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Advancing the integration of ecosystem services and livelihood adaptation

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Abstract

Around the world today, the magnitude and rates of environmental, social, and economic change are undermining the sustainability of many rural societies that rely directly on natural resources for their livelihoods. Sustainable development efforts seek to promote livelihood adaptations that enhance food security and reduce social-ecological vulnerability, but these efforts are hampered by the difficulty of understanding the complexity and dynamism of rural livelihood systems. Disparate research avenues are strengthening our ability to grapple with complexity. But we are only just beginning to find ways to simultaneously account for problematic complexities, including multiscale feedbacks in the ecosystems that support livelihoods, the heterogeneous benefits garnered by different segments of society, and the complex contingencies that constrain people's decisions and capacities to adapt. To provide a more nuanced analysis of the dynamics of transformation in rural livelihood systems, we identified key complementarities between four different research approaches, enabling us to integrate them in a novel research framework that can guide empirical and modeling research on livelihood adaptation. The framework capitalizes upon parallel concepts of sequentiality in (1) ecosystem services and (2) livelihood adaptation scholarship, then incorporates principles from (3) adaptation in social-ecological systems research to account for the dynamism inherent in these often rapidly-transforming systems. Lastly, we include advances in (4) agent-based modeling, which couples human decisions and land use change and provides tools to incorporate complex social-ecological feedbacks in simulation studies of livelihood adaptation. Here we describe the new Ecosystem Services—Livelihood Adaptation (ESLA) framework, explain how it links the contributing approaches, and illustrate its application with two case studies. We offer guidance for its implementation in empirical and modeling research, and conclude with a discussion of current challenges in sustainability science and the contributions that could be gained through research guided by the ESLA framework.

1. Introduction

Over a quarter of the global population, 2.5 billion people, depends directly on natural resources for their principle source of income [1]. But, current rates and magnitude of environmental and social change are straining—and increasingly undermining—the productivity and

sustainability of small-scale natural resource-dependent (SSNRD) livelihood systems worldwide. In such rapidly transforming systems, achieving Sustainable Development Goals simultaneously for improved human well-being, poverty reduction, food security, and environmental sustainability will require effective and holistic strategies for livelihood adaptation [2].

Developing appropriate strategies depends on sound understanding of how particular SSNRD systems function and are likely to respond to social and environmental change. This requires research to address the multiple forms of complexity that characterize these coupled human-environment systems (HES). They include: (1) structural complexities posed by heterogeneity in the human and environmental components of the systems, multiple scales of organization, and multi-way networks of interactions between components [3]; (2) nonlinear dynamics emerging from complex interactions and feedbacks [4]; and (3) the prevalence of localized, case-specific factors that vary between different SSNRD systems [5]. All of these characteristics profoundly affect the way systems function and respond to change [6], and they pose obstacles for conventional disciplinary analytical approaches. Interventions that do not account for these complexities may be ineffective at fostering adaptation, lead to detrimental outcomes, and generate unexpected environmental and societal tradeoffs. Our limited methodological ability to account for the complexity of coupled HES generally, and SSNRD systems in particular, is one of the most restricting bottlenecks in sustainability science research today [7]. Yet, there is considerable progress.

