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Synthesis

Regenerative landscape design: an integrative framework to enhance sustainability planning

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ABSTRACT. Addressing contemporary environmental and social crises requires solutions-based, systems-level changes. To achieve these changes, transdisciplinary research approaches are needed to align problem framing with solution deployment at landscape scales. However, practical frameworks to guide this work are lacking. Here we propose a new framework to help bridge this gap: regenerative landscape design (RLD). We define RLD as a process for finding pattern-based solutions, emphasizing cooperative, iterative, and facilitated engagement for the co-production of locally relevant knowledge for desirable landscape stewardship. To do so, we review how key components of RLD (e.g., landscapes, design thinking, and regenerative processes) have been differentially and unevenly applied in disciplines ranging from resilience, landscape ecology, geography, architecture, agriculture, sociology, tourism, and more. We then put forward research considerations of a RLD approach to enhance social and environmental well-being. We use two emerging case studies (i.e., Chesapeake Bay Watershed, Pennsylvania, USA and Narok County, Kenya) to put forward pathways for implementation of the RLD strategy.

Key Words: *ecological solutions; global environmental change; land management; positive futures; resilience; social-ecological systems; sustainability science; sustainability transition*

INTRODUCTION

People have been markedly influencing the global environment for millennia, with exponentially increasing impacts over the last century (Crutzen 2002, Steffen et al. 2007, Stephens et al. 2019, Ellis et al. 2021). We are rapidly approaching planetary boundaries in biodiversity loss, land use, ocean acidification, and climate change (Rockström et al. 2009, Steffen et al. 2015). As a result, the capacity of nature to support human quality of life and ecosystem services is declining rapidly (Díaz et al. 2019). However, notions of apocalyptic collapse at global scales can stymie progress rather than hasten it if solutions seem intractable or not relevant to lived experiences (Abbott and Wilson 2014). Yet, solutions to address environmental and social crises are complex, requiring cross-sectoral integration across knowledge systems. Moreover, we strive to ensure systems are not just resilient to stressors, but also that they are moving toward more enhanced and stable systems states. To do so, new approaches are needed that address the social boundaries associated with planetary boundaries (Brand et al. 2021), center decision making at people-relevant scales (Sayer et al. 2013, Keller et al. 2021), chart pathways for positive change (Bennett et al. 2016), and address the spatial realities of current and future landscape condition.

Here, we put forward the concept of regenerative landscape design (RLD) as an approach to enhance socio-environmental sustainability, which newly integrates three objectives: (a) enhancing the capacity for positive change (Regenerative); (b) grounding solutions at scales relevant to decision making and that account for interlinked spatial patterns and processes (the Landscape); and (c) ensuring an intentional and iterative process of co-discovery that is coupled to material solutions (Design Thinking). In this paper, we additionally explore the history and disciplinary development of these terms and present their utility through an RLD research strategy and two emergent case studies.

The rapidity and scale of anthropogenic environmental change has led to a persistent and increasing inventory of landscapes in dire need of restorative processes (Luke and Evensen 2021, Molla et al. 2021). More than a quarter of a century ago, Hobbs (1997) called for integrative and active approaches to landscape planning that account for increasing pressures on landscapes to meet social and ecological needs. A decade ago, Sayer et al. (2013) identified ten core principles (e.g., multiple scales, multifunctionality) that characterize integrative approaches needed to restore critical social-ecological patterns and processes, centered on landscapes. Here, we extend these ideas to assert that stewardship of communities and ecosystems should aim to enhance the regenerative capacity of landscape systems. We further argue that regenerative landscape systems are achieved when landscapes are designed and planned purposely and materially to account for the spatial and temporal interactions of social-ecological processes.

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Moreover, designing regenerative landscapes requires the use of co-design methodologies that incorporate the evolving conditions of human livelihoods and that consider cultural resources, social equity, and social justice as they are intertwined with biophysical patterns and processes of place (e.g., Bullard 2000). Centering justice in considerations of sustainability, social-ecological systems, and resilience is not new (Leach et al. 2010, Fischer et al. 2015, Biermann et al. 2016); here, we emphasize its criticality for regenerative solutions. Importantly, engaging with these dynamics at landscape scales can reveal how practices, values, and multiscalar systems dynamics result in emergent outcomes (e.g., Bird et al. 2016, Power et al. 2018). Importantly, transdisciplinary approaches that center rights-holder engagement, by definition, involve communities and non-academic partners, each of whom may hold different values, norms, attitudes, and behaviors, shaped by legacies of race, ethnicity, socioeconomic condition, and, we emphasize, also histories of colonialism, exclusion, marginalization, or disenfranchisement. Attending to, and giving voice to, alternative value systems is fundamental for identifying the full range of potential landscape futures.

Based on these motivations, we define RLD as a "process for finding pattern-based solutions, emphasizing cooperative, iterative, and facilitated engagement for the co-production of locally relevant knowledge for desirable landscape stewardship." The focus on pattern-based solutions acknowledges that contemporary landscape challenges are, at least in large part, rooted in contemporary patterns of socio-environmental processes that either inhibit or promote vulnerability, adaptation, and regenerative capacity. For example, community vulnerability to wildfire is a function of both the biogeographic context of fuels and weather, as well as the proximity to human-based ignition sources; similarly, traditional means of adaptation such as transhumance in pastoral communities is increasingly constrained by land use and land tenure policies and practices that restrict movement away from stress. We posit that, if landscape pattern can limit resilience, an attention to landscape pattern can equally and reciprocally enhance resilience and ultimately regenerative capacity. We outline this idea schematically in Fig. 1, highlighting that spatial patterns of linked social and environmental systems can either accelerate or decelerate systems toward regenerative landscape conditions that result in more desirable system states. Critically, understanding which designs promote the most desirable and regenerative outcomes requires iterative co-design processes that reveal shared values about system states as well as clear understanding of how landscape patterns lead to desirable socio-environmental processes.

