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RESEARCH ARTICLE

Anticipating floodplain trajectories: a comparison of two alternative futures approaches

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Abstract Scenario-based investigations explore alternative future courses of action in a widening array of situations. Anticipating landscape patterns and the values behind them are recurring needs in such investigations. While it is accepted that how scenario assumptions are framed and who frames them matters, the sensitivity of resulting trajectories to contrasting scenario framing and modeling processes is rarely tested. Using comparable scenarios we contrast landscape change trajectories produced from two distinct approaches to modeling scenario assumptions: the first uses lay citizen groups and deterministic land allocation modeling, the second uses experts from biophysical and social sciences and agent-based modeling. Scenarios are defined and mapped for the year 2050 in western Oregon's Willamette River Basin along a gradient of conservation oriented to development-oriented assumptions using first citizen-based and then expert-based approaches. The landscape variability and trajectories for the citizen-based Conservation 2050 and Development 2050 scenarios are then characterized and compared with those of the expert-based Conservation 2050 and Development 2050 scenarios. Results distinguish areas where trajectories always vary regardless of approach or scenario from those that never vary. Policy influence on trajectory is illustrated using agent-based model results where land conversion serves purposes of wealth production and ecosystem function. Results depict areas with strong coupling between policy and trajectory as those places experiencing the same pattern of change over time regardless of scenario. Results also indicate that the greater the variability of a given scenario's trajectories, the more successful the scenario is at avoiding scarcity of wealth and ecosystem function.

Keywords Alternative future scenarios · Variant/invariant analysis · Agent-based modeling

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> "*The future is not a matter of chance, it is a matter of choice. It is not a thing to be waited for, it is a thing to be achieved.*"
>
> William Jennings Bryan, 19th century
> American politician

> "*As a predictive tool, history is useful mainly in warding off the making of predictions.*"
>
> Sean Wilenz, 21st century
> American historian

1 Introduction

Life teaches us early that today's choices affect tomorrow's opportunities. Scenario-based alternative futures studies are ways to explore plausible options for the future of a place, an organization or a community, and to see what effects each option has on things people care about. These types of studies are being used in a widening array of situations in which people seek choice in their future and evidence that the future they are achieving is one they will want when it arrives (Carpenter 2002; Meadows 2003; Robinson 2003; Van Dijk 2003; Hulse et al. 2004; Busch 2006; Liotta and Shearer 2007). As they are more widely used, scenario-based studies are increasingly scrutinized for their adequacy in a growing range of modeling and decision-making constructs.

Paralleling the global development of landscape ecology as a distinct discipline, with its focus on pattern:process:policy:design relationships, there has been a dramatic increase in the use of scientific, quantitative methods for informing landscape change and decision-making in the presence of deep uncertainty. This increase has occurred in both the public and private sectors. The predominant approach in such assessments has been characterized as a *predict-then-act* paradigm, which pairs models of rational decision-making with methods for treating uncertainty derived largely from the sciences and engineering (Raiffa 1968; Lempert et al. 2003). The preferred course of action in predict-then-act assessments is the one that performs “best” given some (typically small) set of assumptions about the likelihood of various futures and the landscape processes that will be sustained if these assumptions prove true. Such assessments are strongly tied to the validity of these assumptions. For the diverse group of people who consider themselves landscape ecologists, these approaches are familiar and fraught with challenge, especially when applied over extents of time and space that matter to landscape processes and the ecosystem goods and services they produce (Holling 2001; Chan et al. 2006).

A second paradigm is emerging that differs from *predict-then-act* in important ways. Rather than seeking strategies and policies that are optimal against some small set of scenarios for the future, this *explore-then-test* approach seeks near-term actions that are shown to perform well across a large ensemble of plausible future scenarios. These approaches offer the promise (but less so the proof) of policies and patterns that are sufficiently robust against future surprise that they can seize unexpected opportunities, adapt when things go wrong and provide new avenues in forging consensus regarding the facts and values that steer landscape change (Lempert et al. 2003; van Notten et al. 2005; Davis et al. 2007).

In this paper we contrast two scenario-based alternative future approaches of the kinds increasingly employed by landscape ecologists that hail from the two paradigms above. Our purpose is to compare their merits and share lessons of their use. To accomplish this we contrast the amounts and locations of key resources in the alternative futures they produce.

1.1 A basis of design for landscape sustainability

We pursue scenario-based alternative futures as a route to a more sophisticated dialogue of facts, values and perceptions, a notion we return to at the end of Sect. 1.2. As contributors to this special issue on the scientific basis of design for landscape sustainability, we argue that a scientific basis is essential, but alone insufficient to achieve landscape sustainability. Following Lynch (1981) we suggest a basis of design for landscape sustainability should: (1) speak to purposes, and in so doing directly address the fundamental constituent elements it seeks to sustain, stating clearly why sustain these elements, where to sustain them, for how long and to what end; (2) be clear enough for all sorts of people to understand; (3) honestly acknowledge the consequences of achieving the desired future circumstances, a task which cannot be done without evaluating landscape state and process together as they co-vary over a span of space and time relevant to the processes of interest; (4) be pragmatic, helping to steer choices when information and knowledge are incomplete; (5) be humble, cognizant of limitations and open to the prospect of improvement. The scientific dimensions of this basis are central to items 3 and 4 and have much to offer items 1, 2 and 5. In regards to the pattern:process:policy:design relationships mentioned earlier, a basis for design requires evidence-based descriptions of past and present pattern:process interactions *as well as* intention-based prescriptions of future policies that will sustain desired patterns and processes and minimize undesired ones. In this article, we compare two studies’ attempt to sustain desired built, riparian and other patterns of land use and land cover for 50 years to enhance the capacity of the study area to generate short-term wealth and long-term ecological function in ways that are robust to surprise and less vulnerable to critical scarcities.

For readers new to scenarios, we conclude Sect. 1 with an overview of scenario approaches and clarify some terms. The remainder of the article is organized into three main sections: Sect. 2 compares citizen-based with expert-based approaches to defining scenarios; Sect. 3 addresses the central role of policies in expert-based approaches; and Sect. 4 reports three types of lessons emerging from this effort.

1.2 An overview of scenario-based alternative future approaches

While the specific characteristics of scenario-based alternative future studies are as diverse as the situations in which they are applied, common threads emerge. Because there are no facts about the future, these studies begin by defining discrete, coherent assumptions about how conditions of interest unfold in some bounded place over some specified period of time (Ducot and Lubben 1980; Hirschorn 1980; Wack 1985; Godet 1987; Schwartz 1991; Hammond 1998; European Environment Agency 2001; McCarthy et al. 2001; van Notten et al. 2003; Liu et al. 2007). A logically coherent group of these assumptions comprise a *scenario*. In this paper we compare and contrast the subset of scenario studies that employ lay citizen groups to those that use experts in defining the assumptions that constitute scenarios. In the next step of a scenario-based study, changing conditions are represented in a manner consistent with the purposes of the study. For many scenario studies it is adequate to represent scenarios with narrative descriptions alone. In this paper we focus on that subset of scenario studies that, to address their purpose, must represent scenarios through changes in patterns of land and water use over space and time, that is, the scenarios must be mapped (Godet and Roubelat 1996; Steinitz et al. 1996; Steinitz and McDowell 2001; Hulse et al. 2002; Nassauer and Corry 2004). A spatially explicit representation of a scenario's land use and land cover (LULC) at multiple time steps comprises an *alternative future*. Here we contrast approaches that model spatial changes deterministically with those that employ probabilistic agent-based models of spatial change. The next step in scenario-based studies subjects these alternative future maps to a series of computational evaluative models to learn what effects each alternative future may have on some defined set of things people care about. From the broad spectrum of human value concerns, this paper focuses on two, the uses of land and water for shorter-term wealth production through more intensive land development, and the uses of land and water for longer-term ecosystem function through habitat conservation and restoration. The final stage of scenario studies seeks to summarize what is learned about the differences and similarities of the alternative futures and to communicate comprehensible findings to relevant audiences. Here we distinguish those parts of a study area whose future conditions vary across scenarios from those that do not.

Trajectory is a concept relevant to all types of scenarios, but especially to those that produce mapped results, i.e. alternative futures. As used here a *landscape trajectory* is a change in land use and land cover emerging from interactions among biophysical and human cultural processes over space and time. A trajectory is evident through observable change of patterns at discrete grain, extent, frequency and duration. As Fig. 1 shows, a scenario directs a trajectory of land use and land cover change through time. The particular patterns of land use and cover observed in an alternative future's time step of interest are influenced by many things, but foremost among them are the processes of defining scenario assumptions and the approach taken to modeling the connection between these assumptions and future changes in land use and land cover.

Where the focus is on anticipating trajectories of change caused by human use of land and water, scenario-based approaches provide a framework for effectively incorporating science into a community-based decision-making process and for *fostering a more sophisticated dialogue of the facts, values and perceptions that underpin informed landscape change*. Our experience shows that, regardless of the type of scenario, common questions arise about who defines the scenario assumptions and how these assumptions will influence the associated trajectories of change in land and water use. In the next section, we briefly compare and contrast two prevalent ways of defining scenario assumptions and modeling their implications.

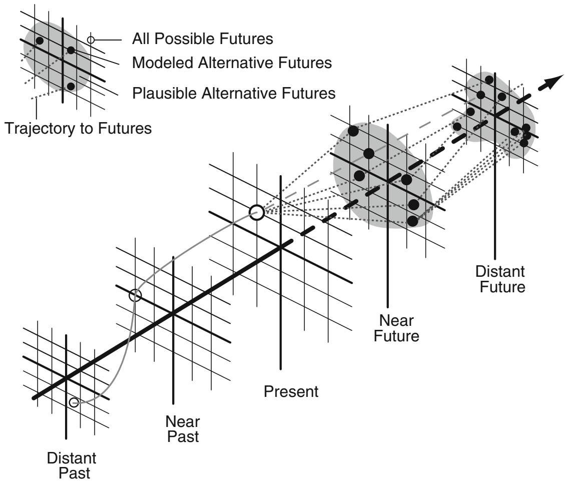

Fig. 1 The mesh grids represent all possible futures at discrete points in time along a continuum from the past into the future. The solid gray line represents the trajectory from the past to the present and the dashed gray lines represent modeled trajectories from the present into the future. The long dashed gray line represents a trajectory in which assumptions and policies model a scenario of present policies and decision-making extending into an unsurprising future. Each modeled trajectory is propelled by the assumptions and policies that define its scenario. A land use/ land cover representation at a given point in modeled time depicts an alternative future. *Adapted with permission from* Shearer (2005)

2 Comparing and contrasting citizen-based vs. expert-based alternative future approaches

In any alternative futures project, assumptions are made about future choices for land and water use, and the resultant spatial patterns constitute a mapped alternative. Coherent sets of assumptions about future resource use form overarching scenarios. Who makes these assumptions is central to the mapped patterns that emerge (Gregory and Slovic 1997; Johnson and Campbell 1999; Shearer 2005). Thus there is a gradient of assumption-defining approaches to creating spatially explicit alternative land and water use futures. On one end of the gradient is an approach that looks to citizen stakeholder groups to define internally consistent narrative assumptions about how future land and water use will unfold. At the other end of the gradient is an approach in which experts define the scenarios.