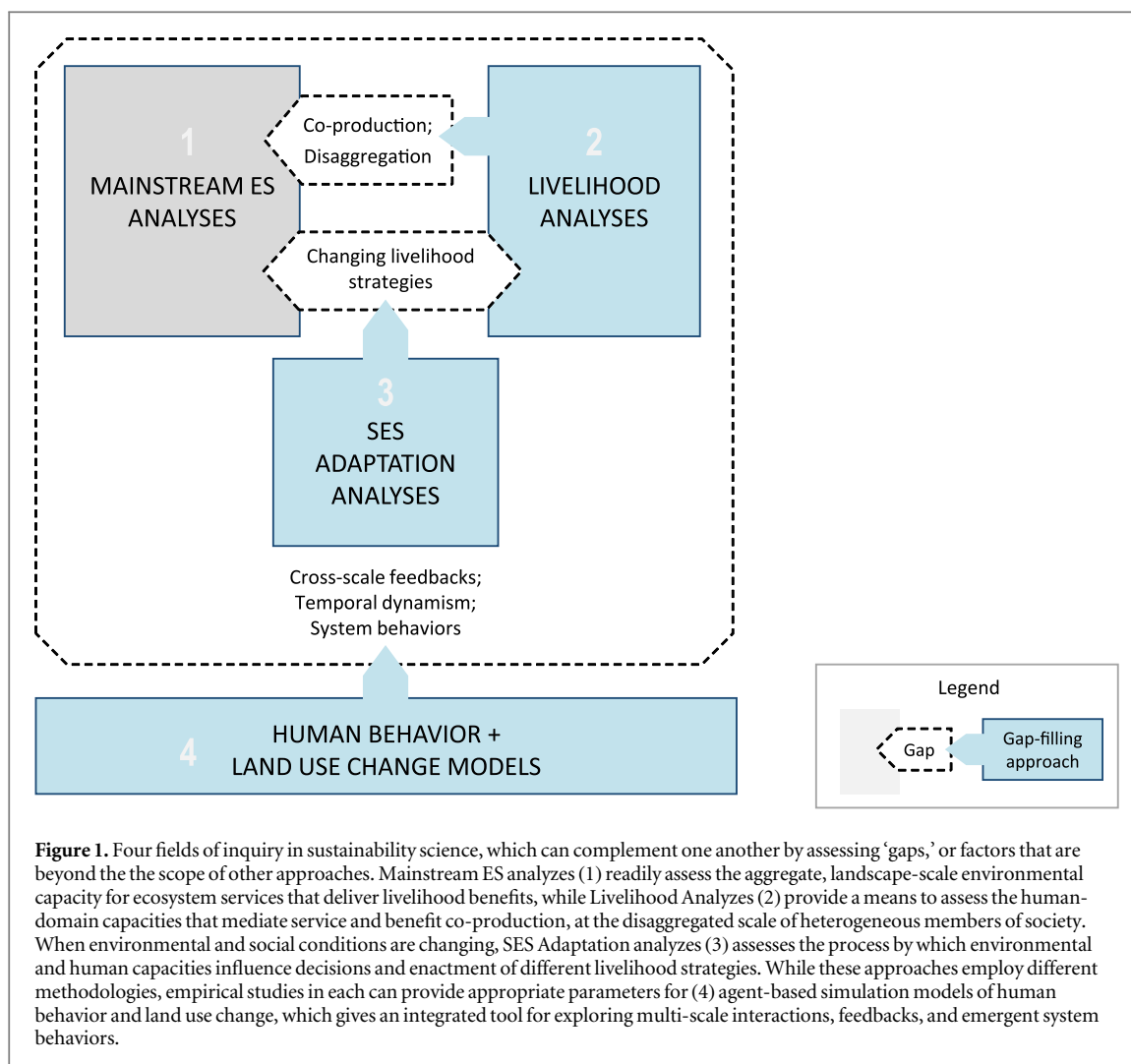
In recent decades, several research avenues have emerged within economics, ecology, earth sciences, and social sciences, which draw upon complex adaptive systems (CAS) theory as a way to represent and address complexities in SSNRD systems. CAS are a class of dynamic systems having: a sustained source of diverse components, networks of interactions among them that can generate feedbacks and cascading effects, selective forces that reinforce some components and interactions more than others, and emergent properties such as self-organization, regime shifts, and adaption [8, 9]. Studies of phenomena such as sudden collapses of ecosystems [10–12], soil degradation and desertification [13, 14], economic poverty traps [15, 16], and governance systems with entrenched inequalities [17, 18] or varying capacities to adapt [19, 20], have adopted CAS concepts and methods to generate more nuanced understandings of domain-specific complexities. These approaches and their methodologies present building blocks for a burgeoning body of studies that link different complexity-based approaches to examine the dynamic coupling of different domains [e.g. 21–26].

