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Preparing for an uncertain future: Merging the strategic foresight toolkit with landscape modeling in northeast Minnesota's forests

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HIGHLIGHTS

- Strategic foresight tools enhance the range of plausible futures considered.
- Landscape models project effects of future scenarios on ecosystem services.
- Merging strategic foresight & landscape models in public engagement strengthens each.
- Strategic foresight & landscape modeling address different dimensions of uncertainty.
- Accounting for uncertainty is critical to sound policy & adaptive management.

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ABSTRACT

"The Great Acceleration" poses serious challenges to land managers, policy makers, and all who are interested in the global sustainability of socioecological systems. Methods that can effectively address the uncertainty of the future to allow more robust and adaptive planning and management are urgently needed. We present a case study from northeastern Minnesota to highlight how strategic foresight methods and landscape modeling can serve as complementary tools to generate divergent yet plausible participatory scenarios to ultimately model the potential impacts of these scenarios on fundamental ecosystem services over 50 years. The landscape scenarios generated from the scenario process ranged widely, from optimistic futures to dire outcomes; these scenarios were far more divergent than outcomes explored in a traditional factorial landscape modeling study. This greater range in possible futures leads to more useful model outputs to guide the decisions of planners, managers, and policymakers. Our study illustrates advantages of blending the power of multiple strategic foresight tools with landscape modeling to generate alternative future storylines that are enlightening (i.e., expanding the scope of possibilities), useful (via strong contrasts), and yet plausible (i.e., grounded by robust science and stakeholder perspectives). Strategic foresight methods such as horizon scanning can also be useful in on-going monitoring of landscapes to support adaptive management aimed at fostering sustainable futures. Combining these approaches enhances creativity and wide-ranging plausibility (strategic foresight) with science-based assessments of outcomes and trajectories (landscape modeling), increasing the likelihood of creating resilient, preferred futures.

Abbreviations: STEEP, social, technology, economic, environmental, and policy and governance systems; Dinamica EGO, Dinamica Environment for Geoprocessing Objects; TRIAD, cross-jurisdictional zoning approach to forestry including conservation, ecological forestry, and intensive forestry zones.

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1. Introduction

The future state of landscapes, ecosystems, and social systems has always been uncertain, but since the last half of the 20th century, forces of change have grown exponentially, with impacts felt globally; this rapid change across many systems has been dubbed the "Great Acceleration" (Steffen, Broadgate, Deutsch, Gaffney, & Ludwig, 2015). Rapid change significantly complicates planning and management, making methods that address uncertainties valuable. In this paper, we illustrate how strategic foresight techniques may augment participatory scenario development in a way that bolsters landscape modeling to ultimately address the many uncertainties surrounding changing forests, climate, and social systems.

There has been growing application of approaches that develop plausible but contrasting scenarios to frame uncertainty in the future states of socioecological systems around the world (Amer, Daim, & Jetter, 2013; Laurent, Friedman, Krantzberg, Scavia, & Creed, 2015; Mitchell, Lockwood, Moore, & Clement, 2016; Creed et al., 2018; Rutting, Vervoort, Mees, & Driessen, 2021). Lambert and colleagues noted that, "Research from behavioral psychology and economics shows that our conceptions of the past anchor our expectations and perspectives about the future, limiting our decisions and reinforcing preconceptions and biases'' (Lambert et al., 2018, p. 14). Methods from strategic foresight, in particular participatory scenario development, can help those involved in planning and decision-making push past their preconceptions of the future and embrace the inherent and growing uncertainty of socioecological systems, thereby better informing policy decisions (Bengston, 2019). Scenarios can help guide decision making towards a preferred future by exploring a range of options and looking at unexpected consequences (McBride et al., 2017; Peterson, Cumming, & Carpenter, 2003), and this is best achieved when participants are assisted in thinking beyond current, business-as-usual, patterns (Bengston, 2019).

Although scenarios are the best-known method in strategic foresight (also known as Futures Research; Bengston, 2019), the strategic foresight toolkit consists of many other tools (Engasser 2022). Strategic foresight is an interdisciplinary field that examines a range of futures to prepare for possible major shifts and upheavals over the coming decades (Bengston, Kubik, & Bishop, 2012). Note that 'futures' is plural–strategic foresight explicitly plans for multiple, contrasting potential future states (Bengston, 2019; Schwartz, 1991). Horizon scanning, a systematic search for signals of change, both within and outside a system, is a foundational practice in strategic foresight (Hines, Bengston, & Dockry, 2019). Horizon scanning can be an ongoing process, as in the Forest Futures Horizon Scanning project (Hines et al. 2019), or it can be conducted for a specific project or on an annual basis such as Sutherland's annual conservation-oriented horizon scan (e.g., Sutherland et al., 2022). An effective scanning effort will uncover signals of change inside the system (e.g., forestry) as well as in the broader social, technology, economic, environmental, and policy and governance systems–known by the acronym STEEP (Hines et al. 2019). Additionally, an effective scanning process will uncover signals of change that are imminent or even starting to appear in the current system (called horizon 1 scan hits), as well as those that are more uncertain and/or further off (horizon 2), and some that might seem even ridiculous, but with potentially significant impacts should they come to pass (horizon 3; Hines et al. 2019).

Analogous to strategic foresight, landscape models are commonly used in participatory scenario development (e.g., Sturtevant et al., 2007), but provide more quantitative guidance for resource decision-making (Lucash, Scheller, Gustafson, & Sturtevant, 2017; Palacios-Agundez et al., 2015; Sturtevant et al., 2009). Landscape modeling has grown in sophistication and capability across multiple disciplines, including land use/land cover change (National Research Council 2014; Ren et al., 2019; Verburg et al., 2019), forest landscape modeling (Sturtevant & Fortin, 2021), and hydrologic modeling (Filoso, Bezerra, Weiss, & Palmer, 2017; Fu, Merritt, Croke, Weber, & Jakeman, 2019). Process-based landscape models improve our ability to project the consequences of multiple interacting drivers on ecosystem processes under novel conditions associated with global change (Cuddington et al., 2013). In contrast to strategic foresight, however, landscape modeling efforts are often focused on ecosystem dynamics, and do not consider human-ecosystem feedbacks that may result in dramatic regime shifts and an expanded breadth of plausible futures (Filatova, Polhill, & van Ewijk, 2016). Conversely, there is an entire interdisciplinary field of study dedicated to investigation of fully-coupled socio-ecological systems (Filatova et al., 2016), some of which apply sophisticated modeling approaches such as agent-based modeling to embed reciprocal feedbacks among ecosystem, social, and economic processes (e.g., Grêt-Regamey, Huber, & Huber, 2019). However, the degree of sophistication in both modeling technologies and domain expertise necessary for such efforts can be prohibitive in many circumstances (Voinov et al., 2018).

Combining strategic foresight methods with landscape modeling efforts should, in theory, enable superior framing of relevant and plausible modeling scenarios by capturing the broader context of the socio-economic forces that ultimately drive human interactions with forested ecosystems. In turn, landscape modeling enables the translation of plausible, qualitative "storyline" future scenarios of socioecological dynamics into quantitative representations, allowing more objective evaluation of contrasting future scenarios on ecosystem goods and services (e.g., forest products, water regulation, carbon storage, and other ecosystem services) (e.g., Mallampalli et al., 2016). Combined, these methods may better support efforts to plan in the face of growing uncertainties, with strategic foresight elucidating the range of possible futures and landscape modeling quantifying system specifics in those alternative futures.