As described below, components of regenerative systems, design, and landscape have been differentially and unevenly utilized within disciplines. Here, we summarize each of these components separately (i.e., regenerative, landscape, design), reviewing their current meaning individually across numerous subfields. From this review, we conclude that regenerative systems, design thinking, and landscape are key elements for stewarding sustainable landscape futures but have been unevenly applied. Then, we put forward strategies for a research roadmap for RLD as an integrative framework and as a frontier in sustainability methodology and action. Regenerative landscape design offers an opportunity for convergence among disciplines and sectors in society to co-create transformative adaptive pathways in the face of rapid environmental and social change. We posit that there are ample opportunities to apply an RLD approach to landscape stewardship and put forward two examples (in the Chesapeake Bay, USA and agropastoral landscapes of Narok county, Kenya) to show its potential application.

REGENERATIVE LANDSCAPE DESIGN: AN INTEGRATIVE FRAMEWORK

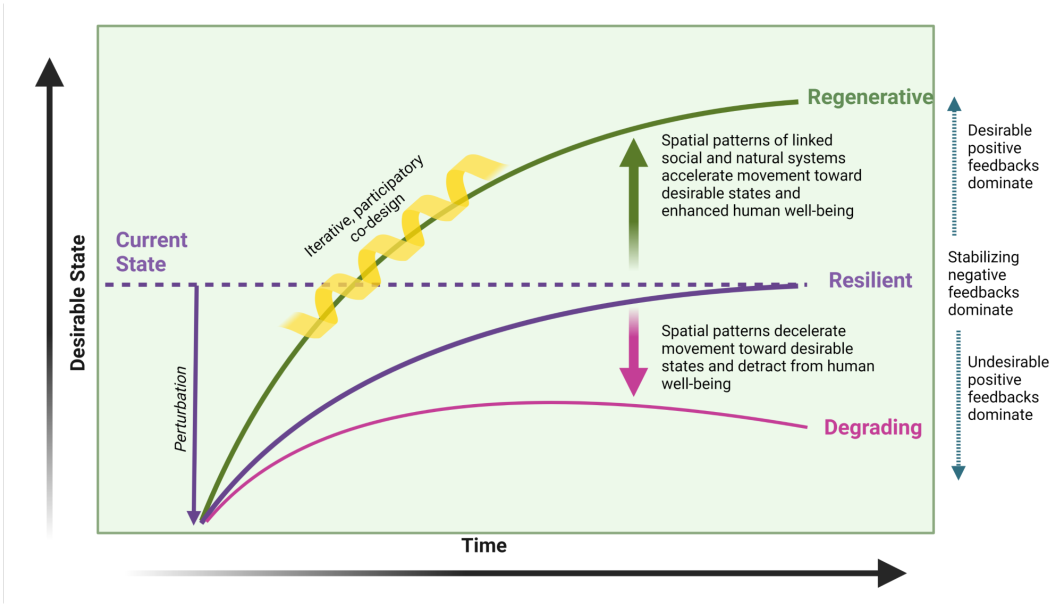
Component 1: Regenerative Approaches

Regenerative systems have the embodied capacity to reorganize and, through stewardship and design, move to a more positive system state (Casarejos 2020). The focus on regenerative capacity spotlights characteristics of systems that promote change to desirable system states, a more specific case of how systems reorganize to the original state in the traditional framing of resilience (Walker et al. 2004, Folke 2016). Like adaptive capacity (Folke et al. 2002), regenerative capacity considers the social, institutional, and environmental factors that determine potential for change. However, regenerative capacity explores how systems can be intentionally reorganized to move to more desirable states, in addition to preventing losses in function or services from the current state. This distinction is important, because it is now recognized that not all resilience is desirable, and it is possible to be stuck in undesirable states (Suding et al. 2004, Carpenter and Brock 2008, Béné et al. 2014).

The concept of regenerative systems builds on frameworks such as complex adaptive systems (CAS; Holling 1973), in which systems dynamics are based on embodied energy capture or release (sensu Odum 1968). In this framing, systems move energetically among states as an adaptive cycle (Holling and Gunderson 2003) within a dominant scale of activity. Complex adaptive systems operate across a range of scales and are composed of multiple adaptive cycles, each with characteristic scale domains. Cross-scale organization means that if one level of a system collapses, this embodied energy and associated dynamics can be absorbed by or affect other levels of the system. As such, systems characterized by an adaptive cycle can exceed resilience boundaries and jump to new systems states. These breaks are explored with concepts such as tipping points, tipping elements, thresholds, and criticality (e.g., Scheffer et al. 2001, National Research Council 2002, Lenton et al. 2008) and early warning systems for regime shifts (e.g., Keller et al. 2007, Scheffer et al. 2009). Building on Odum (1968), Allen and Holling (2010) speculated that the reorganization of CAS offers an opportunity for novelty and innovation such that random or punctuated events can introduce new dynamics or system elements that could amplify system change. This reorganization potential offers an opportunity for intentional regenerative renewal.

Approaches to regenerative systems are being developed in parallel among many fields relevant to social-ecological systems such as agriculture, architecture, urban studies, and tourism (see Table 1). Collectively, these examples highlight many opportunities to uplift social and environmental systems through a regenerative lens from multiple disciplinary perspectives. More generally, regenerative approaches have been a useful construct to frame the renewal, reorganization, or re-creation of social-ecological system identity in the face of dynamic change (Boecker et al. 2009, Mauser et al. 2013) and are related to foundational principles in resilience presented by Future Earth (Rockström

Fig. 1. Regenerative landscape design builds upon core conceptual frameworks within related disciplines, including landscape ecology, social-ecological systems, and resilience, specifically exploring how landscapes could be managed and designed toward more desirable states.



2016) and reflected in the United Nations Sustainable Development Goals (UN General Assembly 2015). However, across these previous approaches, it is unclear how systems could be designed materially and institutionally to embody the capacity for positive change, nor what patterns and processes in both social and environmental systems would serve as indicators of this potential.

Here, we situate regenerative systems on landscapes. Previous efforts have likewise recognized the importance of landscape approaches, e.g., for landscape sustainability science (Wu 2013, 2021), spatial resilience (Cumming 2011), and landscape stewardship (e.g., the Global Landscapes Forum). We suggest here that regenerative designs can be leveraged to purposefully move landscapes beyond maintenance of current conditions to enhancing human and ecosystem well-being. For example, Moritz et al. (2018) suggest that system elements and dynamics can be purposely reconfigured to uplift people and the environment through better understanding of bottom-up interactions among individuals and human systems within heterogeneous landscapes. However, we posit that these approaches have not yet fully integrated landscape perspectives such as spatial resilience (Cumming 2011) or landscape ecology (Turner 1989) that would more deeply emphasize the importance of spatial patterns and multi-scale processes in determining regenerative outcomes on lived landscapes.