Several CAS principles are reflected in broader conceptual frameworks of coupled HES that provide the foundational perspective behind much of sustainability science [27–29], including whole subfields such as ecological economics [30] and resilience theory [17, 31]. Influential examples include the social-ecological systems (SES) framework proposed by Ostrom [32] and

extensions thereof [33], and the Intergovernmental Panel on Biodiversity and Ecosystem Services (IPBES) framework [34]. These frameworks typically represent couplings between system components graphically and heuristically with box-and-arrow diagrams, thereby helping to visualize cross-domain interactions, feedbacks, and dynamism. However, because these frameworks are broad, generalized abstractions, additional scholarship is required to embed more specific models to arrive at articulations that can be used as practical templates for designing and conducting interdisciplinary research [29, 35].

Thus today, we have robust and promising approaches for gaining both specific and generalized understandings of SSNRD systems, with CAS theory providing common, unifying concepts for how we represent the structures and dynamics we seek to study. A chief remaining challenge is therefore to forge linkages between multiple, complementary disciplinary research approaches, within an overarching generalized framework, in a way that can be implemented to design and conduct holistic SSNRD research in study systems of interest. Given the rapid transformation in SSNRD systems, the ability to examine *livelihood adaptation as a dynamic, contingent process* is critical for identifying otherwise overlooked barriers and potentially powerful leverage points for promoting sustainability [36, 37]. This will require an HES framework that represents locally heterogeneous human agents and environmental conditions, the interactions and feedbacks through which they change and adapt, and a way to examine emergent system-level patterns and behaviors. We introduce the Ecosystem Services—Livelihood Adaptation (ESLA) framework as a comprehensive and research-ready platform for empirical and modeling studies of livelihood adaptation, which integrates multiple CAS-inspired research approaches from different disciplines in order to embrace the complex characteristics of SSNRD and allow for integrated analyses.

We begin by introducing analytical approaches from four salient fields of inquiry in sustainability science today—ecosystem services (ES), livelihoods approach (LA), SES adaptation, and coupled human behavior-land use change (HB + LUC) modeling studies. We discuss the complementary realms of SSNRD systems they address, identify key parallels that facilitate their integration, and explain how their complementarities can bridge and fill existing gaps in order to achieve more holistic SSNRD system evaluations (overviewed in figure 1). We then present their integration in the ESLA framework, along with methodological considerations. We conclude by highlighting important sustainability and equity issues, toward which this integrated, dynamic research approach can afford new, holistic insights.