In this paper, our goal is to demonstrate the advantages of combining multiple strategic foresight tools with landscape modeling to generate insightful and quantifiable future storylines and ultimately to simulate forest landscape processes of disturbance, vegetation change, and hydrologic regimes for these alternative future scenarios looking to the year 2070. We present a case study to highlight how these methods were applied to elucidate interconnections of land use, land cover, forest dynamics, and water systems in a large subbasin feeding Lake Superior in Minnesota, USA. More specifically, we describe how we developed future scenarios in a participatory process with key local experts, planners, sovereign Tribal nations, and others with an interest in the future of the people and landscapes of the region. These scenarios framed coupled modeling with the Dinamica Environment for Geoprocessing Objects (Dinamica EGO) cellular land cover model (Soares-Filho, Coutinho, & Lopes, 2002) and the LANDIS-II forest landscape model (Scheller et al., 2007). Finally, because the COVID-19 pandemic necessitated a shift away from in-person meetings, we also discuss the intricacies of conducting a project like this virtually. By providing detailed descriptions of 1) the application of strategic foresight tools in participatory scenario development and 2) the role of landscape modeling in clarifying both the scenario storyline development and the translation from scenarios to modeling, we hope to make the integration of these methods more accessible to a broad audience.

2. Methods

2.1. Study area

Our study area consists of a patchwork of land ownerships across the combined St. Louis River and Cloquet River subbasins that feed Lake Superior near Duluth, Minnesota, plus a 5 km buffer to address any potential adjacencies or edge effects (Fig. 1). The lower portion of these combined subbasins is classified as a Great Lakes Area of Concern, i.e., a place with a significant impairment to beneficial uses of surface waters, typically due to contamination from industry (US EPA, n.d.). The interior of the landscape is primarily working forest including large regions

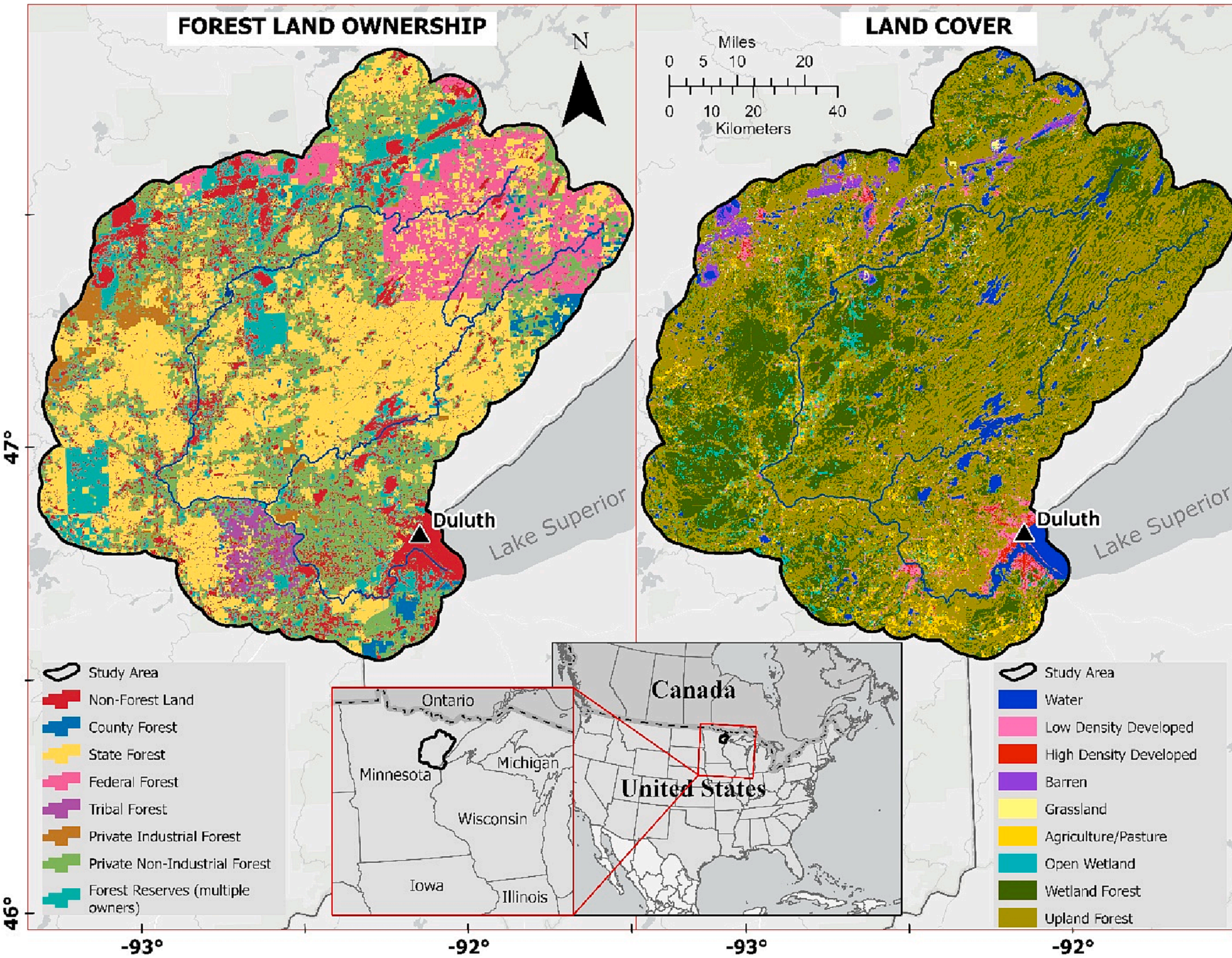

Fig. 1. Map of the study area in northeast Minnesota, USA. The map on the left shows ownership of forest lands and non-forest land. The map on the right depicts land cover.

of forested wetlands. It is bracketed in the south by development around Duluth MN and Superior WI, and in the north by mining operations along the Mesabi Iron Range. Additionally, the Fond du Lac Band of the Lake Superior Chippewa reservation falls within the study area, with most of the remaining area falling within the 1854 ceded territories of northeast Minnesota (Thompson 2020).

2.2. Strategic foresight and participatory scenarios

Our participatory scenario development process included numerous steps: 1) participant identification and recruitment, 2) introductory sessions, 3) survey of drivers and uncertainties, 4) serious game (optional), 5) framing the scenarios, 6) iterative feedback and scenario refinement, and 7) scenario translation into landscape models. We followed common environmental scenario planning methods (Alcamo 2008; Kok, Biggs, & Zurek, 2007), while also drawing on additional strategic foresight methods, such as horizon scanning (Hines et al. 2019), to inform the process. We used a project structure similar to the New England Landscape Futures project (McBride et al., 2017; Thompson, Plisinski, Lambert, Duveneck, & Morreale, 2020), including a 2x2 matrix scenario approach where two contrasting constructs create four distinctly different scenario frames (Bishop, Hines, & Collins, 2007; Schwartz, 1991). We considered alternate scenario approaches such as Aspirational Futures (Bezold, 2009) but decided the 2x2 was an appropriate fit for the project goals.

2.2.1. Participant identification and recruitment

The regional networking body of the Minnesota Forest Resources Council (n.d.)–the Northeast Minnesota Landscape Committee–agreed to participate in the project, and to help us reach people in their networks for potential participation. Our outreach included Tribes with reserved land within or proximate to our study area and access rights to the ceded lands (Thompson 2020), the Fond du Lac Band of Lake Superior Chippewa and the Leech Lake Band of Ojibwe, and a group that represents Tribes, the 1854 Treaty Authority. To add broad, society-wide perspectives of the factors driving changes in the coupled natural-human systems of the region, but not well represented in the forestry-focused Council, we additionally recruited representatives from tourism, economic development, community development, regional foundations, energy, and media. In total, 48 participants were involved, representing a wide range of forestry expertise (public to industry) and conservation, as well as representatives of the broader community.