2.1 Citizen-based approaches to defining scenarios

We return to the expert approach below, but in the citizen-driven approach, these narrative assumptions may be used as inputs to a set of deterministic land allocation models (e.g., urban, rural residential, agricultural, forestry) to produce maps of future land and water use. The citizen-driven approach produces alternative futures that have the arguable advantages of integral citizen involvement and the mutual learning that accompanies it, as well as increased political plausibility of the scenarios and the accompanying greater likelihood of their institutional acceptance. The presumed disadvantages of citizen-driven scenarios are that they are time-consuming to produce, the variation among the scenarios is constrained since stakeholders are reluctant or even unable to conceive drastic shifts from current policies and circumstances, and that it is difficult to statistically quantify the likelihood of the smaller number of alternatives produced, typically three to 10 (Hulse et al. 2000; Landis 2001; Baker et al. 2004).

As an example of a citizen-driven approach we use work of the Pacific Northwest Ecosystem Research Consortium (PNW-ERC), which was created to conduct research supporting community-based decision-making in western Oregon and Washington (Baker et al. 1995). Consisting of 34 scientists from 10 different institutions, the PNW-ERC undertook as the centerpiece of its activities an alternative futures analysis for the Willamette River Basin, Oregon (Baker et al. 2004). Details of the process used to obtain citizen guidance in defining these scenarios are available in Hulse et al. (2004). In the next three paragraphs we briefly introduce some key qualities of the Willamette River Basin, the citizen-driven PNW-ERC project and its lessons. Following that, we introduce the expert-driven Evoland project.

The Willamette River drains an area of nearly 30,000 km^2 between the Cascade and Coast Range Mountains in western Oregon (Fig. 2). Although the basin accounts for only 12% of the land area in Oregon, it produces 31% of the state's timber harvests and 45% of the market value of agricultural products, and is home to 68% of Oregon's population. At the same time, the basin contains the richest native fish fauna in the state and supports several species federally listed as threatened or endangered, including the northern spotted owl, spring Chinook salmon, and summer steelhead trout. Two-thirds of the basin is forested, predominately in upland areas. Much of the lowland valley area has been converted to agricultural use (43% of the valley area) and urban and rural

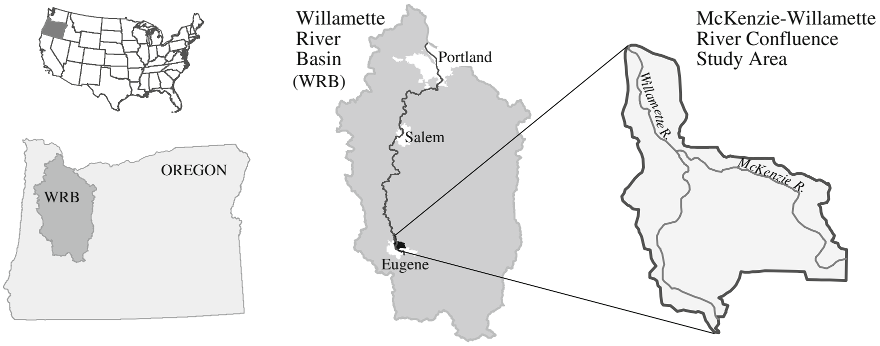

Fig. 2 The Willamette River Basin (WRB) served as the study area for the citizen-driven approach used by the PNW-ERC. Evoland's expert-driven approach focused on major river junctions within the WRB; the study area discussed in this paper is at the junction of the McKenzie and Willamette Rivers and includes part of the Eugene metropolitan area

development (11%). Oregon's three largest cities, Portland, Salem and Eugene-Springfield are located in the Valley, adjacent to the Willamette River, in some of the most geomorphically dynamic zones of the landscape, containing some of the highest levels of biological diversity and habitat complexity (Gregory et al. 1991; White et al. 1999). About 2.5 million people lived in the basin in 2000. By 2050, the basin population is expected to nearly double, placing tremendous demands on limited resources and creating major challenges for land and water use planning.

The PNW-ERC approach built on a rich history of scenario analysis arising largely out of the disciplines of landscape architecture and environmental planning (McHarg 1969; Murray et al. 1971; Steinitz 1990; Harms et al. 1993; Schoonenboom 1995; Steinitz et al. 1996; Hulse et al. 2000; Ahern 2001; Santlemann et al. 2001; Steinitz and McDowell 2001). With the Willamette River Basin as the study area, spatially explicit characterizations of past (ca. 1850) and present (ca. 1990) LULC were created, followed by an intensive 30-month citizen involvement process to define assumptions for three future scenarios for the year 2050 (Hulse et al. 2004). Each of these scenarios contained what the citizen groups conceived as plausible assumptions, with each 2050 scenario accommodating a doubling of the ca. 1990 human population. The scenarios were arranged along a gradient of, on one end of the spectrum, greater reliance on market forces and short-term wealth production (the Development 2050 scenario), while at the other end of the spectrum the focus was on long-term ecological function (the Conservation 2050 scenario). In the middle of the spectrum was the Plan Trend 2050 scenario that represented the expected future landscape in 2050 if current policies are implemented as written and recent trends continue. LULC change for all three scenarios was modeled in six 10-year time steps. The evolving landscape pattern produced by modeling LULC change under each scenario was the result of interactions within and among six principal landscape change processes: agriculture, forestry, urbanization, rural residential development, natural habitats and water use. Each was implemented by means of deterministic computerized allocation models that interacted with each other consistent with the assumptions of a particular scenario. Detailed descriptions of this work are in Hulse et al. (2002, 2004) and Baker et al. (2004).

As they pertain here, there were four key lessons learned from this work. First, the junctions of large rivers are among the most biogeomorphically and socio-culturally dynamic parts of the Willamette River Basin (Hulse and Gregory 2004). The biogeomorphic dynamism is due to the historic and contemporary riverine disturbance regime of variation in river flows and the associated responses of physical, aquatic, riparian and upland terrestrial biotic systems. The socio-cultural dynamism is due in large part to the pattern of historical urban development at large river junction locations and the on-going rapid change in numbers of people and attendant changes in land use and land cover in these urban areas. The second key lesson is that, in landscapes where human settlement is a major force of landscape change, there is a near-universal desire for production of *both* short-term wealth *and* long-term ecosystem services (Hulse and Ribe 2000; Chan et al. 2006). While the relative influence of these desires on realized landscape pattern and policy are in constant flux, our work indicates these desires must be reflected in any plausible future scenario. Third, scarcity of either of these desired goods, fear of it or attempts to avoid it motivates much intentional human action in the landscape (Schroter et al. 2005; Baumgartner et al. 2006). These actions occur at multiple societal levels of organization, from individual people and their families to private corporations and public agencies. Fourth, we found it difficult to answer reasonable questions about the likelihood of the future scenarios we modeled deterministically in the PNW-ERC study (Baker et al. 2004). As a result of these and other lessons we oriented subsequent research towards approaches centered on the most dynamic parts of the basin, and that strive to be more responsive to concerns about scarcity and less constrained by the limits of deterministic modeling.

2.2 Expert-based approaches to defining scenarios

At the other end of the gradient of techniques for defining the assumptions of alternative future scenarios is an expert-driven approach, with experts in the biophysical and social sciences or planning professions defining a set of decision or transition rules, often with input from other groups, that explore a wide range of future land and water use conditions (Garman et al. 1999; Santelmann et al. 2001; Steinitz and McDowell 2001; Parker et al. 2003; Brown et al. 2005b). The decision rules are generally constructed to focus on particular things people care about or illustrate focal policy options (e.g., improved water quality, better wildlife habitat, lower infrastructure costs, less highway congestion, etc.). The effects on landscape patterns of these decision rules may be modeled deterministically or probabilistically. When modeled probabilistically, alternative futures typically have the advantages of quantifiable statistical likelihood (from the large number of alternatives produced) and the disadvantages of unclear political plausibility, which may be due to the encoded decision or transition rules lying outside the political processes actually governing land and water use in the study area. It can also be challenging to accurately identify the causes of modeled results as the stochasticity and complexity of modeled processes grows (Parker and Meretsky 2004; Brown et al. 2005a; Grimm et al. 2005; Janssen and Ostrom 2006).

As an example of an expert-driven approach we use work conducted with an integrative agent-based model named Evoland (for *evo*lving *land*scapes, see http://evoland.bioe.orst.edu/), which was created to conduct research about the nature and properties of coupled human and natural systems in dynamic floodplain environments. The approach employed scenarios, data and evaluative models produced by the PNW-ERC, and built on prior work in agent-based modeling (Ostrom 1998; Janssen and Jager 2000; Parker et al. 2003; Brown et al. 2005b; Grimm et al. 2005) and biocomplexity theory (O'Neill et al. 1986; Levin 1998; Jager et al. 2000; Holling 2001; Michener et al. 2001; Beisner et al. 2003). Central to Evoland, and conceived at the simplest level, are the three-way interactions of *agents*, who have decision making authority over parcels of land, the *landscape* which is changed as these decisions are made, and the *policies* that guide and constrain decisions (Bolte et al. 2006; Guzy et al. 2008).