2. Current approaches, gaps, and complementarities

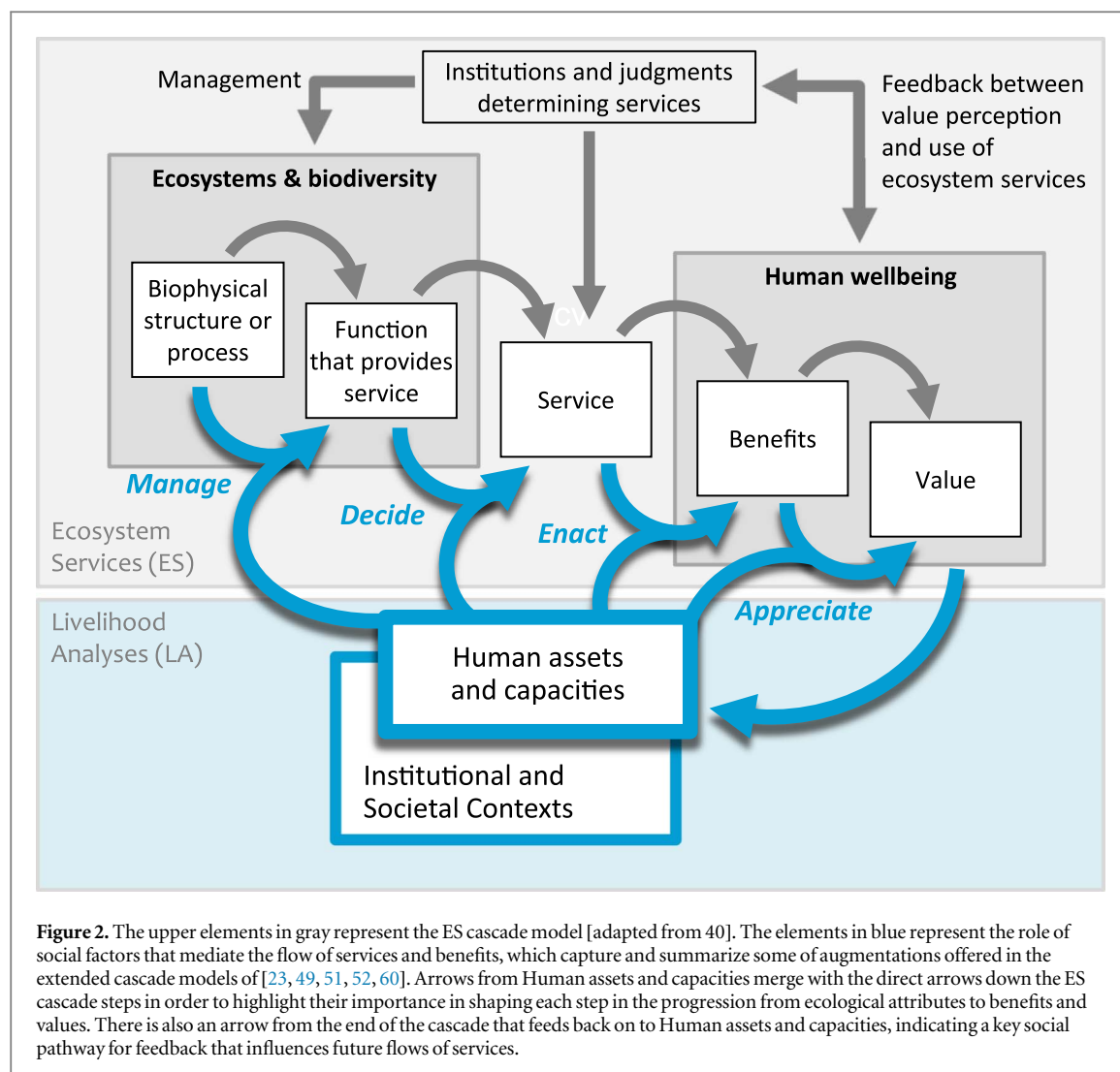
2.1. Ecosystem services

We begin with the ecosystem services approach, which has reached global prominence for describing and evaluating the interdependence of ecosystems and human well-being. The basic premise is that ecosystems and humans exist as coupled systems, in which ecosystems contain many forms of natural capital that can generate flows of goods and services that benefit people [38]. The widely employed Benefits Cascade framework for ES [39–41] defines intermediate steps on the path from natural capital to human well-being: ecological functions, services, benefits, and finally economic and non-economic values (figure 2). Despite its broad utility and impact [42, 43], the application of ES approaches in SSNRD systems has been criticized for underrepresenting key social dimensions and consequently providing faulty understandings and guidance to policy [44, 45]; two such neglected dimensions are service/benefit co-production and social heterogeneity.

Ecosystem services arise when people recognize the utility of an ecological function. Some regulating

services like forest carbon sequestration may arise directly from ecological functions [46], many regulating, provisioning and cultural services, and all benefits and values, are co-produced by people through their decisions, abilities, and actions [47–52]. Furthermore, in SSNRD systems, ES and livelihood benefits are co-produced at local scales, by individuals, households, and communities (for brevity, household is used to refer to all three local levels hereafter), among whom decisions and capacities are heterogeneous [53, 54], with inequalities arising through complex social processes and environmental feedbacks [55]. The flow of services and benefits through the ES Cascade is grossly dissimilar for different members of society. Understanding the social heterogeneity in access, capacities, preferences, and ES co-production is critical for evaluating of how costs, benefits, and tradeoffs are distributed within a SSNRD society or more broadly [56, 57], and is essential to inform policies for poverty alleviation, social justice, or reducing environmental vulnerability [52, 54, 58].

Responding to these challenges, scholars have recently expanded the Benefits Cascade framework to incorporate the roles of human, financial, and material capitals in co-producing ES [49, 59]; feedbacks



from societal rules, individual values, and well-being outcomes onto upstream steps of the cascade [60]; and heterogeneities in capital assets, livelihood activities, and political power [26, 51, 52] (figure 2). These works describe noteworthy empirical applications of integrative cascade frameworks to SSNRD case studies, and indeed revealed critical barriers and compounding inequities that would have remained invisible in mainstream ES assessments. To expand the social scope of their analyzes, these studies have drawn largely on the Livelihoods Approach.