Component 2: Landscape Approaches

Landscapes encapsulate reciprocal and dynamic pattern–process interactions across multiple levels of ecological and social organization. However, quite commonly landscapes are defined as areas large enough to comprise multiple ecosystem types or land uses, and thus represent a scale of great relevance for human management and policy. Therefore, landscape approaches (e.g., Sayer et al. 2013) are increasingly seen as an inclusive strategy to include relevant actors in the system, illuminate a variety of perspectives, and ultimately inform more positive solutions. We suggest, however, that landscapes approaches have not been adequately integrated in the pursuit of regenerative landscape futures yet offer unique potential for supporting novel insights and solutions.

Landscape approaches are particularly useful in at least three key dimensions. First, a landscape helps frame and define relevant boundaries of social-ecological systems and their associated landscape-level governance and planning processes. Thus, landscapes are recognized as an appropriate level of social and environmental organization to help bound multiscale governance and management decision making (Görg 2007, Sayer et al. 2017). Furthermore, given that the concept of landscape emphasizes interconnections among humans and their biophysical environment (Friess and Jazeel 2017), landscapes can be used as a boundary object to address complex challenges at scales relevant to human decision making and planning (Tress et al. 2001, van Rooij et al. 2021).

Use of landscapes as a boundary object is so fruitful because the landscape concept is broadly deployed across disciplines, including landscape ecology, the social sciences, humanities, and the visual and design arts. For example, within human geography, landscapes are culturally defined, viewed, and constructed, and shaped by human and institutional desires and actions (e.g., Sauer 1925, Farina 2000, Fry 2001). Representation of landscapes through the visual arts has long inspired painters, textile artists, and photographers and has led to representation (and critiques of) the sublime wilderness ideas associated, for example, with the birth of the U.S. National Park System (Byrne and Wolch 2009). Calls for collaboration among artists, cultural geographers, and climate scientists has risen exponentially (Tolia-Kelly 2012),

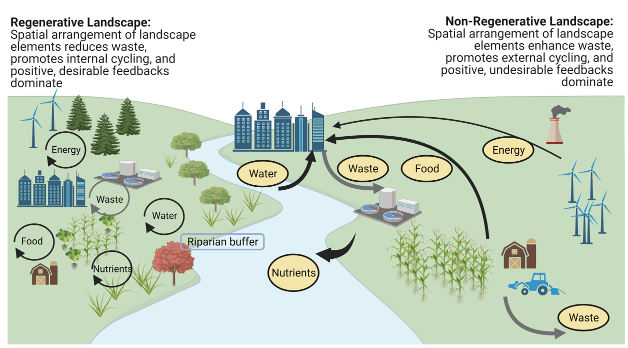
Table 1. Examples of regenerative systems in disciplinary fields relevant to understanding social-ecological systems.

Example	Overview	RLD application	Literature
Regenerative Agriculture	Focuses on semi-closed loop systems, in which waste and materials are recycled, resulting in the need for fewer inputs of limiting resources such as nutrients or water, and may yield net positive outcomes for the producer and the consumer compared with conventional agriculture	Designing social institutions that promote regenerative outcomes on agroecological landscapes is increasingly paramount given increasing industry competition for regenerative branding and increasing pressure on farmers to respond to new standards	Pearson 2007, Rhodes 2017, Newton et al. 2020, Noltemeyer 2020, Giller et al. 2021, Strube et al. 2021
Regenerative Architecture	Embraces a living system approach, taking the specifics of people and place into consideration. Buildings are seen as self-healing and self-organizing and as a catalyst for positive change within the unique place in which they are situated	Maximizing positive impacts in building design related to place, community, and culture requires new questions to be asked "during the design process, who is asked, and how the discussion is guided." (Robinson and Cole 2014: 135)	van der Ryn and Cowan 1995, Reed 2007, Boecker et al. 2009, Busby et al. 2011, Cole 2012, Mang and Haggerd 2016
Regenerative Urban Systems	Creates cities that are more than resource efficient and low polluting, but which enhance ecosystem services within and beyond their boundaries, through reorganization of social and ecological networks, processes, and capital	Financial, technical, social, and natural systems should be designed purposefully to enhance urban well-being and health, with special consideration given to spatial interconnections within and beyond urban systems	Beatley and Newman 2013, Liu et al. 2013, Girardet 2017
Regenerative Tourism	Examines long-term and spatially connected impacts of tourism to more proactively enhance protected areas and ensure thriving communities	Integration of regenerative principles in tourism facilities and support of Indigenous cultures and stakeholders is evident in the mainstreaming of regenerative travel, but alternative models in global tourism that systematically enhance socio-environmental landscapes are needed	Arfwedson 1994, Lyle 1994, Owen 2007, Pollack 2019, Ateljevic 2020, Cave and Dredge 2020, Matunga et al. 2020, Duxbury et al. 2021, Fotiadis et al. 2021, Sheldon 2021

particularly as aesthetic representation of changing landscapes is seen as important for engaging public participation (Steidle et al. 2023).

Secondly, a landscape approach emphasizes the role of spatial connectivity and jumpstarts transdisciplinary and multi-sectoral conversations. This transdisciplinary and spatial perspective is important because patterns of landscape elements (e.g., arrangement and composition of land uses or ecosystem types) interact with processes (e.g., nutrient cycling, hydrologic flow, or social information exchange) (Fig. 2.) to influence the dynamics and outcomes of social and environmental systems (Turner 1989, Forman 1995, Turner and Gardner 2015). These interactions can shape and reshape landscape-level patterns across millennia, incorporating ever-changing human practices and values, and changing ecological conditions. For example, Gergel et al. (2020) explored the evidence that landscape composition and configuration can influence food security and nutrition by impacting the diversity of foods obtained from landscapes with both farms and forests. Landscape diversity—the number and types of different land cover and their spatial distribution (Gergel and Turner 2017)—thus affects nutrition-sensitive landscapes (Powell et al. 2013) as different food and energy resources are obtained from large forest patches vs. sparse scattered trees, as well as from larger vs. smaller agricultural fields. Understanding that dietary diversity can be related to complex landscape mosaics, landscape diversity can shed light on land patterns and associated flows of nutrition that should be restored to enhance human health and well-being, requiring expertise across multiple often disparate disciplines (Bliege Bird and Bird 2021).