In Evoland, agents are entities that make decisions about the management of particular portions of the landscape for which they have management authority, based on balancing a set of objectives reflecting their particular values, mandates and the policy sets in force on the parcels they manage. They do this within the scope of policy sets that are operative on particular landscape elements over which they have decision-making control. Fundamentally, agents are characterized by the values they express through their behaviors, behaviors that, in turn, alter land use/land cover (Fig. 3). These values are correlated with

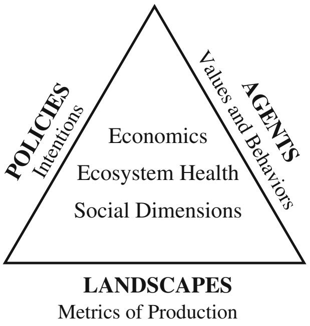

Fig. 3 Evoland provides a common frame of reference for agents, policies and landscape production. In this paper we focus on changes in the landscape and policies associated with those changes

demographic characteristics and, in part, guide the process agents use to select policies to implement; policies consistent with agents' values are more likely to be selected.

Policies in Evoland provide a fundamental construct guiding and constraining agent decision-making. As used in this context, *policies are decisions or plans of action for accomplishing a desired outcome* (Lackey 2006). They make scenario intentions operational and in so doing must integrate the facts of a situation with the values that motivate people to manage lands they control in the ways they do. Policies capture rules, regulations, and incentives and other strategies promulgated by public agencies in response to demands for ecological and social goods, as well as considerations used by private landowners/land managers to make land and water use decisions. They contain information about site attributes defining the spatial domain of application of the policy, whether the policy is mandatory or voluntary, goals the policy is intended to accomplish, and the duration the policy, once applied, will be active at a particular site (see Table 3 for an example). As agents assess alternative land management options, they weigh the relative utility of potentially relevant policies to determine what policies, if any, they will select to apply at any point in time/space. Once applied, a policy outcome is triggered that modifies one or more site attributes, resulting in landscape change. Policies may also be constrained to operating only with selected agent classes (e.g., all home owners, farmers with streams flowing through their property, forest owners with anadromous fish in adjacent streams, etc.).

Evoland represents a landscape as a set of polygon-based geographic information system (GIS) maps and associated information containing spatially explicit depictions of landscape attributes and patterns. Taken as a modeling approach, Evoland employs a spatially explicit multi-agent construct that models relationships of agent's values and behaviors, policy intentions and landscape metrics of production, as the agents attempt to avoid scarcity (Bolte et al. 2006; Guzy et al. 2008). Scenarios differ in the relative importance they assign to scarcities of two principal types, avoiding scarcity of short term wealth production in one scenario (Development 2050), and avoiding scarcity of long term ecological function in the other (Conservation 2050). The scenarios assume that land use patterns now and in the future substantially reflect the desire by people to avoid scarcity both of wealth and of key ecosystem functions, but each scenario emphasizes one over the other.

In summary, we used Evoland to model two of the same scenarios as were used in the PNW-ERC study, used the same assumptions concerning human population growth, and projected simulated futures to the same 2050 endpoint. Whereas the PNW-ERC work produced a single future simulation for each scenario, we produced 75 Evoland runs of each scenario, modeled the 7,094 ha McKenzie-Willamette River Confluence study area instead of the entire 30,000 km^2 Willamette River Basin, used 1 year instead of 10 year time steps, and used 2000 current conditions rather than 1990 (Figs. 2 and 4; Table 1).

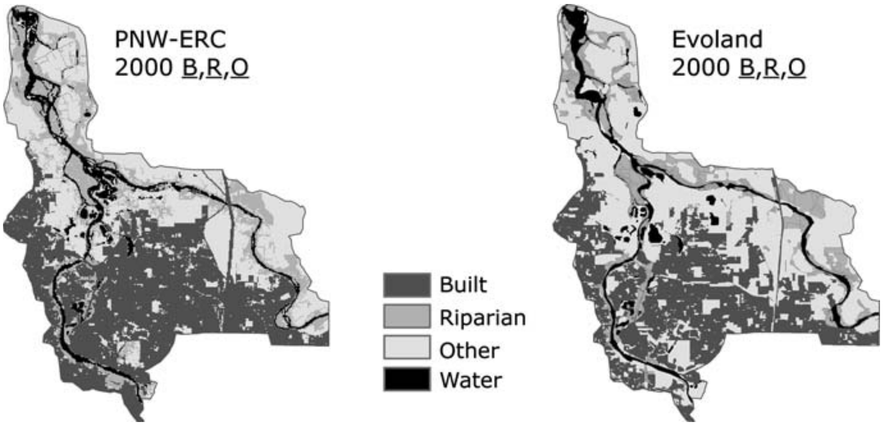

Fig. 4 Starting *B*uilt, *R*iparian and *O*ther 2000 land use/ land cover patterns for PNW-ERC and Evoland approaches. Water, represented with black, was included in the *O*ther class for analysis

Table 1 Comparison of start (2000) and ending (2050) Built (B), Riparian (R), Other (O) area totals for Evoland and PNW-ERC modeled alternative futures

	EVOLAND			**PNW-ERC**			
LULC	**2000** (ha)	**2050** Development (ha)	**2050** Conservation (ha)	**2000** Development (ha)	**2050** Development (ha)	**2000** Conservation (ha)	**2050** Conservation (ha)
Built	2,377	2,918	2,818	2,889	3,229	2,905	3,023
Riparian within 120m[1]	994	720	1,510	1,069	1,110	1,308	1,386
Other	2,711	1,370	1,116	2,020	1,690	1,722	1,402
Riparian outside 120m[1]	335	247	612	525	510	564	580
Water	677	677	677	590	555	595	702
Variant		1,162	362	Not Applicable			
Totals	7,094	7,094	7,094	7,094	7,094	7,094	7,094

2.3 Methods used in this paper to compare landscape trajectory across modeling approach types

In this study, we use the McKenzie–Willamette Confluence study area to compare PNW-ERC's deterministic modeling approach with Evoland's probabilistic approach. The approximately 60 LULC categories in which both approach's underlying data were expressed were aggregated to three summary classes to make essential spatial patterns apparent and the analysis of trajectories more tractable (Fig. 4). The *B*uilt (B) class consists of transportation systems and residential, commercial, and industrial land uses and corresponds to that set of land uses generating the most wealth per unit area (Hulse and Ribe 2000). The *R*iparian (*R*) class is derived from selected riparian vegetative cover classes lying within 120 m of streams and water bodies and corresponds to that set of land cover classes and portion of the landscape where riparian ecosystem functions are most intact (Gregory et al. 2002a, b; Van Sickle et al. 2004). Agricultural crops, water, forests outside of riparian zones and non-riparian categories within the 120 m riparian zone comprise the *O*ther (*O*) class. The *B*, *R* and *O* starting condition patterns for the year 2000 are shown in Fig. 4. These three aggregate categories, *B*uilt, *R*iparian and *O*ther form the basis of the trajectory analysis that follows. For quantitative modeling, the presence of the *B*uilt class represents portions of the landscape where wealth production takes precedence, while the *R*iparian class represents those portions of the landscape where ecosystem function takes precedence.

Direct quantitative spatial comparison between the outcomes is made possible by converting the polygonal GIS reporting units used by the agent-based approach to 30 m cell raster grids co-registered to the digital maps produced by the citizen-based approach. Table 1 presents the starting (ca. 2000) and ending (ca. 2050) *B*uilt (B), *R*iparian (R), and *O*ther (O) areas for each approach.

Tracking of LULC changes through time is spatial in the PNW-ERC deterministic approach and tabular in Evoland's probabilistic approach. For a given scenario, the deterministic approach produces a single alternative future LULC outcome for each 30 m × 30 m grid cell in each decadal time step. In contrast, the probabilistic Evoland approach produces multiple LULC outcomes for a given scenario and tracks annual LULC changes as attributes associated with vector polygons. Multiple alternative future outcomes are produced by repeated iterations of a given scenario's assumptions. In the Evoland work reported here, the Conservation and Development scenarios were each run 75 times creating 75 possible representations of LULC transition from 2000 to 2050. We chose 75 runs as a set of results both large enough to adequately explore the range of possible landscape change trajectories and small enough to be computationally tractable. As we use the term here, a trajectory is evident as a particular start (2000) to end (2050) pair among the B, R, and O classes: B-to-B, for example, represents for a specific location the trajectory in which a built land use did not change from 2000 to 2050, while R-to-B represents a transition from a riparian land cover in 2000 to a built land use by 2050 (Table 2).

2.3.1 *Variant and invariant trajectories*

Each spatial unit (polygon) in Evoland is referred to as an Integrated Decision Unit (IDU) and is associated with a suite of attributes including LULC. To

Table 2 Comparison of variant/invariant trajectories

			EVOLAND (agent-based)						PNW-ERC (deterministic)					
	Type	LULC Trajectory 2000 to 2050	DEV (ha)	Percent of Total Study Area (7094 ha)	Percent of 2000 B,R, or O area[1]	CONS (ha)	Percent of Total Study Area (7094 ha)	Percent of 2000 B,R, or O area[1]	DEV (ha)	Percent of Total Study Area (7094 ha)	Percent of 2000 B,R, or O area[1]	CONS (ha)	Percent of Total Study Area (7094 ha)	Percent of 2000 B,R, or O area[1]
Invariant	1	B-to-B	2,377	34%	100%	2,365	33%	99%	2,889	41%	100%	2,892	41%	100%
	1	R-to-R	617	9%	62%	979	14%	98%	1,021	14%	95%	1,217	17%	93%
	1	O-to-O	1,510	21%	56%	1,446	20%	53%	1,673	24%	83%	1,398	20%	81%
	2	B-to-O	0	0%	0%	0	0%	0%	0	0%	0%	0	0%	0%
	2	B-to-R	0	0%	0%	12	0%	1%	0	0%	0%	7	0%	0%
	2	R-to-B	3	0%	0%	0	0%	0%	43	1%	4%	9	0%	1%
	2	R-to-O	2	0%	0%	0	0%	0%	6	0%	1%	2	0%	0%
	2	O-to-B	531	7%	20%	451	6%	17%	224	3%	11%	80	1%	5%
	2	O-to-R	103	1%	4%	519	7%	19%	62	1%	3%	162	2%	9%
Variant	3	B to variant	0	0%	0%	0	0%	0%	Not Applicable					
	3	R to variant	342	5%	34%	14	0%	1%						
	3	O to variant	820	12%	30%	348	5%	13%						
		Variant sum	1,162	16%	N/A	362	5%	N/A						