2.2.2. Introductory session

At each step, we held multiple shorter meetings rather than one, long, on-line meeting, which provided an added benefit of accommodating busy participants by repeating sessions. The Introductory session provided an overview of the project, expected participant roles and contributions, and introduced both the LANDIS II modeling approach and strategic foresight. We presented scenario development steps, including the concept of critical uncertainties and finding axes to frame scenarios. Using a picture of Elvis Presley and President Nixon in the White House as a culturally-relevant prompt (Fig. 2), participants were asked "what would be surprising in our world now for someone in the 1970 s?", laying the groundwork to think about the potential for significant and unanticipated change in the coming decades. We developed an exercise suitable for on-line meetings based on the serious game IMPACT: Forestry Edition (Bengston, Westphal, Dockry, & Crabtree, 2022). The goal was to foster creative thinking using a set of the impact cards drawn from the Forest Futures Horizon Scanning database (Fig. 3; full description in Supplementary Materials). Last, we introduced a survey to identify future drivers and critical uncertainties, described in the next section.

2.2.3. Future drivers and critical uncertainties survey

Critical uncertainties, the drivers that are rated very uncertain and with significant potential impact, are determined to generate the scenario-framing 2x2 axes (Schwartz, 1991). The Strategic Foresight team, in collaboration with other project investigators, drafted a survey of 19 potential drivers of landscape change covering a broad range of social, technological, economic, ecological, and policy categories (Table 1; details in supplemental materials). These were drawn from the Forest Futures Horizon Scanning project database (e.g., climate migration), from the scientific literature (e.g., population age), and from team members' experience (e.g., land parcelization). Participants were asked to rate each driver on a scale of 1–4 for both impact and uncertainty. They were asked, "Will this driver change NE Minnesota's future a little or a lot?" (1–slightly impactful to 4–extremely impactful) and "Is there one predictable path forward for this driver or are there many unpredictable ways the future of this driver could play out?" (1–course is highly certain to 4–course is highly uncertain). Participants also had the option to submit and rate additional future drivers. Results were analyzed to determine the critical uncertainties to inform the scenario framing (discussed below).

2.2.4. Serious gaming session

Participants were offered the opportunity to play a full on-line version of IMPACT: Forestry Edition; five participants did. This game introduces several strategic foresight methods and emerging issues in forestry while building players' ability to engage actively with the future during the participatory scenario development sessions to follow (Bengston et al., 2022). We made this session optional because the on-line platform for virtual play was difficult for some to access.

2.2.5. Framing the scenarios

Each scenario was the focus of two meetings with five to seven participants to brainstorm the specific scenario. Participants attended one session. After ensuring that: 1) each group had non-forestry participants, 2) Tribal representatives were present in at least one session for each scenario, and 3) players of IMPACT: Forestry Edition were spread across the sessions, remaining participants were randomly assigned to one of the four scenarios.

In each brainstorming session, facilitators from the Strategic Foresight team presented the critical uncertainties survey results and the axes that emerged from the survey. These axes framed the scenarios, creating two conditions for each scenario. Facilitators prompted discussion by asking "For both of these conditions to coexist, what would the year 2070 have to be like?" and "Following the logic of our scenario, how could these drivers form one coherent future?" Participants were presented with two examples of horizon scan hits that illustrated each of the axes end points (Supplemental Materials). The objective was to give a sense of what the future could look like in each scenario without presenting too much information that could stifle or unduly influence participants' thinking. Facilitators guided participants through a process to further flesh out how they believed the other future drivers from the survey would interact to create a plausible future.

Following the participatory scenario development sessions, the Strategic Foresight team integrated input from the participants into a bulleted outline for each of the four scenarios. The few contradictory elements brainstormed were noted to ask for participants' feedback; very few were outliers that did not fit logically within the entire scenario and could be left out. The scenario outlines were then presented to the participants in feedback sessions (again repeated twice to accommodate participant schedules). The Strategic Foresight team presented the synthesized storyline outline for each scenario and asked participants to suggest adjustments to align the storyline with what their group had crafted during the participatory scenario development sessions. The Strategic Foresight team posed the clarifying questions mentioned above to gather missing elements or rectify logical inconsistencies within the scenarios.

Fig. 2. President Richard Nixon meets with Elvis Presley in the White House, 1970. This picture was used as a culturally-relevant prompt about how much change can happen in a few decades.

Fig. 3. IMPACT: Forestry Edition foresight exercise used in introductory session breakout groups. Each card (e.g., "fake plastic trees") is a horizon scan hit, with game-play instructions used to support creative thinking in the small groups.

Table 1
Drivers of change from the participant survey, sorted by STEEP category. Each was rated by participants for uncertainty and impact.

STEEP category	Driver in the participant survey
Social drivers	population age, climate migration, community diversity
Technological drivers	workforce automation, adoption of advanced forest product technology, shift to renewable energy
Economic drivers	financial security, recreation economy, parcelization of land ownership, global supply chains
Environmental drivers	severity of climate change, forest species composition, water quality, spread of invasive species and pathogens, natural disturbances
Policy/governance drivers	rights of nature, policy to address climate change, environmental regulations & oversight, geopolitical stability

2.2.6. Scenario storylines

The Strategic Foresight team used all input from the participatory scenario development and feedback sessions to write narrative scenarios from the perspective of the year 2070. Each storyline moves the scenarios through three time periods: early days (2021–2035), transition period (2036–2050), and recent past (2051–2070). However, not all drivers were accounted for in each time horizon. The Strategic Foresight team added driver impacts if they were possible within the logic the participants created in their stories. Draft scenario storylines were then sent for input to the wider project teams: landscape modeling, hydrologic modeling, and land cover change. The additional detail necessary to implement the scenarios within these models, described in brief below, further clarified and refined the models into their near final form. Two sessions were held with participants approximately one year following the introductory sessions to report back on the land use/land cover modeling work, early output from LANDIS II modeling, and the full scenarios. Participants offered a few small modifications of the scenarios, which were included in the final storylines.

2.3. Landscape modeling–scenario translation

We used Dinamica EGO (Soares-Filho et al., 2002, 2009) to model land use/land cover (LULC) change for each scenario annually from 2020 to 2070. Dinamica EGO is a spatially explicit cellular change model capable of multi-scale simulations that incorporate spatial feedbacks (Rodrigues & Soares-Filho, 2018). We used the National Land Cover Database (NLCD) 2016 (Dewitz, 2019) to define the initial landscape conditions for each scenario and used the changes between NLCD 2001 (Homer et al., 2007) and 2016 to parameterize a "Recent Trends" simulation (see below) such that rate of LULC change, change patch size and shape, and the spatial allocation of change on the landscape would mimic this historical reference period. For more detail on our implementation of Dinamica EGO, see Supplemental Materials.

We used the LANDIS-II forest landscape model (Scheller et al., 2007) to simulate forest landscape processes of disturbance and tree species competition and succession. LANDIS-II includes several options for modeling a broad range of forest disturbances in time and space, including forest management, fire, wind, and insect disturbances (Lucash et al., 2018). The model further includes the Land Use Plus disturbance extension (Thompson et al., 2016) that enables the coupling of forest dynamics with alternative land use change scenarios derived from land use change models–in our case, Dinamica EGO (Soares-Filho et al., 2002). Among the strengths of LANDIS-II is its ability to simulate the effects of climate change on forest succession and disturbance processes, such that climate change scenarios may be explicitly considered within the context of the alternative futures. We parameterized the LANDIS-II model to represent a continuation of past disturbance regimes, both natural and anthropogenic (i.e., land use/land cover change and logging practices), given the initial forest landscape conditions of the year 2020 (Supplementary Materials).