Fig. 2. Connectivity is a fundamental concept in RLD because of its role in facilitating flow of social and environmental elements, often facilitating regime shifts and influencing cross-scale interactions. In the example above, excess nutrient flows to hydrological systems are reduced when flowing from left to right because of strong vegetative uptake that reduces nutrient inputs to the watershed, but are increased when flowing from right to left due to minimal vegetation uptake along the flow path and higher inputs to the waterways.



Thirdly, a landscape approach helps understand patterns and processes that may produce emergent behaviors and surprises. The type, arrangement, and multiscale dynamics of landscapes can sometimes lead to surprises at higher levels of organization (Peters et al. 2004). For example, the spatial arrangement and connectivity of fuels on fire-prone landscapes can amplify or dampen fire behavior, such that highly connected fuels can accelerate positive feedbacks in fire intensity leading to "mega-fires" governed more by the chemistry and physics of the fire plume than by the original fuels that initiated the combustion process (Peters et al. 2007, Newman et al. 2019). In the case of complex social-ecological systems, non-linearities in policies can lead to abrupt social and environmental change (Cumming 2011, Garmestani 2014) and, similarly, abrupt changes in environmental conditions, e.g., in climate (Alley et al. 2003) or the COVID-19 pandemic, can result in substantial societal changes. Understanding how spatial arrangement coupled with cross-scalar interactions in coupled natural and environmental systems affect regenerative capacity of these systems is a research frontier in RLD.

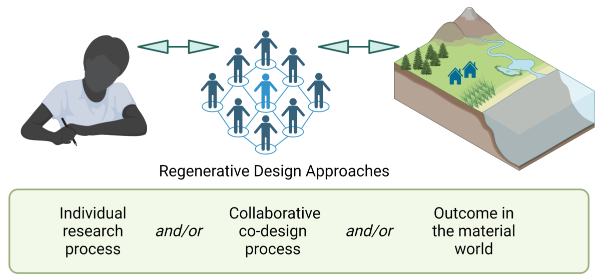
Given these reasons, it is not surprising that landscapes are also increasingly recognized as the appropriate scale for engendering system-level transformations. For example, the multi-level perspective (MLP) has been widely used to study sustainability transitions, such as energy systems (Geels 2002), suggesting that sustainable transitions must attend to both the social and technical dimensions of change as well as the transformations in human–environment interactions that emerge through the process (Calvert et al. 2017). Furthermore, geographers have called for better integration of landscape theory and the MLP to better assess the specific places and spaces of energy transition (Bridge et al. 2013) along with considerations of justice and equity in sustainability planning. Here again, the concept of landscape can offer guidance by facilitating a more systemic analysis of the effects of human–environment transformations linked to environmental justice by specifically considering equitable sharing of benefits and costs and their distribution across space (Schlosberg and Collins 2014, Sovacool et al. 2017, Mainzer et al. 2019, Carley and Konisky 2020).

To our knowledge, these landscape perspectives have not been applied to regenerative systems planning. Specifically, we suggest that attending to existing pattern–process dynamics and scale dependencies can reveal new opportunities for spatial planning that help guide holistic and flourishing systems into the future.

Component 3: Design Approaches

The intersection of environment, society, and design has been approached from various scholarly perspectives for decades (McHarg 1969, Alexander et al. 1977, Lyle 1996, Chapin et al. 2011, Moreno et al. 2016, Arroyo-Rodriguez et al. 2020). Perhaps because of these different disciplinary histories, design has multiple meanings and is used in different contexts across disciplines. Overall, we posit that design presents an approach to reconcile and integrate objectives when stewarding biophysical and social change. We suggest that the term has at least three specific meanings across disciplines: as the evolution of a research process (a verb), as an intentional approach to collaboration through co-design (a verb), and as a pattern outcome (a noun) in which elements are arranged purposely to meet a certain set of objectives, be that an architectural drawing or a land-use planning map (see Fig. 3). These three meanings should be considered as a design thinking continuum that can be applied to RLD approaches.

Fig. 3. Design approaches can be differentially defined as the evolution of an individual research process (a verb), as part of a collaborative co-design process (a verb), and as a pattern outcome (a noun) in which elements are arranged purposely to meet a certain set of objectives in the material world.



In the arts and related fields, design is characterized as a process for finding solutions through experimentation, deconstruction and reconstruction, and iteration. In this view, the research process itself is created intentionally—designed—to support idea evolution (Rottle and Yocum 2010). The process is often, although not necessarily, individualized more than collaborative. Obviously, the outcome of the design process is a product that has implicit pattern, but the creative innovation is dependent on an intentional and evolutionary design process.

Co-design, on the other hand, is a special case of the design process that emphasizes the importance of cooperation and facilitated teamwork. It recognizes that solutions are most robust when different perspectives, viewpoints, and value systems work together on the project design process. Co-design differs from related concepts, such as translational or implementation science (Madon et al. 2007, Enquist et al. 2017). Both translational and implementation science address the challenge that knowledge generated by scientists is often not available to decision makers in society, and thus is not used (as much as it could be) to address societal challenges. The implementation gap is a result of many structural and cultural factors, including language barriers or access to publications or knowledge experts. On the other hand, the co-design concept is complementary to co-production approaches in transdisciplinary science, including participatory action research (e.g., McIntyre 2007, Smith 2013, Stringer and Aragón 2020), decolonial methodologies (Grey and Patel 2015, Dengler and Seebacker 2019, Wijsman and Feagan 2019) and landscape governance and transition approaches (e.g., Ostrom 2009, Frantzeskaki et al. 2012, Aalbers et al. 2019), which emphasize stakeholder participation and purposefully involve stakeholders' values and needs iteratively through the design process (e.g., Verweij et al. 2016, Norström et al. 2020). The goal is to have greater confidence that the solutions are more robust because they were created with the end-user in mind. Importantly, this collaboration occurs early in the design, ideally at the stage of problem definition and then continues iteratively throughout the research process. This focus on "iterative" engagement with stakeholders is a prominent element of the co-design process.