compare scenario outcomes across approaches, it was necessary to produce a single representation of 2050 LULC for each Evoland scenario. To do this, the LULC attributes for each IDU were characterized in terms of *B*, *R*, *O* transitions from 2000 to 2050. Most IDUs in the study area do not experience a change from their starting classification as *B*uilt, *R*iparian, or *O*ther at any time during any of the 75 repetitions of each scenario's policies. These IDUs are classed as Invariant Type 1, i.e., no change. We place locations that do experience a LULC transition into one of two groups: those with high likelihood transitions and those without. Figure 5 shows the basis on which we distinguished transitions with high likelihood from those without through an examination of the transition frequencies of IDUs that made at least one transition in the 75 repetitions of a scenario. Common to both scenarios, the histograms show a conspicuous inflection at an 85% transition frequency (Fig. 5). Above this frequency, IDUs make the same transition from their starting class to their ending class after 50 years of modeled time with high confidence. We class these IDUs with a transition frequency ≥85% as Invariant Type 2, i.e., confident change. For these IDUs with confident trajectory change across all 75 runs, we assign the 2050 cover class that occurred ≥85% of the time. IDUs whose transition frequencies are less than this selected threshold are regarded as having no high confidence outcome state after 50 years and are called Variant Type 3. The trajectory of every IDU in both Evoland's Conservation and Development scenarios will conform to one of these three primary trajectories: Invariant Type 1 (no change); Invariant Type 2 (confident change); or Variant Type 3 (Table 2; Fig. 6). We use these trajectories to compare and contrast alternative futures.

2.4 Comparing results across modeling approach types and alternative future scenarios

In both citizen-driven deterministic and expert-driven agent-based approaches, the Development scenarios produced more land area in *B*uilt uses than did Conservation scenarios, and both Conservation scenarios produced gains in *R*iparian area. Between the two Development scenarios only the agent-based Development 2050 scenario produced *R*iparian losses (Table 1).

In contrast to the deterministic approach, the probabilistic agent-based approach explores more fully the range of possible outcomes through stochastic sampling of parameter value probability distributions in multiple runs for each scenario. This results in the Variant rows in Table 2 and in Fig. 6. These are areas on the landscape in which no specific transition among starting and ending B, R, and O classes occurred with a frequency ≥85% among the 75 model runs. Simply put, the trajectories of these parts of the landscape varied even within a given scenario. Looking more closely, while it appears that the Development scenario of the deterministic PNW-ERC approach results in almost 50% more riparian area than the Development scenario in the agent-based Evoland approach, the latter also places 1,162 ha, 16%

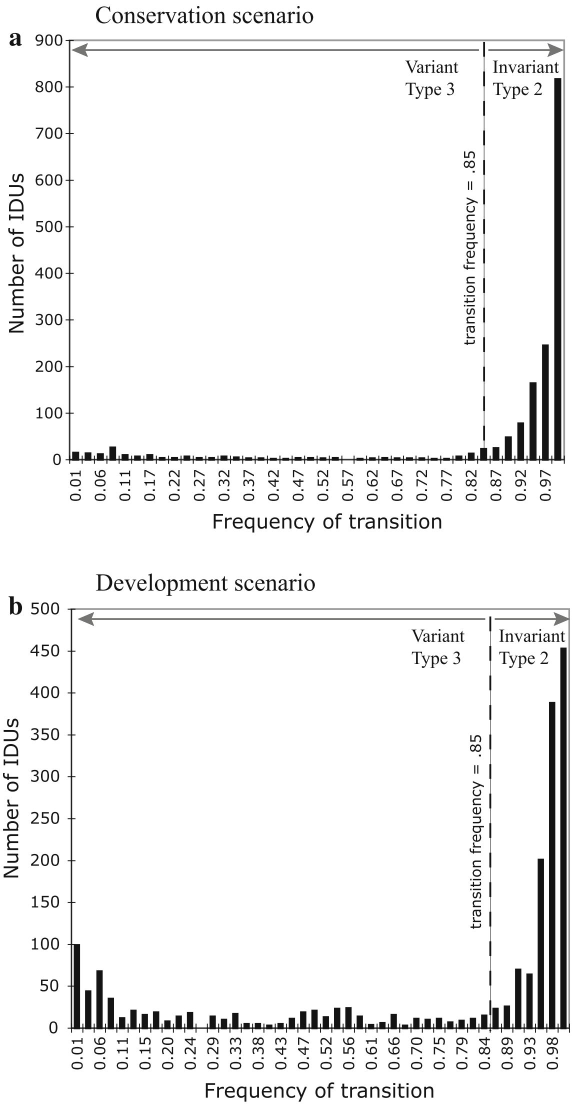

Fig. 5 Each scenario is run 75 times through 50 years of modeled time. The majority of IDUs do not change LULC status at any time during any of the runs. For those that do change, however, the number of IDUs that experience a change are plotted in these histograms against the frequencies with which they make any *particular* transition from their starting B, R, O class to their ending B, R, O class

of its area in the Variant trajectory type, one in which no end condition can be stated with confidence. By comparison with the two approach's Development futures, there is much less difference in riparian outcomes between the two approach's Conservation futures and 69% less land in the Evoland Conservation future Variant trajectory type relative to the Evoland Development future (Fig. 6; Table 2).

For all scenarios in both modeling approaches the majority of their ending 2050 LULC class is the same as their starting 2000 LULC class. Parts of the landscape following this invariant trajectory are shown in the Type 1 trajectory rows in Table 2. It is clear that among trajectories with outcomes of high confidence, i.e., those labeled as Type 2 in Table 2, the *O*ther LULC category provides the majority of land available for transition. The two modeling approaches agree that more territory that was LULC class *O*ther in 2000 changes to *B*uilt uses in 2050 Development scenarios, and that more territory changes from *O*ther to *R*iparian in 2050 Conservation scenarios.

It is axiomatic in real estate development that the interests of wealth production are best served by increasing intensity of human use of land (i.e., by developing land to its 'highest and best use') (Hulse and Ribe 2000). While the Development scenarios of both approaches did indeed convert more land to *B*uilt uses by 2050 than their respective Conservation counterparts, in the agent-based Evoland approach, where Variant trajectories were possible, the Development scenarios placed more than three times the area in this Variant trajectory (1,162 ha) than did Evoland's Conservation scenario (362 ha) (Table 2).

We focus in Sect. 3 solely on the agent-based approach to examine more closely the relationships of Evoland's Conservation and Development scenarios, the policies that comprise them and the LULC trajectories they produce.

3 Modeling scenario policies as integrators of facts and values

Those charged with crafting land management policies have an understandable wish to know, in advance of implementing a policy, whether the policy is likely to have the desired effect, and if so where and when the effect is likely to occur. Accomplishing this requires a way to confidently simulate the effects of different policies on how places change over time, and whether or not such changes cause the wrong things to become scarce. To offer a specific characterization of the coupling of policy and landscape pattern and its effect on scarcity, we focus on the alternative future results produced using the Conservation and Development

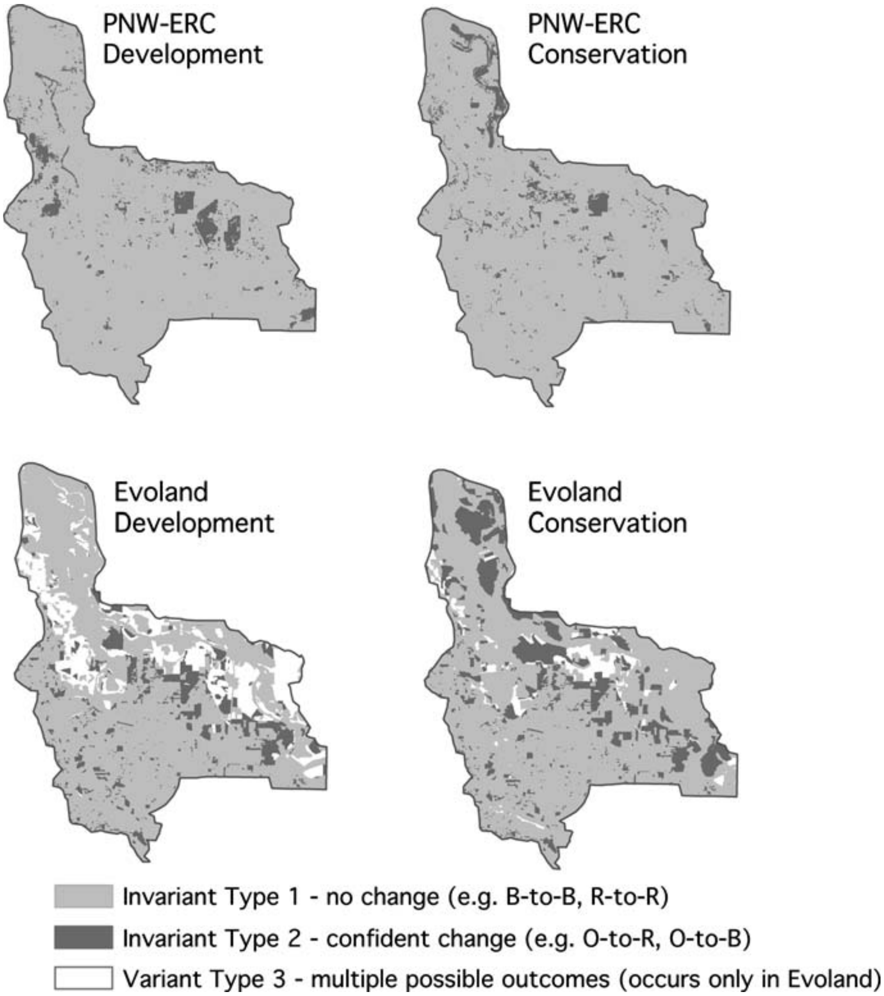

Fig. 6 Landscape trajectories from 2000 to 2050. Locations that do not change LULC from 2000 to 2050 are classed as Invariant Type 1; those with high certainty of a particular LULC change are classed as Invariant Type 2. In the Evoland approach, multiple outcomes are possible at a specific location; these are classed as Variant Type 3

scenarios with Evoland's agent-based modeling approach.