Using the landscape models to support participatory modeling and scenario refinement consisted of three primary steps. First was the initialization of Dinamica EGO and LANDIS-II for the study area using available geospatial, climatological, and forest inventory data. The second was to parameterize each model to simulate land cover and vegetation change according to drivers of the recent past–termed the "Recent Trends" scenario that was refined in part by the expertise of the local participants. This step served three critical purposes: 1) a baseline projection that could be vetted by local experts to enhance the confidence in the modeled outcomes, 2) a baseline in underlying drivers that could be modified to fit the specifics of the alternative future scenarios, and 3) clear definitions of those processes that could be explicitly modeled, and those that were outside the scope of the landscape modeling (thereby serving as contextual factors–see below). This third purpose informed the third step of the modeling process–the translation of qualitative narrative statements from the scenario storylines into quantitative drivers and processes. At times this required refinement of the storylines themselves. Notably, participants were not shown any landscape projections until *after* the storylines were completed. We did not want to influence visioning in the scenarios with too much information about current conditions and past drivers. Steps 1 and 2 above are described in the Supplementary Materials. Step 3 is elaborated briefly below.

2.3.1. Scenario translation

Translating the scenarios to the models started with categorizing statements made in the draft scenario storylines into factor domains (e.g., economy, human population, forest management practices, natural disturbance, climate, etc.). Once defined, these factor domains were then separated into three broad categories. *Contextual factors* were defined as those elements that informed model parameterization and implementation but were not explicitly modeled. For example, we did not model the economy explicitly, but did ensure that the processes we modeled were consistent with the economic issues outlined in the scenario. *Direct model inputs* included those factors that could be defined explicitly as inputs to either Dinamica EGO or LANDIS-II such as approaches to forest management and disturbance factors. *Model outputs* included the predictions of the participants for those elements that will ultimately be quantified as outcomes of the landscape modeling, such as trends in vegetation change and ecosystem goods and services such as carbon storage, wildlife habitat, harvest outputs, and water yield (Fig. 4).

3. Results

3.1. Strategic foresight

3.1.1. Generating the axes

The drivers of change survey results informed the selection of two axes of change which in turn set up four plausible yet distinct images of the future. The mean participant survey responses scored three future drivers highly on both potential impact and uncertainty: "policy to address climate change", "rights of nature", and "financial security" (Fig. 5). These were the critical uncertainties. We selected "financial security" for one axis, ranging from "financially struggling individuals and communities" to "financially secure individuals and communities". The other axis was "action to address climate change", defined as "proactive, coordinated action to address climate change" to "reactive, uncoordinated action to address climate change". The four scenario frames were each given an animal name and summary quote evoking the gist of the scenario (Fig. 6): financially secure and proactive approaches to climate change ("School of Fish: Collective action to thrive in face of common threat."); financially secure and reactive, uncoordinated response to climate change ("Brown Rat: Highly adaptable, do well no matter the conditions."); financially insecure and coordinated responses to climate change ("Bee Colony: Despite their coordination, they still struggle to survive."); and financially insecure and uncoordinated responses to climate change ("Sumatran Rhino: What survivors are left have little hope."). The remaining drivers from the survey are categorized as driving forces and predetermined elements, as uncertainty about the driver decreased (Fig. 5).

3.1.2. Scenario outlines

Ideas generated in the initial brainstorming sessions were the primary input to the scenarios. The scenario outlines generated from this input are presented in Table 2. There were common topics in each scenario, like the amount of timber harvesting, climate change effects and policy levels (local to international), and aspects of the local economy. But each scenario is distinctly different. For example, in Bee Colony, participants suggested climate policy would be set at the national level, would favor carbon storage, and would therefore drastically limit timber harvest. In Brown Rat, participants anticipated local planning and cooperation leading to a thriving local economy and wood products industry (Table 2).

While each scenario brainstorming session was attended by a small group of participants, the feedback sessions were open to all, allowing feedback on a scenario from those not initially involved in its development. This allowed participants from specialized sectors to comment on aspects of other scenarios they found unrealistic. One example was response to a proposed decline in aspen in the face of climate change, which the industrial foresters thought was unlikely–they expected aspen to adapt to a drying climate. The inclusion of all participants also allowed for discussion across various perspectives, such as restoration ecologists and forest industry representatives. The second form of

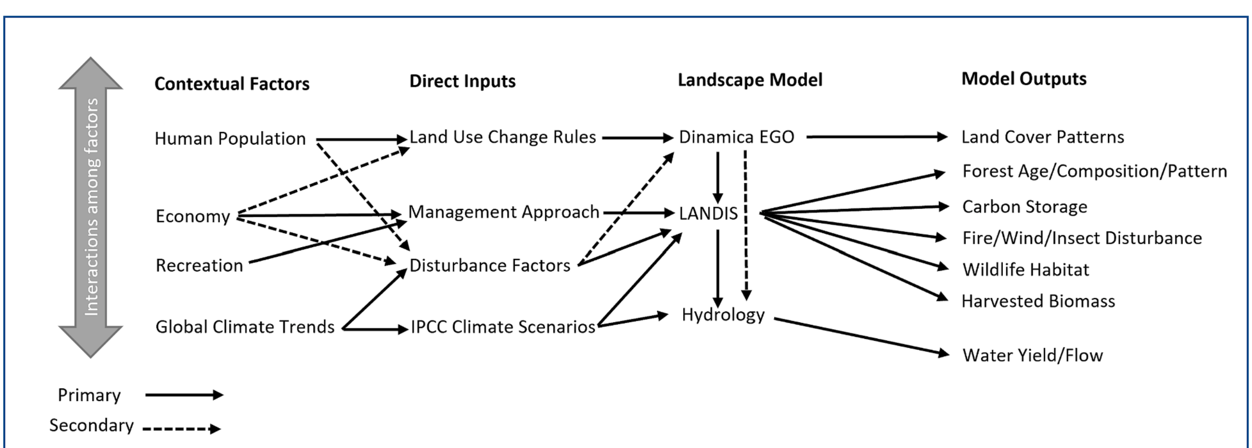

Fig. 4. Scenario translation involved both intra-level and inter-level exchanges of information. Note that these are examples of contextual factors (not exhaustive), and these factors are interrelated.