Table 2. Research roadmap for applying an RLD approach.

Component	Methodological considerations
Regenerative	Identify system components (elements), flows, and feedbacks including common units (where applicable). Prioritize key stressors on system structure and function. Identify mutualisms, untapped potential "energy," and potential "offramps" that promote or detract from regenerative capacity. Decide a priori what features of a regenerative system are collectively "desirable" and best support human and environmental well-being.
Landscape	Collect geospatial data that define past and current land use and environmental conditions (e.g., historical aerial imagery, remote sensing, historical land policy maps). Qualify and/or quantify how spatial patterns of social and environmental factors have changed through time (e.g., using landscape metrics). Define and characterize actors, institutions, and policies that influence past and current landscape governance. Assess how landscape structure influences landscape function (and vice versa) (e.g., through connectivity of social information flows, resource flows, or critical adjacencies).
Design	Identify key partners, considering previously excluded or marginalized groups and influential decision makers. Convene workshops, "charrettes," or meetings to co-frame the problem and identify common or competing values and objectives. Co-design a research strategy that is intentionally iterative and participatory, and which includes assessment parameters. Explore how alternative pattern-based outcomes affect systems' processes, identity, and feedbacks (e.g., through scenario-based, landscape-level modeling).

In addition to the use of design as process—as research methodology, or in a transdisciplinary co-design praxis—design also refers to physical patterns on the landscape as the outcome of the research process. A built design as a project outcome has a clear meaning in such fields as, for example, engineering, architecture, landscape architecture, and the arts, but is also prominent in fields such as restoration and landscape ecology. Across landscapes, design may mean the intentional placement of patch elements to support highly valued landscape processes. For example, planned placement of movement corridors along with removal of barriers to distant habitats that can support the flow of organisms (Lookingbill and Minor 2017, Arroyo-Rodriguez et al. 2020). Similarly, strategic design of vegetated riparian buffers can help minimize nutrient pollution into waterways (Peterjohn and Correll 1984, Lintern et al. 2020). Strategically placed strips of native vegetation near agricultural fields can promote pollinators and enhance multiple ecosystem services (Schulte et al. 2017, Garibaldi et al. 2021).

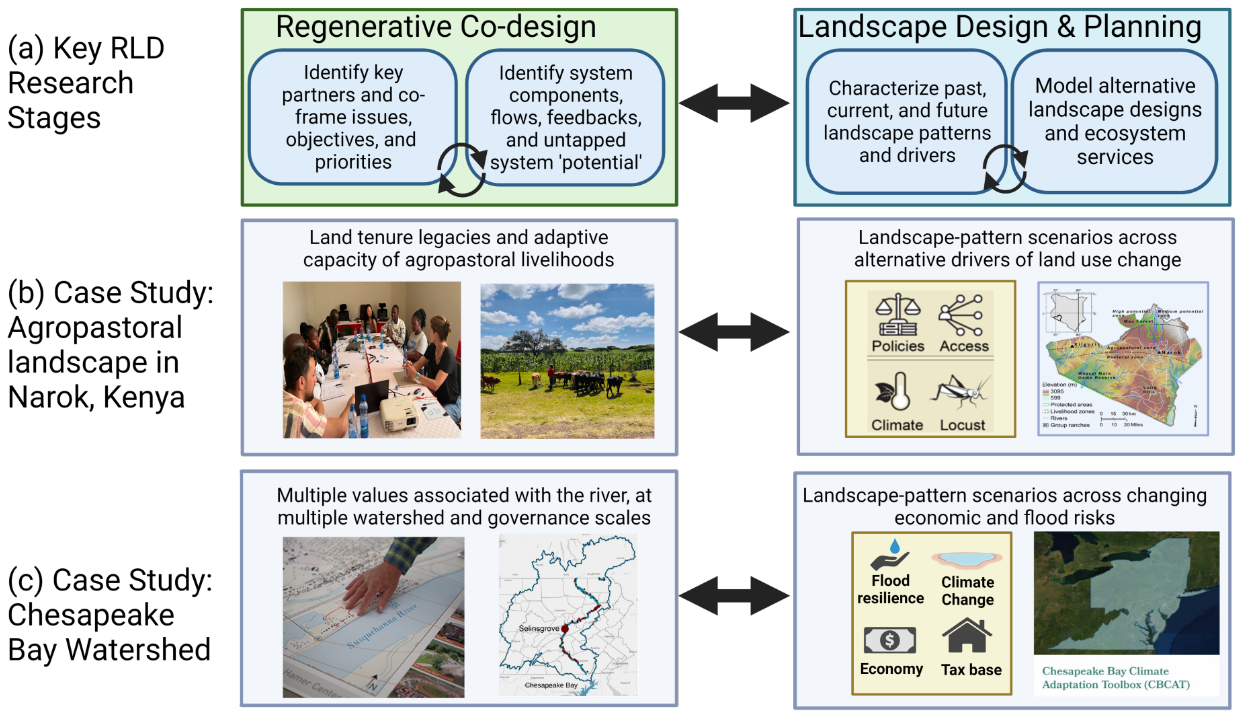
This design continuum highlights the opportunity in RLD for an intentionally designed methodological process that allows for iterative project planning, co-discovery, and co-design with key partners, as well as the exploration of alternative design outcomes through scenario elucidation. It requires deep integration of social, natural, and design fields with associated methodologies, ethical dimensions, policy, and practice. Through this intentional process, research should continue to center values and ethical dimensions that are important to the system and to identify strategies—often more than one—that account for alternative outcomes across a multivariate value-based system state. They should also identify pattern-based outcomes in social systems and the biophysical landscape that optimize across multiple objectives. For intensive examination of strategies to support this process see, for example, Mayer et al. (2017), Tuana (2020), Helgeson et al. (2021), and Keller et al. (2021).