3.1 Strength of trajectory:policy coupling

In alternative futures projects, the policies of a scenario play a central role in determining its LULC pattern trajectory. Evoland employs policies in a two-level hierarchy. Meta-policies influence the behavior of the most fundamental processes—the distribution of the growing human population across the landscape and the association of human values to locations based on measured demographic variables. The structure of these meta-policies does not vary between scenarios, but parameters that affect their behavior are set by users as part of scenario definition.

In this study we track a second level of policies that operate at the IDU level and are written by users in a formal syntax. Each scenario has a unique set of IDU-level policies based on overall scenario assumptions. The basic format of these policies is shown in Table 3. A policy's site attribute specifies the IDU characteristics that must be present for the policy to be applicable. The outcome specifies the change in LULC that will occur over time if the policy is applied at that location. The application of a policy at a particular IDU is influenced by multiple factors: site attribute requirements, overall scenario goals, the alignment of agent objectives with policy intention, the efficacy of a policy in addressing resource scarcity and LULC change model stochasticity.

The previously discussed *B*uilt, *R*iparian and *O*ther LULC characterization and variant/invariant

Table 3 Example of policy expression in Evoland

Public lands restoration policy

Policy assumptions and intentions: Assumes more willingness and better ability to restore habitat on public lands. Such lands do not include those with substantial infrastructure such as schools, city parks or public buildings

	Site attributes	Policy outcome
Evoland syntax	Dist_Str < 1000 and Is_Public = 1 {Public Lands} and Lulc_A != 4 {Forest} and Is_Devable = 2	LULC_C = 87{Shrubland} and Conserv = 1:50
English	The site must be less than 1,000 m from a stream, publicly owned, not in forested land cover and not suitable for development	The new LULC will be shrubland which will age over time to forest. 50% of the time, the site will become permanent conservation land.

Site attributes must be met for a policy to be considered for application at a particular site; policy outcome states the changes that will occur if the policy is applied

trajectories apply here. A policy's site attribute requirement contains the equivalent to "start BRO" (i.e., which cover class, *B*uilt, *R*iparian or *O*ther occupied the IDU in 2000) and the policy outcome specifies the "end BRO" (i.e., which cover class occupied the same IDU in 2050). To illustrate the coupling of policy and LULC, we focus on the trajectory of places in the landscape that start as *O*ther. Table 2 shows these locations have the highest frequency of LULC change; for both scenarios essentially all of Invariant Type 2 starts as *O*ther in 2000 and the highest proportion of Variant Type 3 starts as *O*ther in 2000 as well. Figure 7c shows those locations that followed the O-to-R trajectory in *both* Evoland's Conservation and Development scenarios (i.e., those places that started as *O*ther in 2000 and were converted to *R*iparian by 2050 in *both* scenarios). Figure 8c shows those locations that followed an Invariant Type 2 O-to-B trajectory in *both* Evoland's Conservation and Development scenarios. Given the relatively large number set (75) of alternative futures produced and mapped for each of the scenarios tested, we argue that the strongest coupling between policy and LULC change occurs with Invariant Type 2 trajectories, i.e., where the same LULC transition occurs in at least 85% of runs, regardless of scenario and model stochasticity. Strong coupling is evident in those places where confidence is highest that a LULC

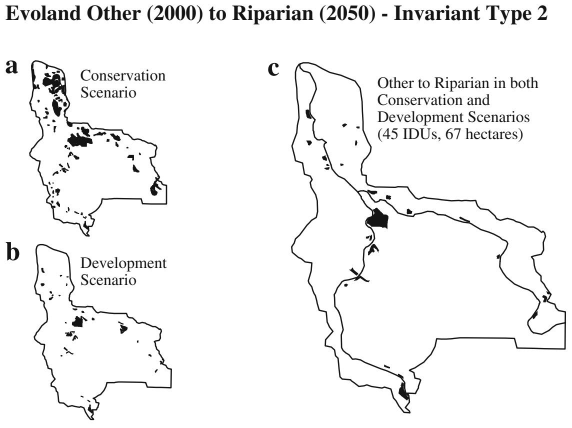

Fig. 7 (Evoland *O*ther-to-*R*iparian). Locations showing an Invariant Type 2 trajectory from Other in 2000 to Riparian by 2050. The Other trajectory is shown for the Conservation scenario in (**a**) (O-to-R) and for the Development scenario in (**b**). Locations where *both* the Conservation and Development scenarios went from *O*ther-to-*R*iparian (**c**) or from *O*ther-to-*B*uilt (Fig. 8c)

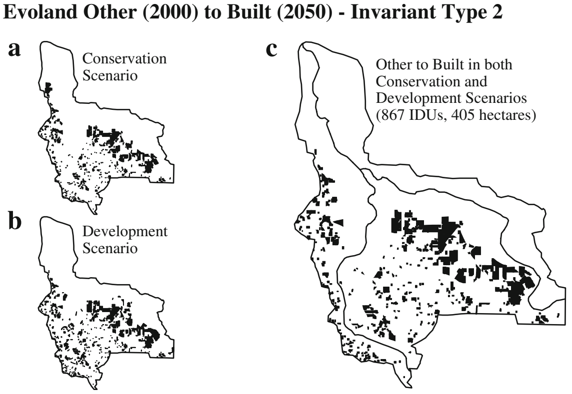

Fig. 8 (Evoland *O*ther-to-*B*uilt). Locations showing an Invariant Type 2 trajectory from Other in 2000 to Built by 2050. The Other trajectory is shown for the Conservation scenario (**a**) (O-to-B) and for the Development scenario in (**b**) (O-to-B). (**c**) Locations where *both* the Conservation and Development scenarios went from *O*ther-to-*R*iparian (7c) or from *O*ther-to-*B*uilt (**c**)

change was triggered by a policy. To illustrate we track ecosystem function using the *O*ther-to-*R*iparian trajectory and wealth production using the *O*ther-to-*B*uilt trajectory.

Although some policies are shared, the Conservation and Development scenarios each have a unique set of policies intended to achieve specific scenario goals. A subset of the policies associated with the LULC changes in Figs. 7 and 8 are shown in Table 4. This subset includes the policies for each scenario with the highest frequency and area of application. The frequency of application is the sum of all applications of a policy in all time steps and the area of application is a sum of the areas of the IDUs in which a policy was applied. The 'Public Lands Restoration' policy is one that has a high frequency of application associated with the *O*ther-to-*R*iparian trajectory in both scenarios.

In this study, pattern is the window through which we view process. For the *O*ther-to-*R*iparian trajectory, the strongest coupling between LULC change and policy can be seen with two policies: Public Lands Restoration and Riparian Conservation Easement on Rural Lands. The Public Lands Restoration policy is identical in both scenarios and the Riparian Conservation Easement on Rural Lands contains minor scenario specific modifications. These two policies have the highest frequencies of application and significant areas of application in both scenarios. Table 4 shows that the highest frequency of application does not necessarily correspond to the greatest area of application.

Although the same increase occurs in human population from 2000 to 2050 in both the Conservation and Development scenarios, the way in which the population is accommodated varies between the two scenarios. Each scenario has policies to increase the amount of four types of residential land use distinguished by density class. Each scenario also has policies to increase commercial and industrial land use. These policies are modified for each scenario but are intended to achieve the same outcome. For example, the site attributes allowing low density residential are slightly more restrictive in the Conservation scenario than in the Development scenario, since the Conservation scenario prefers the more land-efficient higher density forms of housing. Comparing the low and high density residential application rates in Table 4 shows the differences in scenario intentions. The 'increase high density residential' policy is applied 85,898 times in the Conservation scenario but only 15,600 times in the Development scenario. In contrast, the 'increase low density residential' policy is applied 6,629 times in the Conservation scenario and 15,440 times in the Development scenario. The area of application shows a greater total area affected by residential policies in the Development scenario (1,449 ha) compared to the Conservation scenario (1,248 ha). The Conservation scenario restricted low density residential (240 ha) compared to the Development scenario (383 ha), but the areas of application for the other three residential densities were comparable. In both the frequency of application and area of application, the Development scenario was more accommodating of commercial and industrial uses than was the Conservation scenario.

3.2 Scarcity avoidance

The motivation to avoid *both* scarcity of wealth production *and* ecosystem function are evident in the policy sets for both Evoland's Conservation and Development scenarios. Each scenario's assumptions and priorities influence the degree to which these two types of scarcity are addressed in their respective policy sets. In the analysis that follows we use increase in hectares of *R*iparian LULC to indicate scarcity avoidance of ecosystem function and

Table 4 Policies associated with O-to-R and O-to-B trajectories shown in Figs. 6–8

	Frequency of application	Area of application (ha)
Policies associated with Other-to-Riparian trajectory		
Conservation scenario policies		
Public lands restoration	2,492	48
Riparian conservation easement on rural lands	2,772	32
Agriculture encouraged to plant hybrid poplar near roads and streams	197	55
Agricultural floodplain conservation easement	732	63
Protect areas with high quality habitat	1,967	60
Forest harvest on private lands	400	62
Development scenario policies		
Public lands restoration	2,370	11
Riparian conservation easement on rural lands	1,920	56
Development restriction/agricultural zoning	675	11
Policies associated with Other-to-Built trajectory		
Conservation scenario policies		
Increase low density residential land use	6,629	240
Increase medium–low density residential land use	18,815	313
Increase medium–high density residential land use	18,727	332
Increase high density residential land use	85,898	363
Increase commercial land use	6,891	183
Increase industrial land use	8,590	195
Development scenario policies		
Increase low density residential land use	15,440	383
Increase medium–low density residential land use	30,506	348
Increase medium–high density residential land use	16,012	348
Increase high density residential land use	15,600	370
Increase commercial land use	9,090	249
Increase industrial land use	12,569	363

The policies shown in this table are ones with the highest frequency of application and the greatest area of application

Frequency of application = the total sum of all applications for the policy (all time steps, all runs)