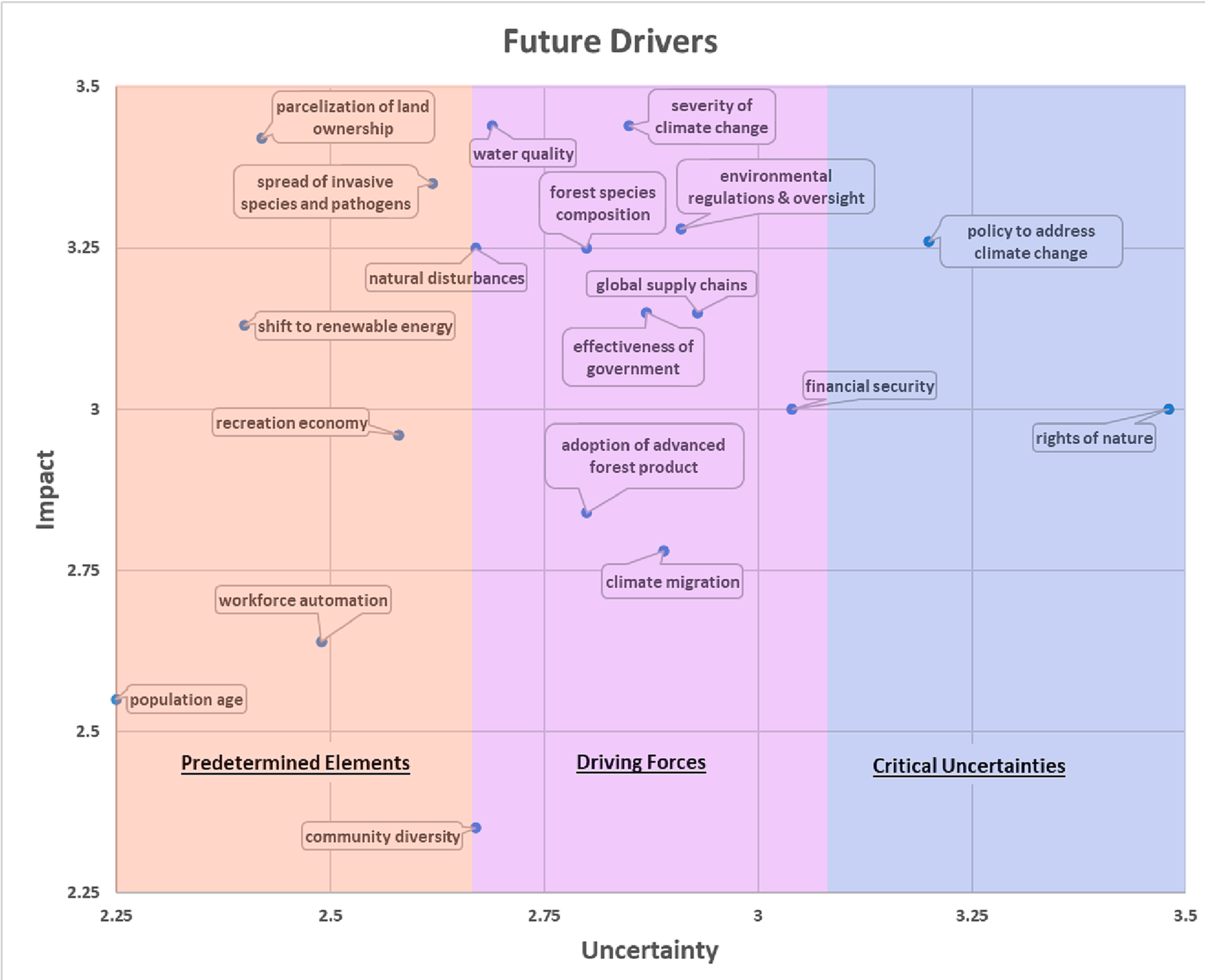

Fig. 5. Average participant ratings of the drivers of change. Rated on a scale of 1–4, slightly-extremely impactful and highly certain to highly uncertain. Highly rated drivers (in blue) are the critical uncertainties. Low rated drivers (in pink) are predetermined elements. Drivers rated in the middle (in purple) are driving forces. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

feedback in these sessions was in response to questions from the Strategic Foresight team, providing information needed to reconcile conflicts between the two development sessions or to clarify what was meant by some comments in the development sessions. For example, participants who had contributed to the Bee Colony scenario were asked, “If the forest product industry is gone, and the forests are ‘locked up’, will there be any harvests at all?”.

With this feedback and the scenario outlines, the Strategic Foresight team wrote full narrative scenarios (Supplementary Materials). Landscape Modeling team members conducted some plausibility stress-testing, leading to a few changes if the modelers thought something was impossible or highly unlikely. For example, participants had included an increase in spruce budworm (*Choristoneura fumiferana*) in a scenario that would also experience a warming climate. Experts believe a warming climate will lessen the impact of spruce budworm in this region over time (Régnière, St-Amant, & Duval, 2012), so this was modified to refer to increased insect disturbance more generally, including invasive species. No changes were made to the scenarios if they altered the intent of the participants without participant feedback and concurrence.

3.2. Scenario translation

The Landscape Modeling team extracted elements of each scenario storyline and categorized them as contextual factors, direct model inputs, or model outputs (Fig. 4). Critical contextual factors included human population change in time and space, economic drivers, recreational patterns, and global climate trends. These factors logically related to domains that required greater specification as direct inputs into the landscape models. For example, patterns of human population were fundamental to the specification of the land use change rules ultimately used to parameterize Dinamica EGO (e.g., how much will the population increase or decrease relative to recent trends). The economic context further justified specifics of those land use change rules (e.g., where will changes in populations manifest in terms of urban, exurban, or rural housing development; Fig. 4). Similarly, climate change depends upon factors outside of the study area but provides context for the specific climate scenarios feeding into the landscape models for each scenario (see below), while also providing relevance to specific disturbance factors (e.g., catastrophic fire, invasive insects) necessary to drive the behavior of the landscape models. Notably, the term “contextual” refers only to what can and cannot be modeled with available tools and resources. Clearly these drivers had direct relevance to how the

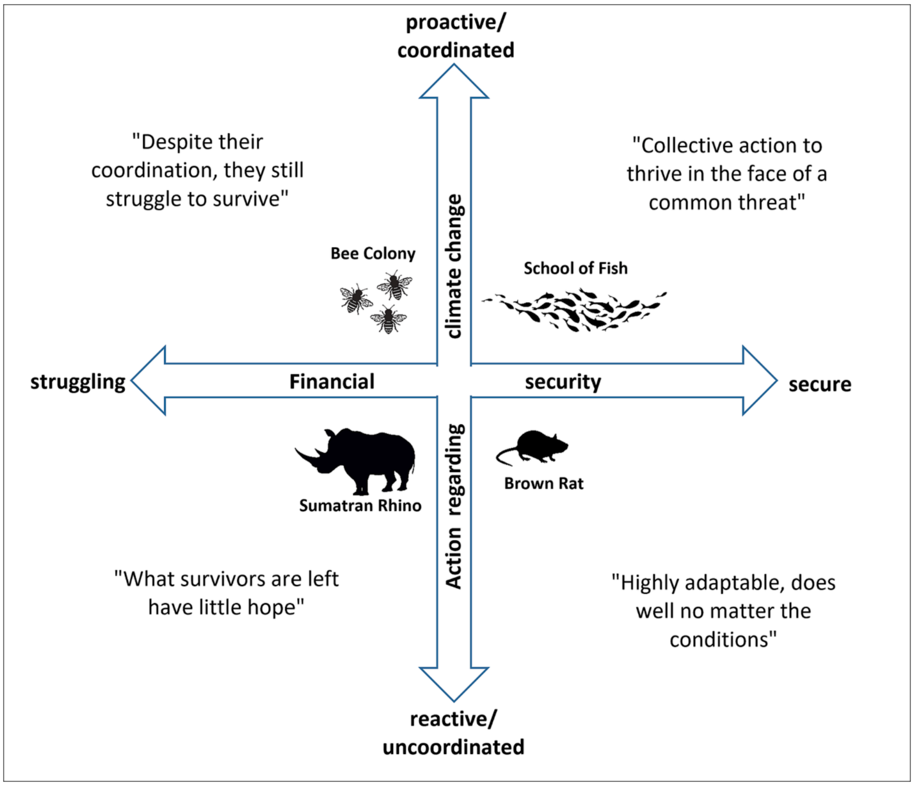

Fig. 6. The scenario axes–response to climate change and financial security–and scenario names.

scenarios were implemented within the models. However, many elements of the storylines, such as trends in forest composition, were best defined as model outputs–emergent behavior defined by the inputs to the model and the logic underlying their results. Elements of the storyline fitting within the model output category were therefore considered as the predictions of the participants that may be either confirmed, modified, or challenged by the ultimate model results.

The process of scenario translation presented another opportunity for storyline iteration and during this process the modeling team identified landscape issues (e.g., housing, climate, forest disturbance) that were unequally addressed across scenarios. Where appropriate, additional context was added to the storylines to address these issues, i.e., when the additional refinements were relevant and did not create a logical inconsistency with participants' ideas. Another benefit of this analysis was finding additional internal inconsistencies within each scenario. The modelers brought their questions to the Strategic Foresight team who resolved these inconsistencies with storyline adjustments consistent with the participatory process. None of the issues raised were significant enough to alter the storyline but were important for accurately parameterizing the models.