A ROADMAP FOR REGENERATIVE LANDSCAPE DESIGN

The integration of these components described above (regenerative, landscape, design) to address applied research challenges is supported by a transdisciplinary approach that centers iterative co-design and co-creation. Specifically, the co-design process is critical for identifying relevant participants and convening shared values and objectives about landscape design futures. This is because regenerative systems are defined as occupying more desirable system states, necessitating an agreed-upon consensus of what may be most desirable and valued among alternative outcomes (Yarime et al. 2012, Keller et al. 2021). An RLD approach roots this participatory process on identifying, characterizing, and quantifying landscape designs and patterns that are most likely to promote desirable regenerative outcomes. More specifically, the approach might ask what landscape elements and arrangements enhance regenerative processes, building on geospatial modeling or analysis. Subsequently, participatory processes might explore, for example, how landscape heterogeneity, homogeneity, composition, and/or diversity affects key social and environmental objectives. We outline such a methodological roadmap in Table 2 and describe these steps in more detail below.

First, an RLD approach (Fig. 4a) can result in a collectively shared characterization of the system being considered, including the system's structure (elements, flows, feedbacks) and changes (stressors), together with the consideration of regenerative capacity (untapped potential energy), offramps (energetic leaks from the system), and desirability of future systems states identified through co-design. For example, open systems can absorb untapped energy from outside the system boundaries, and these opportunities should be identified. In practice, this may mean expanding the boundaries of the system under consideration. For example, in the case of agricultural systems, new mechanisms to harness microbial nutrient cycling could enhance soil quality, resulting in fewer energy inputs needed, less

Fig. 4. (a) Overview of potential RLD approaches that integrates three co-design and landscape considerations to promote regenerative systems. (b) Potential application of the approach to Narok County, Kenya. Co-design involves collaboration with key partners to identify important system characteristics (e.g., historical land policies and land access, climate change, and emerging threats [e.g., locusts]). Alternative landscape patterns can be explored through geospatial analysis and modeling to identify whether alternative land patterns can enhance transhumance practices and support regenerative agropastoral landscapes. Geospatial mapping credit: Susan Kotikot. (c) Potential application of RLD to the Chesapeake Bay watershed, USA, including consideration of co-design to support community identification of key drivers and interactions of system change and opportunity (e.g., inland flood resilience, climate change, economy, and tax base), as well as multi-scalar contextualization of how community decisions about landscape re-design at a local scale, informed by spatially explicit decision tools, influence the regional Chesapeake Bay watershed.



waste, and more production. Also, new institutions could be co-designed to better incentivize equitable farmer transitions to fair, regenerative agricultural practices. At the same time, identifying the factors that promote waste in the system is critical. These could be defined as knowledge, skills, social capital, or biophysical materials. Identifying what people or processes, tools or technologies, or strategies that could be deployed to track system leaks, once defined, could aid regenerative efficacy and illuminate pathways that maximize thrivability (sensu Gibbons et al. 2018).

Second, RLD aspires to explicitly root system dynamics on landscapes, addressing opportunities for spatially explicit solutions based on understanding of critical pattern–process interactions. Using quantitative or qualitative methodologies, it is important to assess historical, current, or future patterns, as well as assessment of important actors, institutions, or policies that govern these patterns. Given that social, economic, and environmental systems have pattern–process interactions at multiple levels of organization, it is important to define the scale of analysis and relevant mechanisms through a transdisciplinary co-design process. When intentionally using that understanding to design landscape elements for positive change, it is important to understand how landscape elements interact and what processes, social and environmental, are influential. Ensuring data (e.g., geospatial maps) exist at the relevant scale to characterize these patterns and processes is thus critical. Moreover, integration of qualitative and quantitative data and identifying innovative solutions to complex socio-environmental challenges is best addressed through interdisciplinary, team-based research, which is fraught with well-known challenges, including limited resources and communication barriers (Hall et al. 2018).

Third, the design component could be addressed through consideration of the three design perspectives (process, co-design, spatial outcomes) and should include iterative, participatory approaches as well as outcomes assessment. The critical, ethical first step in any design process is identifying who should be included, with special attention to ensuring previously marginalized voices are prioritized. Related, important consideration should be given to the engagement mechanisms, both in terms of frequency and mode of engagement, to ensure equitable and iterative participation. Advancing many traditional participatory approaches, RLD methodologies should additionally ensure that materially designed solutions (e.g., scenario-based maps of alternative outcomes) are discussed as part of the co-design process.

Steps in our proposed methodological process often cut across components and are cyclical. For example, identifying what features of a regenerative system are desirable requires integration of regenerative perspectives in a co-design framework, which should occur early and iteratively. For example, scenario development often occurs early in transdisciplinary research, allowing for common framing of desired outcomes, and the set of values to be weighed in the decision-making process (C. Helgeson et al., *unpublished manuscript*). Similarly, ensuring landscape-level approaches are considered may expand the systems' dimensions and necessitate the inclusion of a broader (or more specific) set of actors in the design process. Incorporating such a broad range of methodological dimensions will necessarily require an inter- and transdisciplinary, team-based approach (e.g., Mauser et al. 2013, Wilson et al. 2021).

Below we provide two case studies to exemplify the need and potential for these methodological considerations to help innovate RLD solutions. Both examples highlight the importance of long timescales of landscape change and the importance of landscape pattern and the socio-cultural meaning of these changes. They also highlight the importance of correcting for deleterious legacy patterns and processes when designing for improved landscape systems. They are both emergent and active research activities, with the potential to identify pathways for RLD project development.

POTENTIAL APPLICATIONS OF THE RLD FRAMEWORK

Example 1. Semi-arid Landscapes of Narok county, Kenya

Arid and semi-arid landscapes support millions of agro-pastoralists worldwide but are increasingly vulnerable as climate extremes drive drought, insect outbreaks, and declining agricultural productivity (Golla 2021). The situation in Narok County, Kenya, is representative of the challenges seen globally, which include loss of nomadic pastoral livelihoods (i.e., transhumance) and an increase in sedentary agriculture. Such transitions have disrupted long-held adaptive strategies of communities facing environmental stress (Amman and Duraiaippah 2004, Aggarwal and Thouless 2008) and reduced adaptive capacity (Golla 2021). In many contemporary landscapes with restricted land rights and declines in access, transhumance no longer represents a viable strategy for finding grazing lands, further degrading the community connections supporting cooperation and land sharing (e.g., Miriti et al. 2019). Furthermore, highly variable, and increasingly heterogeneous water availability limits agricultural productivity across the region.