Area of application = the sum of the areas of all IDUs in which the policy was applied (even if it was only applied once). A single IDU's area is only counted once in the sum, no matter how many times the policy was applied in that IDU. A single IDU's area may be present in more than one policy's tabulation; i.e. multiple policies may have been applied to a single IDU and its area is part of the sum for each of those policies

increase in hectares of *B*uilt LULC to indicate scarcity avoidance of wealth production. The priority of ecosystem function over wealth production in Evoland's Conservation scenario is manifest in its policy set; there are fourteen policies provided for the purpose of improving ecosystem function. With its priority on wealth production, the Development scenario has only three policies to address the scarcity of ecosystem function. The difference in the number of policies addressing ecosystem function between the two scenarios is consistent with hectares of *O*ther-to-*R*iparian (O-to-R) shown in Table 2; in the Conservation scenario 519 ha are converted from *O*ther-to-*R*iparian while only 103 ha follow this trajectory in the Development scenario. With wealth production as the priority one might expect a significantly greater number of hectares to follow the *O*ther-to-*B*uilt (O-to-B) trajectory in the Development scenario compared to the Conservation scenario. However, Table 2 shows the hectares of *O*ther-to-*B*uilt are similar in both scenarios (531 ha in Development, 451 ha in Conservation). The number of hectares on the *O*ther-to-*V*ariant trajectory is significantly different between the two scenarios (820 ha in Development, 348 ha in Conservation). The area differences in the *O*ther-to-*B*uilt and *O*ther-to-*V*ariant trajectories between the two scenarios suggest that the *absence* of policies to address ecosystem function in the Development scenario is important. The relatively large number of policies addressing ecosystem function in the Conservation scenario influenced the number of hectares following

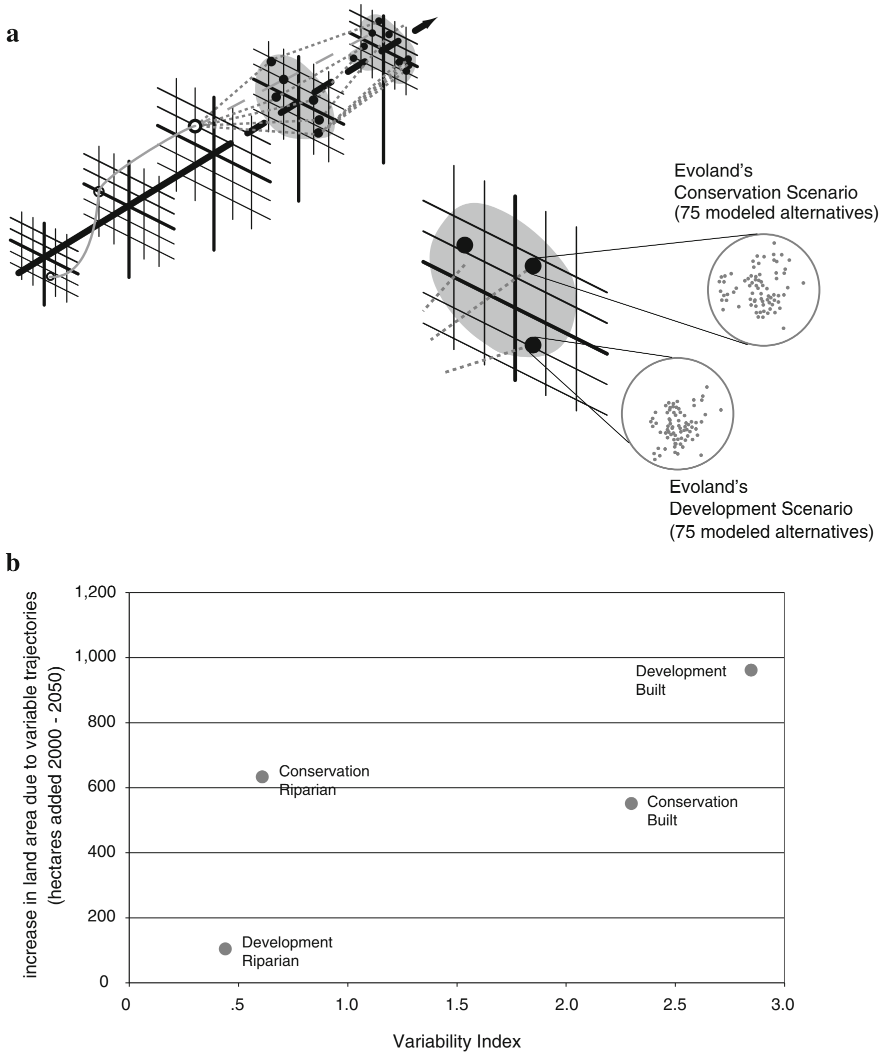

Fig. 9 (**a**) In Evoland's agent-based approach, each solid dot on the grid represents a point in time where there are 75 modeled alternatives resulting from the 75 runs for each scenario. *Adapted with permission from* Shearer (2005). (**b**) Relationship of landscape variability and availability of built and riparian land cover in Evoland's Conservation and Development scenarios. Each dot on the graph represents either the built or riparian portion of the landscape whose trajectories over 50 years and 75 repetitions were variable, i.e., not static. For any IDU, variability in land cover classification can occur both between the time steps of a single modeling run, and between runs for any particular time step including the "final" land cover classification at 50 years of simulated time

the *O*ther-to-*R*iparian trajectory in that scenario (Fig. 7a). In the Development scenario, the small number of ecosystem function policies did not correspond to a significant increase in the area of *O*ther-to-*B*uilt but rather to an increase, relative to the Conservation scenario, in the number of hectares following the *O*ther-to-*V*ariant trajectory (Table 2).

3.3 Scarcity and landscape variability

The probabilistic Evoland approach implements its Development scenario policies by avoiding the scarcity of wealth production, which is measured as the market value of real property and expressed as the total area of *B*uilt LULC. The Conservation scenario implements its policies so as to avoid scarcity of ecological function, measured in area of *R*iparian LULC. Both scenarios must accommodate the same human population increase. As used in this study, landscape variability is the tendency of a particular location to change its land use or land cover over modeled time Fig. 9b plots the Built and Riparian outcomes of the two scenarios in a space defined by dimensions of scarcity—new land area added to a LULC class, and variability—an index of the outcome uncertainty locations classed as *R*iparian or *B*uilt experience over 75 runs of the model for each scenario. Each run creates a potentially different trajectory through the *B*, *R*, and *O* classes for each IDU location over 50 years of modeled time.

The variability index is computed as a ratio of the amount of variation in outcome each of the Built and

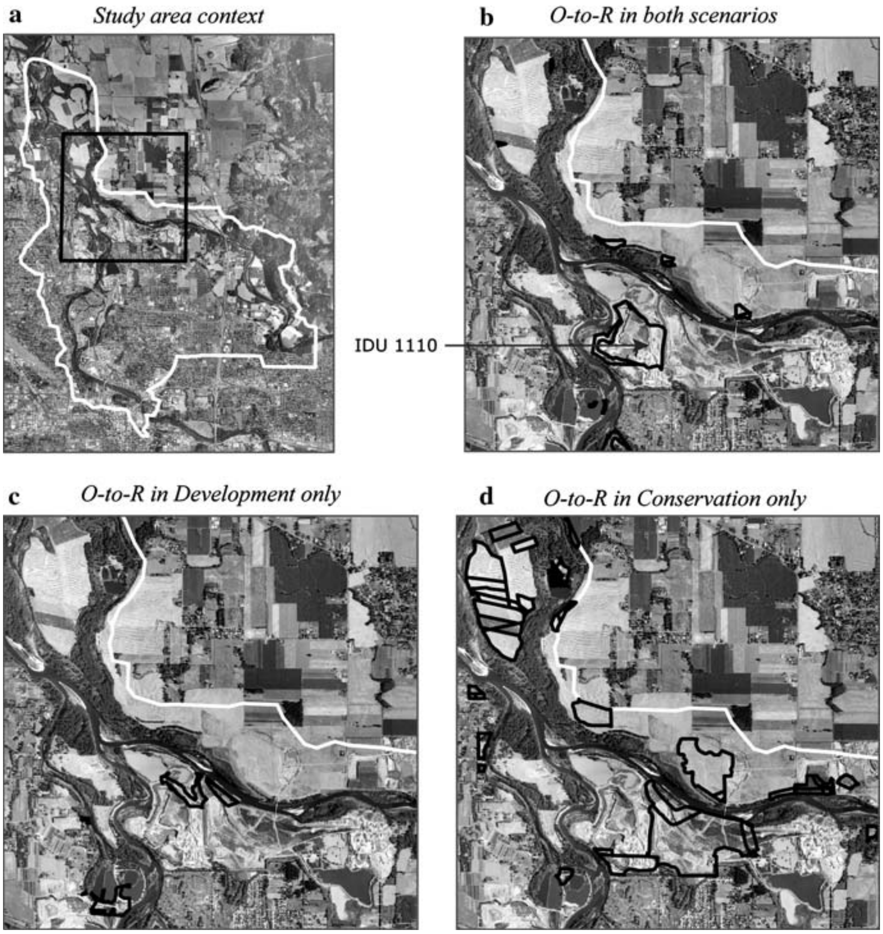

Fig. 10 Study area sub-set showing IDUs following an Invariant Type 2 trajectory from *O*ther-to-*R*iparian. (**a**) Shows the sub-set location within the study area. (**b**) Outlines IDUs that followed the O-to-R trajectory in both the Conservation and Development scenarios. (**b**) Also identifies IDU 1110 whose policies are shown in Table 5a. (**c**) Outlines IDUs following the O-to-R trajectory in the Development scenario but not in the Conservation scenario. (**d**) Outlines IDUs following the O-to-R trajectory in the Conservation scenario but not in the Development scenario

Riparian land cover types experienced in the 75 runs, to the total variation possible in the landscape for all three of the B, R, and O classes. At the end of each decade of simulated time, the current B, R, or O classification of an IDU is tabulated. These are summed over five decades for 75 runs of the model, and expressed as a fraction of 75. If an IDU started as *R*iparian, R, for example, and never once in five decades over 75 runs was classed as anything other than R, its variability is zero, and it is classed as Invariant Type 1 in Tables 1 and 2. To the extent that IDUs initially classed as R or B experienced other classifications, those frequencies, expressed as decimal fractions of 75, are tabulated and summed for the study area for a particular Evoland scenario. These sums are then divided by the total potential variability in the study area, and adjusted in scale to produce the variability index value.