The direct inputs served as the principal elements distinguishing among the modeled scenarios (Table 3). In the case of climate, the fifth Assessment Report from the Intergovernmental Panel on Climate Change (IPCC) used four Representative Concentration Pathways (RCPs), each representing a different trend in an atmospheric CO_2-equivalent concentration (Change, 2014). Based on the scenario storylines, we selected the most closely aligned RCP for each. The lowest increase in atmospheric CO_2eq was assigned to School of Fish, the scenario with a proactive, coordinated response to climate change and economically stable communities. The highest CO_2eq increase was assigned to the Sumatran Rhino scenario, with reactive and uncoordinated climate change response and economically struggling communities. Brown Rat was assigned the second lowest increase while Bee Colony was assigned the second highest. This decision was based on the economic impacts of climate change, suggesting that the more economically secure scenario would have a lower increase in CO_2eq.

Some of the model inputs differentiating scenarios could be defined as simple proportional changes to the Recent Trends scenario. For example, Bee Colony's forest management protocol was: lowest overall harvest rate *("forests locked up");* no harvesting on public land, and harvest rates on upland private and tribal lands are greatly reduced; reforestation of riparian and open lands; incorporate assisted migration species; perhaps assisted migration after disturbances. Other model inputs required more creative interpretation but were nonetheless both plausible and consistent with the storyline narrative. For example, the School of Fish scenario was characterized by proactive forest management with high levels of cooperation. This situation suggested the "TRIAD forestry" approach, a cross-jurisdictional zoning approach where high-productivity industrial forestry offsets losses in timber production associated with conservation reserves, and theses extremes are embedded within a broader matrix of "ecological forestry" (Himes, Betts, Messier, & Seymour, 2022). In the case of land use change patterns, rules associated with the Bee Colony and Brown Rat scenarios could be expressed as relatively simple modifications to the rule sets driving Recent Trends, whereas the Sumatran Rhino scenario required more detailed specification of the initiation and growth of human encampments by climate refugees, while the School of Fish was consistent with a "smart-growth" policy that would restrict the expansion rate of housing developments despite increases in human populations.

Elements categorized as model outputs indicated the expectations of participants in terms of the forest ecosystem conditions, goods, and services that fall within the model domains to be applied to the different scenarios portrayed in Table 1 (Table 4). In these cases, the modeling results will ultimately offer an objective method of either confirming, challenging, or modifying participant expectations of how alternative futures might influence the region's forests based upon the science encapsulated within the models.

Table 2
Summary of scenario storylines, by scenario era. *Scenarios were written looking back from 2070.

Scenario Era*	Scenario outline
Bee Colony: Despite their coordination, they still struggle to survive. *Proactive/coordinated response to climate change, financially struggling individuals and communities*	
Early days: 2021–2035	National and International climate policies prevailed; emphasis on global carbon markets. By 2025, forests were managed primarily for forest biomass as a carbon sink resulting in forests largely "locked up," with a disappearing wood products industry. Some harvesting on private land still occurred, with focus on wildlife or local needs (e.g., firewood). Tribes harvested on their lands to meet food, material and cultural needs. Slow but steady growth in rights of nature. The Nature Conservancy (TNC) initiated a partnership of government, NGO, and landowners to manage forests. This partnership started adaptive migration and bought from local suppliers to support the local economy. Recreation still important, winter recreation declining. Climate migrants and other newcomers moved in around 2030, many bringing jobs with them.
Transition: 2036–2050	Renewable energy on the rise. Harnessing lake movement, home-based wind & solar, by 2050 most energy produced locally. Decline in winter cold meant remaining logging had to adapt to warmer conditions–no more frozen ground during harvests. TNC partnership continued, focused on hardwoods. Workers in forestry and recreation under- or unemployed.
Recent Past: 2051–2070	By 2070, forestry and recreation workers were gone. Forest owners made some money in carbon markets. But Duluth was cited as one of the most climate resistant cities, so drew new residents from around the country and world, leading to a new mix of cultures, and a more urban focus. The TNC partnership continued to gain support, and broadly implemented its work throughout the region by 2070. This work changed forest composition. Because of this work and climate change, there was much less spruce, much more maple, oak, basswood.
School of Fish: Collective action to thrive in face of common threat. *Proactive/coordinated response to climate change, financially secure individuals and communities*	
Early days: 2021–2035	Collective response to all the natural disasters: fires, hurricanes, etc. Coalition across government, Tribes, NGOs, business, landowners to create a climate resilient NE MN–coalition named Growing Minnesota's Future. Incentive and asset-based approach: strong forest-based way of life, recreation, and real estate. Smart growth for influx of new residents. Leveraged existing programs and created new programs to build on forest and recreation economies. Tribes played a central role in deciding actions, in part to maintain and coordinate their access to ceded territories. Tribes gathered foods, medicinal, and other products from their lands for their own use and for sale. Federal policy emphasized carbon storage–including in long term wood products. Tax credits and other policies encouraged use of carbon-friendly and local products. This led to job training programs and campaigns to buy from regional makers which brought back the local forest industry. Bio-energy industry grew, using forest industry waste. Collectively, these initiatives supported living wages and poverty declined. Growing Minnesota's Future was also active in ecological management: restoration, adaptation, and significant monitoring. They also led effective cross-jurisdictional land management efforts. An Inter-Tribal Commission and member of Growing Minnesota's Future led planning and implementation of these efforts.
Transition: 2036–2050	Aspen (*Populus* spp.) adapted to the drying conditions, so provided ongoing feedstock to numerous wood products. More hardwoods started to grow in the region. Ecological monitoring and management provided new jobs. Over time, forest and recreation workers shifted from living-wage to solid middle-class incomes. Landscape benefits of cross-jurisdictional management included minimal invasive plants, and catastrophic wildfire kept to a minimum.
Recent Past: 2051–2070	All the coordinated management led to keeping cold-water streams cold, maintained forest cover, and supported good jobs. Workers stayed, tourists came, and the region thrived.
Sumatran Rhino: What survivors are left have little hope. *Reactive/uncoordinated response to climate change, financially struggling individuals and communities*	
Early days: 2021–2035	Recreation economy held on for a while, but other industries declined quickly. Politicians and managers were focused on the effects, not causes like climate change, with little room for anything beyond the most urgent crisis. Efforts to address climate change never materialized. Climate change increased derechos and ice storms. The resulting downed, dry wood fed the Great Fire of 2024.
Transition: 2036–2050	Even with transformations from climate change, NE MN was seen as one of the more climate resilient regions in the US. Winter was in decline, affecting timber harvesting and recreation. Winter sports were gone, replaced initially by biking and other activities. Sea level rise drove many to migrate within the US, many coming to NE MN. This influx of new residents was a disruptive change for long-time residents. Not all new residents brought their work with them, some started to camp rough in the woods. Migrant camps started to impact interest in forest-based recreation. The consequences of climate change continued to grow: mass unemployment, homelessness, decline in health and well-being. This decline motivated private landowners to sell. Others lost their land to tax delinquency. This resulted in nearly all of the forest land being owned by either a handful of wealthy owners, or the public. Small forest holdings were few and far between.
Recent Past: 2051–2070	Catastrophic fire and other climate change effects changed NE MN forest to savanna. Forest industry disappeared from the region. Climate migrants continued to arrive, finding respite in a relatively hospitable climate. However, many were unemployed, and made camps wherever they could, spreading further out to avoid detection. Game species were depleted by unregulated, subsistence hunting. Climate migrants brought problems with them, from invasive species to drugs. Encampments were sources of wildfires and water quality degradation. Tribes protected their lands, defended against would-be squatters. Tribal lands became refugia for native plants and animals.
Brown Rat: Highly adaptable, do well no matter the conditions. *Reactive/uncoordinated response to climate change, financially secure individuals and communities*	
Early days: 2021–2035	Ineffective federal and state governments left regions on their own. Divisions between land management agencies, jurisdiction, and departments were exacerbated. No coordinated response to climate change, and slowly evolving climate change impacts. Mills closed, because harder and harder to find workers–young people had moved away. Towards the end of this period, Californians and others flocked to the Upper Midwest, seeking a climate resilient region in which to live. Housing was available from the earlier population loss. Corporations also saw a promising future in NE MN. Given the slower pace of climate disruption, there was time to adapt.
Transition: 2036–2050	Remote office workers were a boon to a struggling economy; middle- to upper-class folks spent locally, supporting local jobs in recreation. Duluth outskirts were popular for the combined access to urban and recreation amenities. The timber and wood products industry made a comeback in this period, developing flexible technologies and processes such as AI and automation. These advances allowed wood products like cross-laminated timber and cellulosic nanotech to hit their stride in the late 2030′s. Consumer demand was there, now that prices were more affordable. Low-skilled labor was abundant in climate migrants, and these workers took on work that was not possible to automate. Smaller forest holdings were sold, and often converted to agriculture. Lack of effective governments allowed some freedom, but also left a void. This was filled in 2049 with the Duluth Industrial Infrastructure Pact. The booming forest and recreation industries provided utilities, internet, climate resilient roads networks, and healthcare.
Recent Past: 2051–2070	Unlike other parts of the country, NE MN's economy continued to flourish. Tall Timber Bottling Co shipped bottled water across the country. Water also grew the recreation economy. Most forests are now industrial, and able to treat forests for new invasives. Almost no small forest owners remain, and those that do eke out a living in the biofuels market. Forest product workers are now high-skilled, overseeing the automation processes. These workers advocated for workers' rights broadly, leading to increased unionization in all sectors. Mining also benefited from automation, demand was stable, while reduced labor costs allowed increased profits. Tribes maintained their traditions separate from the surrounding region. The overall result of changing land use, ownership, and varying management led to a very patchy forest structure.