Designing adaptation strategies at the landscape scale is challenging given the complexity of linked social (policy, livelihoods) and biophysical (settings, stressors) levers and their inherent spatial heterogeneity and ethical dimensions, including social and environmental justice. These tensions have been termed the "politics of resilience" by Biermann et al. (2016). In response, an RLD research strategy would use a co-design approach to explore landscape patterns and scenarios of systems-level transformation (Fig. 4b). Goals of such an approach would be to assess how historical land-use policies have influenced contemporary livelihoods and ecosystem patterns, how patterns of water availability have differed historically within arid land mosaics, how livelihood strategies of farmers and pastoralists can be adapted to fluctuating ecosystem services, and what land-use patterns and policies best support regenerative processes under increasing environmental stress and given contemporary injustices. Once these patterns and processes are known and included alongside ongoing and future drivers of change, alternative landscape structures can be modeled. For example, historical group ranch policies in Kenya established following colonialization served to constrain movement of pastoralists, often leading to overgrazing, soil degradation, and ultimately a need for livelihood diversification. Many group ranches have transitioned into crop agriculture, while others remain intact, leaving legacies of land use that continue to shape livelihoods, ecosystem services, and ultimately resilience to increasingly variable precipitation patterns. Understanding how these legacy land-use patterns historically and currently shape socio-environmental processes can aid insights into how best to modify land-use policies in the future. For example, land-use models can be used to explore scenarios of landscape change and regenerative capacity in response to changing land-use patterns. Through iteration with rights holders and decision makers in the co-design and implementation of these scenarios, landscape planning can also be made to be more equitable, enhancing social, economic, and environmental well-being.

This example highlights the importance of considering systems that are not just resilient to future stressors, such as locust plagues or climate change, but regenerative in that the system moves to more desirable state, correcting for historical land-use failures by explicitly accounting for coupled social and environmental systems and how they respond to, and shape, landscape pattern. Ethical considerations of who is participating in the co-design process are critical for success, as is collective decision making about how to assess change.

Example 2. Chesapeake Bay Watershed, USA

To meet increasing demands for food and energy, humans have doubled the amount of nitrogen and phosphorus flowing through global ecosystems (Galloway et al. 2008), causing deleterious environmental and social impacts. Aquatic ecosystems are especially sensitive to increased nutrient loading, wherein pollution from food and energy systems can result in hard-to-predict algal blooms and persistent dead zones that alter biodiversity and trophic interactions. As the largest estuary in the USA, the Chesapeake Bay is an integrated landscape system that exemplifies this nutrient pollution challenge. Importantly, the Chesapeake Bay is influenced by processes occurring across broad spatial extents and long timescales, whose legacies continue to impact current landscape structure and function (Rick and Sandweiss 2020). As a highly populated region, stresses caused by urban and suburban development affect water quality and quantity throughout the watershed. Impermeable surfaces and increased precipitation and severity of storms in the region exacerbate flooding. Increased nutrient loadings have had a significant impact on aquatic systems. Community and even individual landowner decisions for development and flood mitigation have far-reaching consequences up- and downriver. Both affect the regional economy.

Despite the scope of the nutrient pollution and flooding issues in the Chesapeake Bay, simple and feasible solutions have been elusive, attributed to what is often referred to as the "wicked" nature of the system, a term that reflects the complex interplay among ecological and anthropogenic subsystems that are characterized by lags, discontinuities, and multi-scalar processes. Teleconnections among these coupled systems (Liu et al. 2013) can extend the network of complex systems beyond their physical boundaries to include flows and interactions with other locations. Often those interconnected complex systems involve a profound temporal legacy of human practice and social justice. For example, demand and supply for food and energy products or housing across other regions influence land-use decisions and nutrient fluxes within the physically disconnected sub-watersheds within the Chesapeake Bay. Likewise, variability across a 3,500-year human history in the Chesapeake Bay—including long-term sustainable use by Native Americans, followed by the removal of Indigenous practice and subsequent collapse of intertidal mollusk populations—profoundly shapes the capacity of the Chesapeake Bay to absorb new nutrient fluxes (Rick et al. 2016). As another example, the built environment is replete with legacy historic milldam structures (Walter and Merrits 2008) that have significant cultural value but also pose strong sediment release risk to downstream waterways (Lutgen et al. 2020).

The Chesapeake Bay thus represents a challenging but necessary setting to explore the historical baselines, emergent landscape patterns, and socio-economic contexts—across scales and co-designed with community interests—that can be used to support regenerative planning that supports human quality of life and ecosystem services (Fig. 4c). Questions related to this approach include the design of optimal land-use plans and the spatial prioritization of activities that would restore and enhance water quality while adding value to communities through flood protection, a reliable tax base, recreational opportunities, recognition of agricultural livelihoods, and deepened sense of place. How did historical shifts in development and human food demand influence aquatic health of the Chesapeake Bay over time and space? What do these past patterns and interactions imply for land-use patterns and harvest levels today, or where conservation should be pursued? Was sustainability a function of transitory settlement and optimal foraging rules by humans across space and time, or were there other complex trophic interactions that mediated these impacts? When considering other land-use demands, such as for renewable energy through solar farms, additional questions arise. What are the trade-offs between land availability for solar photovoltaics vs. food and water quality? Should the availability of solar energy be used to design agricultural systems or the built environment? Within this complex decision space, what type of deep uncertainty matters the most for a given decision maker / objective? What are robust strategies in the face of deep uncertainty and learning that would help align renewables along a mixed-use landscape?