Figure 9a expresses the fact that a single point in outcome space, a solid dark dot on the grid, is actually the composite result of multiple trajectories for each of thousands of IDUs. Also, each of the 75 small dots in the breakout circles of the figure expresses the aggregate endpoint state of 16,005 IDUs for a specific run of a particular scenario. Figure 9b depicts the relationship between the variability among these outcomes for the B and R classes as it relates to the new area each scenario allocates to these classes by the year 2050. A dot on the Fig. 9b chart is comparable to the B or R components of the heavy dots for the applicable scenario on the Fig. 9a graph.

The Development scenario, seeking primarily to avoid scarcity of wealth, adds more new area and shows higher variability than the Conservation scenario for the *B*uilt class. Conversely, the Conservation scenario, seeking primarily to avoid scarcity of ecological function, adds more new *R*iparian area and shows more variability in this land cover class than does the Development scenario. Based on the

Table 5 Each table shows the number of policy applications by decade for a single IDU and includes all policies applied over the course of the 75 runs for each modeled scenario

	2000–2010	2010–2020	2020–2030	2030–2040	2040–2050
(a) Policy applications for IDU 1110					
Conservation Scenario Policies					
Riparian conservation easement on rural lands	32	27	11	11	5
Protect areas with high quality habitat	8	16	34	51	46
Avoid sprawl and preserve rural character	15	5	3	3	1
Public lands restoration	1	6	4	3	1
Development scenario policies					
Riparian conservation easement on rural lands	50	18	7		
(b) Policy applications for IDU 9013					
Conservation scenario policies					
Increase commercial land use	5	1	0	0	1
Increase industrial land use	7	2	0	0	1
Increase low density residential land use	10	5	0	0	0
Increase medium–low density residential land use	7	8	8	7	4
Increase medium–high density residential land use	9	7	3	7	4
Increase high density residential land use	14	28	23	27	27
Development scenario policies					
Increase commercial land use	5	2	1	0	0
Increase industrial land use	9	5	0	0	1
Increase low density residential land use	10	6	1	2	1
Increase medium–low density residential land use	12	8	8	11	5
Increase medium–high density residential land use	3	8	3	3	3
Increase high density residential land use	3	1	4	5	4

IDU 1110 (panel *a*; Fig. 10b) followed an invariant Type 2 trajectory from *O*ther-to-*R*iparian. IDU 9013 (panel *b*; Fig. 11b) followed an invariant Type 2 trajectory from *O*ther-to-*B*uilt

results from the seventy-five runs in each of these two scenarios, the greater the variability of its alternative futures, the more successful the scenario is at avoiding scarcity. Conversely, scenarios whose trajectory pathways were more constrained were less successful at avoiding scarcity.

3.4 Anticipating trajectories, policies and patterns at the spatial grain where land use decision-making happens

While the previous section focuses on trajectories of change and corresponding scarcities at a landscape extent, in Sect. 3.4 we use examples from Evoland's approach to illustrate smaller area site-extent trajectories realized through scenario intentions and policies. Using the *O*ther-to-*R*iparian and *O*ther-to-*B*uilt trajectories, we focus on a subset of the study area to track policy influence on two individual IDUs and to compare differences in the Conservation and Development scenarios.

IDUs following the *O*ther-to-*R*iparian trajectory are shown in Fig. 10 with 10b highlighting IDUs following that trajectory in *both* the Conservation and Development scenarios. Comparing Fig. 10c (*O*ther-to-*R*iparian in Development) and Fig. 10d (*O*ther-to-*R*iparian in Conservation) illustrates the difference in scenario intentions, policy sets and LULC change between the two scenarios. Figure 10d shows a larger number of IDUs and a greater total area following the *O*ther-to-*R*iparian trajectory in the Conservation scenario compared to the Development scenario (Fig. 10c). This comparison also shows a resulting LULC pattern in the Conservation scenario with larger, more spatially connected riparian patches.

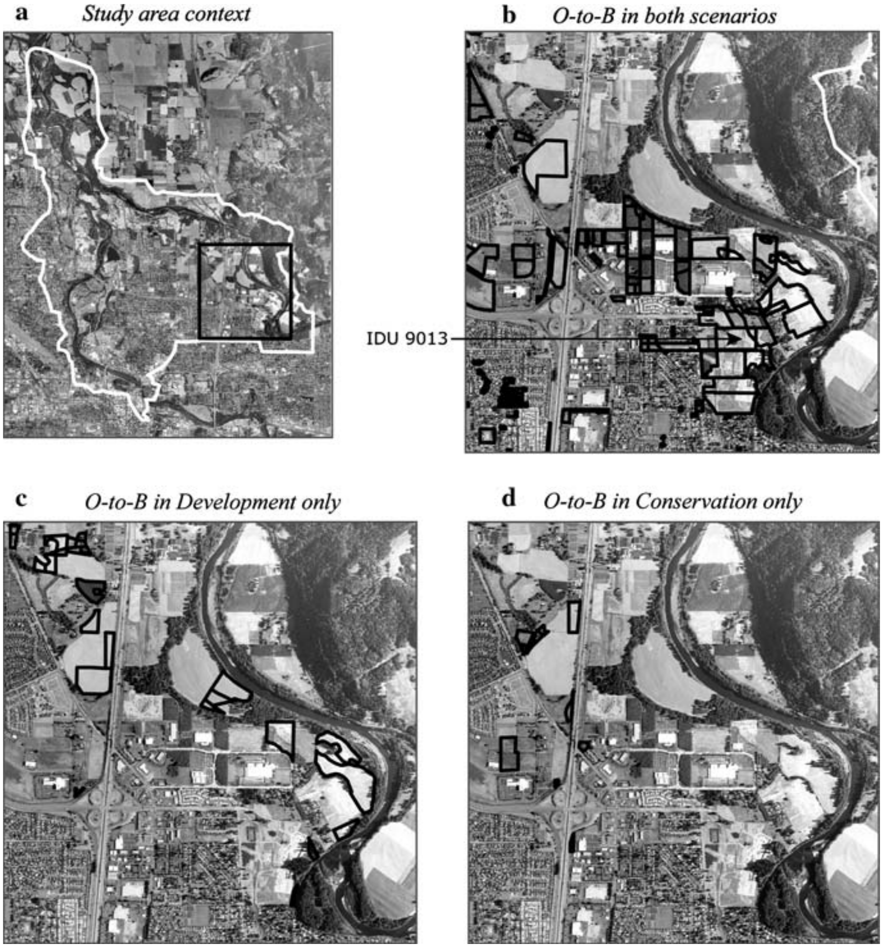

Fig. 11 Study area sub-set showing IDUs following an Invariant Type 2 trajectory from *O*ther-to-*B*uilt. (**a**) Shows the sub-set location within the study area. (**b**) Outlines IDUs that followed the O-to-B trajectory in both the Conservation and Development scenarios. (**b**) Also identifies IDU 9013 whose policies are shown in Table 5b. (**c**) Outlines IDUs following the O-to-B trajectory in the Development scenario but not in the Conservation scenario. (**d**) Outlines IDUs following the O-to-B trajectory in the Conservation scenario but not in the Development scenario

Table 5a shows policy applications by decade for IDU 1110 identified in Fig. 10b. The table includes all policies applied over the course of 75 runs for each modeled alternative. In both scenarios, IDU 1110 followed an Invariant Type 2 (confident change) trajectory from *O*ther-to-*R*iparian. The table shows that in the Conservation scenario, there were more policies leading to that trajectory and the decades in which policies were applied spanned the entire range of modeled time. In the Development Scenario, a single policy was responsible for the *O*ther-to-*R*iparian trajectory of IDU 1110 and this trajectory was set in motion within the first three decades.

IDUs following the *O*ther-to-*B*uilt trajectory are shown in Fig. 11 with 11b highlighting IDUs following that trajectory in *both* the Conservation and Development scenarios. Comparing Figs. 10b and 11b shows a greater number of IDUs on an O-to-B trajectory in both scenarios than on an O-to-R trajectory in both scenarios. Although Figs. 10 and 11 show different locations within the study area, the observation is representative. Within the entire study area, 45 IDUs ($\sim$1% of the total area in Fig. 7c) follow the O-to-R trajectory in both scenarios while 867 IDUs (over 5% of the total area in Fig. 8c) follow the O-to-B trajectory. The greater overlap of IDUs on the O-to-B trajectory can be partly attributed to the same increase in population from 2000 to 2050 in both scenarios and to the limited number of IDUs with site attributes suitable for built uses.