Table 3
Scenario contrasts by those factor domains serving as direct model inputs (Fig. 4). Text from scenarios is provided parenthetically (supplemental materials). RCP means Representative Concentration Pathway.

	Bee Colony	School of Fish	Sumatran Rhino	Brown Rat
Climate	RCP 6.0–significant decline in cold weather months	RCP 2.6–significant action to address the effects of climate change	RCP 8.5–rapidly accelerating climate change	RCP 4.5–gradual climate change
Disturbance	continuation of recent trends (spruce gave way to climate change and increased spruce budworm activity and fire)	lowest rate of invasives and return to 'normal' rates (careful monitoring… to intervene if needed); reduce rate of large wildfires (catastrophic wildfire continued to be rare)	2024 fire and largest increase in disturbances (Great Fire of 2024 was a shock; spruce budworm and invasive insect outbreaks worsened); introduce human caused fires (wildfires from encampments)	increased infestations for small landowners (small operators couldn't afford to treat their forests)
Forest management	lowest harvest rate; no harvesting on public land (forests largely "locked up"); 25–50% of current harvest rates on upland private and tribal land (some harvesting occurred, mostly on private land); reforestation of riparian and open lands incorporates assisted-migration species (partnership continued assisted migration)	increased harvesting, to second highest rate (emphasis on carbon storage); TRIAD management (cross-jurisdictional shared management approach); prescribed burns, reforestation including near water, and largest assisted-migration effort (ensure resilient forests… prescribed burns and other ecological restoration techniques; success maintaining many cold-water streams)	second lowest harvest rate (mills and mines close); 70% of private land equally divided between wealthy and small government (small family forests were very few); relatively high subsistence logging, especially near encampments (subsistence conditions; Tribes… were more successful in providing refugia)	highest harvest rate, including on private land (bigger timber industry); little restoration; wealthy and 5% of remaining landowners incorporate assisted migration, especially after biomass harvests (restoration is now only done when it can be demonstrated that inaction would be detrimental to the recreation economy)
Land use/land cover change	10% increase in urban footprint between 2030 and 50 (newcomers started to move into the region around 2030; by 2070… a more urban focus)	10% increase in adjacent urban development (workers not only stayed… they thrived; smart-growth style principles to minimize ecological and climate impacts)	temporary, shifting encampments arise near Duluth and elsewhere, 10–25% of Duluth footprint every 10 years; (alarmed by the number of people starting to move into the woods surrounding Duluth… many spread further out to avoid detection)	random permanent growth outside Duluth and elsewhere, 3x recent trends (flocked to the Upper Midwest); 80% of private forest industrialized by 2070 (many small family forests… chose to sell); starting in 2040, 5% of those sold are converted to agriculture each year (agricultural investors… buy up forests considered unviable… and convert them to farmland)

4. Discussion

Participatory scenario development is a well-established method for engaging people in thinking about multiple alternatives of the future, far beyond simplistic projections of current patterns (Amer et al., 2013). Landscape modeling is frequently applied to help make scenarios more concrete, and to examine the consequences of alternative futures on ecosystems and societal needs and values (Sahraoui et al., 2021; Trutnevyte et al., 2014). However, methods from strategic foresight are underutilized to inform landscape modeling, where they can meaningfully enhance stakeholder engagement. Our study illustrates some advantages of blending multiple strategic foresight tools with landscape modeling to generate alternative future storylines that are enlightening (i.e., expanding the scope of possibilities), useful (via strong contrasts), and yet plausible (i.e., grounded by robust science and stakeholder perspectives).

The Strategic Foresight team brought expertise in methods to address the difficulties most people have in thinking beyond business-as-usual. The scenarios looked 50 years into the future, so we used a culturally-relevant photo from 50 years in the past–a photo of Elvis Presley with President Nixon–as a prompt to spark conversation about how much change can happen over a few decades. This was engaging and effective, getting participants to think about many of the changes since the 1970s, opening the idea of how different 2070 might also be. Initial plans to play IMPACT: Forestry Edition needed to be modified given pandemic restrictions. The game is designed to teach basics of strategic foresight and to promote thinking about impacts of potential significant change. We used several of the impact cards as discussion prompts in the introductory session. Additionally, foresight team members asked probing questions during scenario development to guide participants beyond business-as-usual thinking. And while expert engagement in the Recent Trends scenario helped build trust in landscape modeling, our decision to delay that participation until *after* alternative scenarios were framed kept participants focused on the future rather than the past. Hence, our scenario development approach addressed a limitation noted by McBride and colleagues (2017), that the type of thinking required to draft useful scenarios is "unfamiliar" and can be difficult for participants (McBride et al., 2017 table 2). Our approach facilitated developing markedly contrasting scenarios: different from current conditions, different from a "business as usual" future, and different from each other.

Horizon scanning is a structured process to search for signals of possible change both inside and outside the domain of interest (in our case, forestry) because significant and disruptive change often comes from outside the domain (Hines et al. 2019). The wide-ranging effects of the COVID 19 pandemic is a recent case in point. Epidemiologists and public health experts knew a pandemic was a matter of *when*, not *if* (Osterholm & Olshaker, 2017), but if such scan hits were only captured in scanning for health issues, the impacts on education, outdoor recreation, and more could all be missed. As discussed earlier, horizon scanning uses two standard organizing constructs: STEEP domains, for social, technological, economic, environmental, and political/governance, and three horizons (near/certain, next/moderate uncertainty, new/uncertain; Hines et al. 2019). Ensuring that horizon scans include items across these categories and horizons helps produce a database that can help uncover and plan for future surprises.