Addressing these questions would require a mixed-methods approach that considers geospatial patterns and long timescales of human interaction with the landscape. For example, historical maps of milldam locations can be overlain on geospatial maps of priority stream reaches in need of water quality restoration, thus attending to landscape pattern. Qualitative, participatory research with landowners can help identify the social, environmental, and economic goals of potential restoration activities, helping to frame regenerative systems objectives and assessment. In the case of increased flooding threat to communities and agricultural landscapes, co-designed plans can be integrated into land-use planning as biophysical outcomes of the design approach. Although not exhaustive, such approaches have the advantage of incorporating multiple knowledge systems, integrating human values about landscape change, and accounting for biophysical patterns that mediate, for example, nutrient flows.

FUTURE CONSIDERATIONS AND LIMITATIONS

As these potential application areas exemplify, applying RLD to compromised landscapes globally is challenging for several reasons. First, it is difficult to know in advance what systems levers (components, processes, feedbacks) are most influential in the system to support regenerative processes. One approach to address this challenge is to examine long-term trends in patterns and processes at the landscape scale, taking advantage of anthropological and archeological data, historical records, narratives, and geospatial data. For example, in both the Kenyan and Chesapeake Bay case studies, historical patterns of land use, determined from aerial photos, Indigenous knowledge, or archival narratives, can be used to better understand the pace, scale, and magnitude of change, setting important baselines for interpreting contemporary patterns and processes and opportunities for spatial planning. Unfortunately, ensuring these historical social, technical, and environmental data exist at landscape scales relevant to decision making is non-trivial. Often data do not exist, are incomplete, or are represented at different resolutions or extents.

Second, co-design approaches challenge traditional research methodologies, timelines, funding mechanisms, and deeply rooted social inequities. Addressing these barriers requires concerted and integrative consideration of ethical dimensions of participatory processes and outcomes. The National Academies previously identified funding mechanism limitations in pursuit of convergent research (National Research Council 2014) and RLD falls prey to these challenges too. If funding agencies wish to support such efforts, innovation is needed in funding design, review, and implementation. This work also requires trust building that demands time, patience, values transparency, and goodwill, and ultimately should acknowledge that there are alternative ways of knowing, including Indigenous worldviews (e.g., Berkes 2009, McGuire-Kishebakabaykwe 2010, Whyte et al. 2016) and alternative solutions outcomes (Armitage et al. 2011, Smithwick et al. 2019). It is critical to identify who should be involved in the research process and who is not in the room that should be, with special consideration to those who may have been historically marginalized and excluded, as well as how and when to include decision makers who have the most influence on desired outcomes (Joaquin and Biana 2020, Tuana 2020). For example, it is important to be aware of the potential of bad-faith actors in the co-design process who may attempt to manipulate research processes to gain advantage (Glenna and Bruce 2021). Teams should reflect upon how the epistemic and epistemological decisions are influenced by inclusion (or exclusion) of key actors, as well as disciplinary and cultural biases, moral motivations, assumptions, and knowledge gaps. Transparency of these limitations is important at all stages of this process, from problem framing to solutions application (Tuana 2020; C. Helgeson et al., *unpublished manuscript*).

Third, consensus strategies for assessment and statistical metrics of regenerative landscape designs do not yet exist. Indicators are emerging that provide useful guideposts (Sayer et al. 2013, Gibbons et al. 2020). We suggest that, prior to project initiation, reflexive team deliberation within teams is critical to decide upon assessment goals. Analytical approaches that qualitatively and quantitatively diagnose key dynamics within the system, which can attribute causation of change, and that identify or develop appropriate threshold indicators and multi-level mechanisms for sustainable transitions will also be important (sensu multi-level perspective, e.g., Geels 2011). At a minimum, such assessment should consider effectiveness of co-design processes and methodologies, process and pattern-based outcomes, and relevant systems-level characteristics to be measured (e.g., identity characteristics, key feedbacks, and landscape metrics).

Although not exhaustive, such considerations focus a research process on achieving robust solutions that are inclusive of stakeholders' objectives, values, and contributions, are rooted in the material realities of landscapes and the people who live in them, and are focused on enhancing (not just sustaining) human and ecosystem well-being.

CONCLUSION

Humans have played a dominant role in shaping landscapes for millennia (Plieninger et al. 2016, Ellis et al. 2021). Here, we assert that humans have an opportunity to proactively and collaboratively direct that change for the positive. We suggest that society has an opportunity to pivot toward more sustainable and resilient futures by capitalizing on inherent regenerative capacity that exists within both environmental and social systems. We define RLD as a unifying concept that moves a step toward the goal of bringing together ongoing, but currently compartmentalized, disciplinary frameworks in resilience, landscape ecology, planning, architecture, landscape architecture, agriculture, geography, and more, to explore how landscape patterns can be used to promote planning that reinforces regenerative capacity. For example, the approach asserts that ecological (e.g., dispersal, disturbance spread) and social (e.g., information flow, transhumance) processes are inherently spatial, operating within a complex landscape mosaic; the reconfiguration of these patterns can enhance regenerative processes, unleashing new potential for positive change. Rather than bouncing back to a resilient state that may be undesirable, the RLD approach suggests that system states can be promoted that are more desirable than the initial state, but to do so means attending to the social and environmental factors, and their spatial arrangement, that promote regeneration.

In this synthesis, we hope to inspire common understanding of regenerative systems, landscape, and design thinking that, to date, have not been linked. We also consider cross-cutting themes related, for example, to transdisciplinary methodologies, ethical dimensions, and systems thinking that are foundational to these efforts. Future work should advance these concepts and approaches across environmental and social landscapes experiencing different rates of environmental change, alternative social and biophysical structures, and gradients of socio-cultural-economic characteristics. Our research roadmap is a starting point for engaging in transdisciplinary methods for RLD that require greater examination and testing across a range of geographies and contexts.

Collectively, the proposed case studies highlight the call to action of RLD as a transdisciplinary methodology that focuses on the integration of social and natural sciences with the design fields, attends to the long temporal and spatial patterns of landscape change, and which is grounded in ethical dimensions, public policy, and practice. As the concept of regenerative systems continues to evolve within respective disciplines (e.g., urban systems, tourism), opportunities for collaboration and co-design are likely to grow and thrive. Rooting this engagement on landscapes in dire need of restoral, renewal, and regrowth presents a frontier in systems science.

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