Comparing Fig. 11c (O-to-B in Development scenario only) and d (O-to-B in Conservation scenario only) shows the difference in individual site characteristics and in the overall pattern of the built environment between the two scenarios. IDUs on the O-to-B trajectory in the Development scenario only (Fig. 11c) are more numerous, larger in area and may be adjacent to or very near the river. In contrast, IDUs

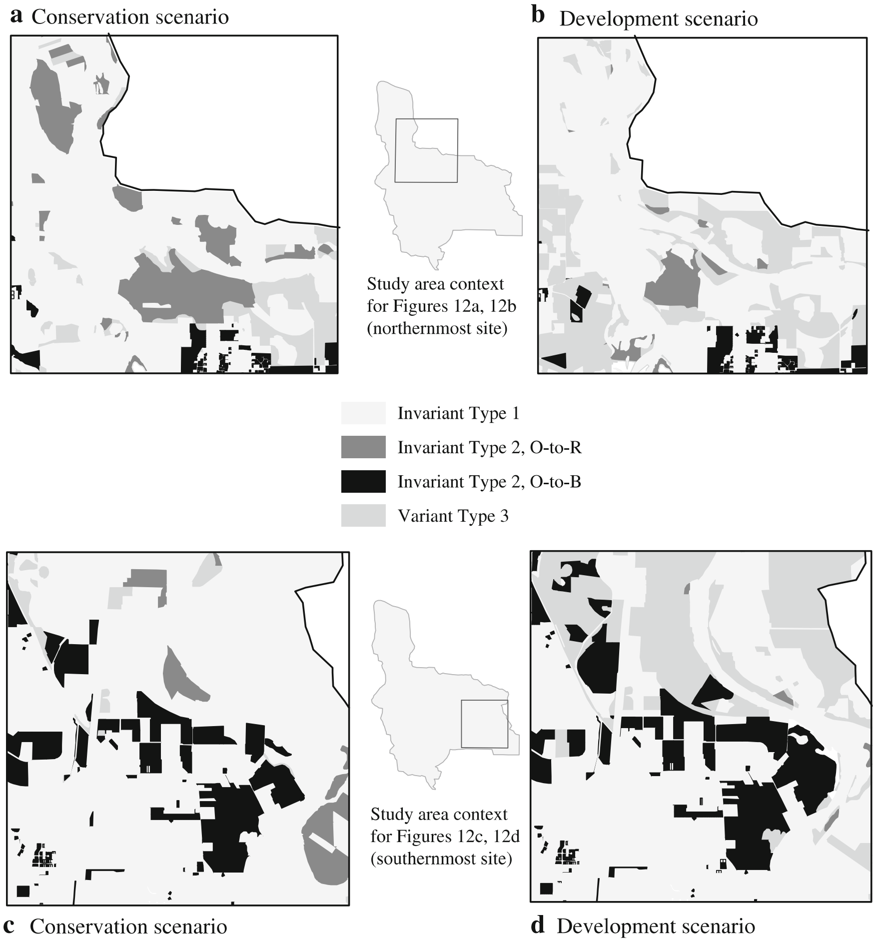

Fig. 12 A finer grain representation of the landscape trajectories shown at the study area extent in Figs. 6–8. The spatial extent of (**a**), (**b**) corresponds to that of Fig. 10; the spatial extent of (**c**, **d**) corresponds to that of Fig. 11

on the O-to-B trajectory only in the Conservation scenario are very few, comparatively small in area and located away from the river.

Policies applied to IDU 9013 (Fig. 11b) during the 75 modeled runs are shown by decade in Table 5b. In both scenarios this IDU followed an O-to-B Invariant Type 2 trajectory. In the first two decades, the conversion to commercial, industrial and low density residential is similar in both scenarios. The most noteworthy distinction between the two scenarios is the difference in the way each accommodates the increase in population. In the Conservation scenario, the primary residential conversion is to high density residential with no conversion to low density residential after the first two decades. In the Development scenario, residential conversion is spread over all four residential densities with most into low and medium-low densities and little into high density.

Figure 12 uses the spatial extents of Figs. 10 (Fig. 12a,b) and 11 (Fig. 12c,d) to provide a finer grain view of what is shown at the study area extent in Figs. 6–8. This figure allows a side-by-side comparison of the Conservation and Development scenarios for both subset areas (Figs. 10 and 11) and emphasizes some of the characteristics noted at the study area extent. One such example is that more of the study area is on a variant trajectory in the Development scenario than in the Conservation scenario (Fig. 6; Table 2). Comparing the finer grain view in Figs. 12b,d (Development scenario) with Figs .12a,c (Conservation scenario) reinforces this distinction between the scenarios. Figure 12 clarifies the choice of study area subsets for Figs. 10 and 11 and illustrates the degree to which past influences future. The northern most site (Figs. 10, 12a,b) is in a more rural part of the study area and the southern-most site (Figs. 11, 12c,d) is closer to the urban core.

In both scenarios, the *O*-to-*B* trajectory dominates the southernmost site where past land use provides nearby infrastructure and facilitates continued wealth production from built urban land cover. For both scenarios, the *O*-to-*R* trajectory is most evident at the northernmost site. At this location, conversion to built land uses is likely to be less lucrative and the ecosystem benefits of riparian land cover more cost effective than at the southernmost site.

3.5 Limitations

We made a number of simplifying assumptions to allow comparison of the two modeling approaches. We aggregated land use/land cover into three very broad categories (*B*uilt, *R*iparian and *O*ther). Even at this coarse level of LULC aggregation there remain differences in starting conditions between the PNW-ERC ca. 2000 LULC and Evoland ca. 2000 LULC (see Fig. 4). Evidence is persuasive that starting conditions are a powerful influence on ending condition patterns derived from agent-based models (Parker et al. 2003: Brown et al. 2005a). Comparison across approaches was also complicated by the presence, in the agent-based Evoland approach only, of the Variant trajectory. There was no comparable trajectory in the PNW-ERC approach. And, as others have noted, it can be challenging to establish cause/effect relationships when interpreting agent-based model results (Janssen and Jager 2000; Janssen and Ostrom 2006).

Despite these limitations, congruencies in the outcomes of the two approaches suggest that the difficulty in verifying or validating the agent-based approach does not equate to a lack of policy modeling usefulness. Overall, a scenario expressed in the deterministic model produces landscapes that experience similar trajectories as the same scenario implemented in the probabilistic agent-based approach. This signal stands out clearly in spite of the difference in the manner of policy expression in the two approaches, the highly aggregated, inarticulate land classification system employed, and the difference in ca. 2000 land use/ land cover representations underpinning the two analyses.

4 Conclusions

We organize our conclusions into three types of lessons: (1) lessons from comparing results of the expert-driven probabilistic agent-based modeling with results from the citizen-driven deterministic modeling; (2) lessons regarding strength of coupling between landscape trajectories and policies, and (3) lessons regarding the avoidance of landscape scarcity.

4.1 Lessons from comparing approaches

Comparing results from the two approaches, we find that the expert-driven agent-based techniques do indeed produce alternative futures that are more likely than their citizen-driven deterministic counterparts to push the envelope of plausibility. This is due both to the reluctance of citizen stakeholder groups to conceive drastic change and the capacity of agent-based models to explore more fully a much larger set of alternative future landscape trajectories for a given number of scenarios. While the existence of the *Variant* trajectory in the agent-based approach complicates comparisons, we did find the results from the agent-based modeling of the two 2050 scenarios were more different from their 2000 starting conditions than were their deterministic counterparts. This conclusion is based on the highlighted rows of Table 2 and the larger territory of changed LULC in Fig. 6 in the alternative futures produced by Evoland. We also found that regardless of approach or scenario, the majority of area that was *B*uilt, *R*iparian, or *O*ther in 2000 was *Invariant Type 1*, i.e., it remained in the same cover class in 2050 that it started in 2000. For those portions of the landscape where this was not the case, again regardless of modeling approach or scenario, the majority was in the *O*ther category in 2000. One potential implication for landscapes in rapid transition is that policy discussions may center on small, critical portions of the landscape that expert-informed, agent-based models can identify, while citizen-led processes and site-specific design explorations can better inform the choices that must be made regarding these pivotal parcels.

4.2 Lessons regarding strength of coupling between policies and landscape trajectory

The deterministic approach produced outcomes in which 78% (Conservation) to 79% (Development) of the study area remained unchanged in *B*, *R*, and *O* classes, while the agent-based approach produced outcomes in which 63% (Development) to 68% (Conservation) remained unchanged. The two approaches differed by 16% points in the amount of invariant area between their Development-oriented scenarios and by 10% points between their Conservation-oriented scenarios. In its Development scenario, the agent-based approach identified 16% of the study area as having uncertain outcomes (Variant Sum, Table 2), and 5% as uncertain in its Conservation scenario.

In spite of their different modeling formalisms and manner of expressing policies, the two approaches agree that a substantial majority of the landscape (almost two-thirds) will remain in the same generalized LULC classification over a 50-year period. The agent-based approach may be estimating the amount of outcome uncertainty more realistically, making explicit uncertainty artifactually concealed by the deterministic approach.

If, as is the case for the Development scenario in the agent-based approach, 63% of the landscape does not change, and an additional 17% has an unknown outcome, then 20% of the area appears to have changed over the 50 years of modeled time in response to expressed policies and model structure. In this scenario, the agent-based approach suggests that 83% (63 + 20%) of the landscape would express a predictable trajectory when trajectory is expressed in the admittedly coarse LULC categories of *B*uilt, *R*iparian and *O*ther. For its Conservation scenario, the comparable value is 95%.

The tracking of Evoland's policies suggests that scenario intentions, expressed through similarly intentioned policy sets, do have an influence on landscape trajectories. In Evoland's Conservation scenario where improving ecosystem function was a higher priority, a suite of policies was created in service of that goal. The 50-year modeled landscape for the Conservation scenario indicates that implementation of those policies created a more extensive, better connected riparian habitat when compared to the Development scenario. In Evoland's Development scenario, where improving ecosystem function was a lower priority, only a few policies had an outcome resulting in new riparian land cover. As expected, the Development scenario's modeled riparian landscape was less extensive when compared to the Conservation scenario. In locations where the Conservation scenario added new riparian land cover, the Development landscape trajectory was often unchanged (Invariant Type 1) or expressed variable outcomes (Variant Type 3). This suggests that the mere *presence* or *absence* of a scenario-compliant suite of policies from which to choose is an important influence on landscape trajectory.

4.3 Lessons regarding anticipating and avoiding scarcity in future floodplain trajectories

While few things can be said with certainty about the future, one thing is clear, surprises will happen. Rather than making predictions about the future, the agent-based probabilistic approach and its associated large number set of alternative futures offers the possibility of narrowing the range of policy options likely to address key scarcities. Specifically, it allows exploration of where, when and how much area a given policy will effect, and examines the efficacy of a policy suite at avoiding key future scarcities. Using two linked factors as evidence of effect (the number of times a policy was invoked and the total territory it effected), this study showed that a comparatively small number of pivotal parcels may have influence disproportionate to their size on avoidance of key future scarcities and the variability of future trajectories.

Within the limitations of this study, the Evoland results indicate that scenarios and policy sets whose LULC pattern intentions can be met by a variety of alternative trajectories are better at avoiding scarcities of the kinds modeled here than scenarios and policies that are less tolerant of variant trajectories. Agent-based models are in their infancy, especially as applied to modeling policy and human value influence on LULC change. A key final lesson for us is that spatially explicit scenario modeling needs better ways to incorporate surprise in modeled futures. Given the inherently dynamic nature of urban centers located at the confluences of major rivers, the exploratory capacity of agent-based models is compelling.

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