We used horizon scanning numerous ways in developing the scenarios: identifying drivers for the survey, IMPACT: Forestry Edition play, and providing exemplar scan hits in the scenario brainstorm sessions. But there is a way that the horizon scanning process could be used *after* the initial modeling is completed. Most of the discussions in the literature about participatory scenarios discuss monitoring and evaluation as looking at the impact on participants of the scenario workshop process itself (e.g., learning about ecosystems, getting to know each other; Thorn et al., 2020). But an important part of environmental scenario projects, including our own, should be an ongoing eye on the horizon. As time

Table 4
Storyline elements categorized as model outputs (see Table 3), i.e., processes and states predicted to emerge from scenario conditions.

	Bee Colony	School of Fish	Sumatran Rhino	Brown Rat
Forest composition	Forests age and densify, with shift towards maple, oak, and basswood as spruce declines	Pines and oaks more common; assisted migration results in more diverse, climate-adapted forests	Decline in forest cover, and conversion to savanna and farmland in SW portion of project area; forests age and densify in northern region	Increased contrasts among different landowners
Invasive species	Increased spread	Decreased spread	Increased spread	Spread of emerald ash borer and other invasives in private forests
Water	Decreased infiltration and groundwater recharge; increased salinity	Decreased evapotranspiration; increased groundwater storage; cold water maintained	Loss of cold-water habitat; less surface water; increased groundwater storage	Increased flooding; consequences of wetland tiling

goes by, which scenario is looking most likely? Or, more accurately, which *parts* of *which* scenarios are starting to show signs of coming to be? Horizon scanning can provide early signals of these changes, and the scenarios can inform ongoing scanning (Hines et al., 2021). In the case of our scenarios, this would involve scanning for a wide range of signals, including those indicating cross-jurisdictional coordination in response to a changing climate, a lack of actions to address climate change (perhaps shown as an absence of relevant scan hits), a continued influx of climate migrants, or rising numbers of unhoused people whether in this region or elsewhere. Equally important would be checking the scanning database for new wild cards and other possible disruptions that could substantially alter the direction of any scenario. Ongoing scanning can be combined with regular refreshes of the modeling aspects of a project: land use changes, novel species, changing disturbance rates, climate, and more. Together, such monitoring of the changes and futures that seem to be taking shape allows continued adaptive management by the workshop participants and those that follow in their footsteps in related positions in the region. Although this requires ongoing interest, coordination, and effort, conducting such an ongoing monitoring process would enhance the value of projects like ours and would promote proactive management and decision making. Other strategic foresight methods, like the Futures Wheel and backcasting, can also be employed to help make sense of the model output and ongoing scanning (Bengston, 2019). These additional foresight tools help managers make decisions on actions to take now by thinking through possible implications of a change or the steps needed to reach a desired future state.

The process of quantifying the storyline scenarios for the landscape models provided multiple benefits. Not all relevant factors can be modeled given constraints of available modeling software and available input data. As such, scenario translation provided useful focus to the study. Classifying storyline elements into critical domain factors, and then further separating those domains into their respective roles (Fig. 4), at times required greater elaboration than early draft narratives provided. For example, land cover change associated with housing development was unevenly described in terms of when, where, and how much residential area changed. In all such cases, any added detail in the models was constrained to be consistent with the scenario's contextual factors defining the broader narrative. The result was a richer and more balanced set of storyline scenarios. Meanwhile, storyline elements classified as model outputs provided insight into the domains of knowledge where participants have strong expectations (e.g., forest composition) relative to elements where they have less confidence in outcomes (e.g., water regulation; Table 4). The model outputs will provide a way of comparing and evaluating participants' ideas of future outcomes.

Storyline translations also facilitated participant engagement via consultation of local experts. For example, we surveyed forestry experts in the Minnesota Department of Natural Resources (the area's largest landowner) to specify management practices applied to state lands. Given the template of practices emerging from the state experts, we could then approach other landowners such as the Superior National Forest and the Fond Du Lac Band of Lake Superior Chippewa to specify how their practices differed from that of the state. This kind of iterative consultation and feedback is well known to foster shared ownership and build trust in the resulting landscape models (e.g., Sturtevant et al., 2007).

Application of strategic foresight methods greatly expanded the range of possible futures to be simulated via landscape modeling. Landscape modeling studies–including participatory modeling efforts–commonly apply a factorial design to evaluate the effects of different factors, such as the severity of climate change, contrasting harvest practices, and their interactions as they affect ecosystem resilience and/or ecosystem services (e.g., Lucash, Scheller, Gustafson, & Sturtevant, 2017; Miller et al., 2020; Sturtevant et al., 2009; Fortin et al., 2001). The power of a factorial design is in the interpretation of the relative effect of a small set of factors on modeled outcomes. However, more realistic alternative futures are driven by multiple interacting drivers that are challenging to parse in a model. For example, what difference can any specific detail in forest management practices aimed to increase the timber yield make if there are no mills left supporting timber harvesting? The scenarios depicted in Table 2 are far more divergent than most published landscape modeling studies (Sturtevant & Fortin, 2021), and yet still plausible. There is no reasonable factorial to accommodate such contrasts–because the drivers are both diverse and interconnected. Hence, the factorial design, though statistically sound and appropriate for answering some questions, is generally too constrained to explore the effects of multiple plausible alternative futures within coupled human-natural systems. These systems are a complex mix of external drivers and internal processes where local residents have some control.

The "Great Acceleration" suggests unprecedented change, and with it, increasing uncertainty (Steffen et al., 2015). "Uncertainty" is yet another concept with a meaning that varies depending on discipline. Strategic foresight methods account for contextual uncertainty, what Walker and colleagues call "scenario uncertainty" that frames the bounds for meaningful models (Walker et al., 2003, p 8). Conversely, model requirements from different scientific domains (in our case, forest and land use dynamics, respectively) help to reduce the potentially limitless uncertainties possible in developing scenarios (Walker et al., 2003). Hence there is a general "push and pull" with respect to uncertainty as defined by Walker et al. (2003) when strategic foresight tools are used in combination with quantitative landscape models to inform policy decision-making. Strategic foresight expands the scope of interest (greater appreciation of uncertainty) to qualitatively capture highly relevant issues beyond the capabilities of landscape models, while the landscape models provide more concrete evaluation (i.e., reduction of uncertainty) of the consequences of plausible alternative futures on ecosystem services of interest. Landscape models themselves contain their own dimensions of uncertainty (Scheller, 2018; Verberg et al. 2019; Walker et al., 2003)–but in this paper, "scenario uncertainty" is the primary focus (Walker et al., 2003). Future papers will address in greater detail the mechanisms to manage uncertainty in the landscape models.

5. Conclusions

This study illustrates the value of guiding landscape modeling with participatory scenario development. The landscape scenarios generated ranged widely, from the optimistic future depicted in "School of Fish" to dire outcomes depicted in "Sumatran Rhino"; these scenarios were far more divergent than outcomes explored in a traditional factorial landscape modeling study. This greater range in possible futures leads to more useful model outputs to guide the decisions of planners, managers, and policymakers. The strength lies in combining the two approaches: strategic foresight's power lies in its ability to both foster creativity, think through implications of change, and providing bounds on what is truly a plausible future, while landscape modeling assesses specific ecosystem interactions with human and environmental drivers, leading to actionable information about potential future conditions. Each field provides complementary methods to identify unintended consequences of policy options. While many of the individual tools from each discipline are applied to participatory scenario development–they are far less commonly applied in combination (Voinov et al., 2018). Both approaches can be applied to on-going monitoring of change in a system, beyond the initial modeling effort. Implementing an ongoing monitoring process combining horizon scanning and model updates could be a useful step in adaptive landscape management.

The Great Acceleration (Steffen et al., 2015) poses serious challenges to land managers, policy makers, and all who are interested in the sustainability of socioecological systems. Methods that can effectively address the uncertainty of the future to allow more robust and adaptive planning and management are urgently needed. Combining landscape modeling and strategic foresight methods can play a meaningful role in addressing this pressing need.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

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