the Web; https://www.khronos.org/webgl/).

WebGL was designed to render images on standard computer displays and thus can access data in standard image formats with three or four 8-bit color channels. Because LANDIS-II model outputs are encoded as single band rasters with 8, 16, or 32 bits per cell,

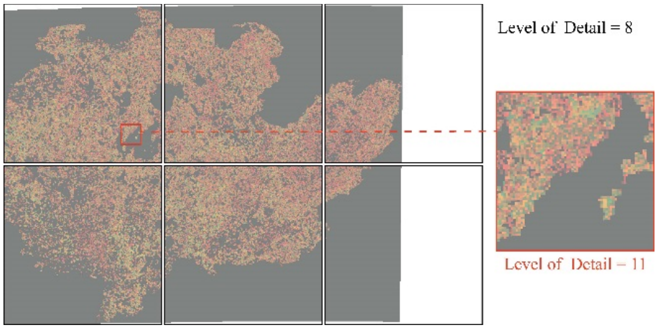

Figure 9.—Result of preprocessing LANDIS-II raster maps into subsets (tiles) at relevant resolution to speed the display of the map: PNG map tiles storing the original 16-bit values within two 8-bit channels with level of detail appropriate for user pan and zoom activity.

depending on the measurement scale of the grid parameter (nominal, ordinal, interval, or ratio scale), the preprocessing component must convert the data into image pixel values.

Single channel images are split up into four channel images; bit shifting is used to pack 16- or 32-bit bands into two or four 8-bit channels (which results in a coloring as seen in Figure 9). This method was inspired by Auer's (2012) approach to visualize terrain with WebGL based on 16-bit grayscale digital elevation models. After the bit-shifted grids are loaded into the Web-based visualization client, the original grid value can be accessed again by inverting the process, which makes interactive reclassification and thus resymbolization possible (Fig. 7). Changing the symbolization of a map interactively thus does not require additional loading of Web tiles as long as spatial extent and zoom level are not altered. To decode the bit-shifted grids and symbolize them on the client, the OpenLayers 3 WebGL renderer was extended with a self-developed fragment shader.

Output grids can be too large to be loaded by the client at interactive frame rates. To get around this problem, the preprocessing component creates different resolution levels and tiles the grids by using Tilers-Tools (scripts for raster tile sets from digital maps; http://tilers-tools.sourceforge.net/) following an OpenGIS standard. It creates PNG image tiles composed of four 8-bit channels with a size of 256 pixels × 256 pixels (Fig. 9).

Flickering between animated time steps may break the flow of the animation (Garlandini and Fabrikant 2009). Often time-step patterns in model output differed among parameters. To avoid flickering, a map from a previous time step is displayed until the animation reaches the next time step where a dataset is available. Maps showing different parameters may thus be updated at different moments during an animation. Raster tiles for the next time step are preloaded, rendered in the background, and then swapped to create a fluid animation.

2.5. An Extendable System Architecture

The architecture of LandViz was designed to accommodate different combinations of outputs depending on location, model selection, model configuration, and stakeholder needs. For example, LANDIS-II has a core framework and all ecological processes are represented within model extensions that can be substituted, removed, and added as necessary. The flexibility required a generic design, which makes it easy to adapt the system to different models, projects, spatial areas, and datasets. The configurable and modular architecture also allows use of the visualization tool with any cell-based landscape model.

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Forest managers are increasingly considering how climate change may alter forests' capacity to provide ecosystem goods and services. But identifying potential climate change effects on forests is difficult because interactions among forest growth and mortality, climate change, management, and disturbances are complex and uncertain. Although forest landscape models can account for most factors that structure forest landscapes (including climate change), the sometimes overwhelming amount of output from these models can make it hard for some managers to interpret and understand the projections. In an effort to help managers visualize and analyze model output, we developed an intuitive Web-based system: LandViz. We applied LandViz in a collaborative, iterative approach to conduct a Climate Change Vulnerability Assessment for the Chippewa National Forest in Minnesota using the LANDIS-II landscape model. LandViz enhanced managers' collaboration with model experts and increased their understanding of the tradeoffs between amounts and types of various resources in a changing climate. Managers can use the insight gained from LandViz to inform their strategic and tactical planning as they manage these tradeoffs.

KEY WORDS: forest management planning, decision support, forest landscape model, model visualization, climate change assessment, LANDIS-II model

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