2.2. Livelihoods approach

The Livelihoods Approach (LA) uses place-based, socially disaggregated inquiry to examine how livelihoods are constrained and enabled by people's capabilities, assets, activities, and institutional contexts [61, 62], thus it specifically addresses the identified gaps in ES research of heterogeneity and co-production. In LA, capabilities encompass tangible and intangible things that people are able to do or be, and from which one may derive a sense of well-being [63, 64]. They originate from sets of assets—typically categorized into five types of capitals—human, social,

financial, material, and natural capital. The granularity of the LA captures heterogeneity of capacities across and within communities, but also emphasizes the role of institutions and power relationships in mediating asset distribution and the way people can mobilize their capacities to pursue livelihood strategies [5, 65, 66]. This contributes to our ability to understand *which* ES are produced, *who* benefits, and how benefits depend on people's *varying capacities*.

Conceptually, LA and the ES Benefits Cascade use a similar potential-to-actualization sequence: from natural capital to actualized services and benefits in ES analysis, and from people's capacities to actualized livelihood outcomes and well-being in LA. They derive from wholly different epistemologies and research methods, but the recent interdisciplinary elaborations of the Benefits Cascade framework [49, 51, 52, 60] effectively demonstrate that LA inquiry can be linked to ES assessments in an analytically tractable way to represent the processes by which natural capitals and human capacities are mobilized and aligned to create livelihoods. A remaining limitation for SSNRD systems is that neither approach is equipped to account for social adaptation in response to environmental

change [24, 67]. This gap is addressed in SES adaptation research.

2.3. SES adaptation

In SES adaptation research, adaptation is defined as livelihood adjustments made to actual or anticipated changes in environmental conditions [68], and adaptive capacities are sets of social and material assets and the ability to mobilize them in order to adapt [69]. The focus on assets and mobilization provides overlap with livelihood studies, but adaptation research directs attention to process, change, and trajectories [24, 70], which is often outside the scope of livelihood studies [5]. Methodologically, adaptation research complements and merges with the ES and LA coupling at a more granular level. Adaptation is represented as a multi-stage process of decision-making, enactment, and outcomes. This mirrors the sequencing of the ES Benefits Cascade framework: decision-making is the process by which people identify desired services; livelihood strategy enactment is the process by which people accrue benefits from services; and outcomes encompass both the value of those benefits to meeting people's livelihood goals, and the consequences of livelihood strategies on the future condition of the system.

While merging ES and LA provides a process-based way of understanding the production of benefits and well-being, adaptation research offers the ability to evaluate those processes while contexts and livelihoods change, to identify leverage points to change trajectories, and break down path-dependent trends [71]. At a societal scale, the SES adaptation approach accounts for constraints that may limit response opportunities to help understand how to move beyond incremental change to promote more transformative adaptations [72]. The cognitive dimension of households' perceptions of environmental change, available alternatives, and their own capabilities for adaptation [73, 74] provides a valuable complement to the livelihood approach [24]. Moreover, there is conceptual space for ecological change to be incorporated as a factor influencing decisions, livelihood implementation and outcomes [75]. Together, these attributes can help pinpoint specific barriers to livelihood adaptation as they are experienced by resource users themselves.

In the past, adaptation research generally focused on proximate drivers of vulnerability to environmental change and the ability of households to undertake incremental vulnerability-reducing steps, such as engaging in irrigation in response to more arid conditions. In response to the rates and magnitude of environmental change, more recent efforts utilize adaptation research methodologies to explore household- and community-level processes of deliberate transformational change [76–78] and regime shifts [79, 80], in which there is a fundamental restructuring

of the relationships and feedbacks within system components.

2.4. Coupled human behavior—land use change (HB + LUC) models

Together, the complementarities of ES, LA, and SES adaptation studies can help us integrate empirical findings and build holistic understandings of SSNRD systems in transition. Exploring how the behavior and trajectories of a SSNRD system and its constituents would unfold, under various conditions, and different leverage points that may potentially lead to (un)desired regime shifts, is only possible with modeling and simulation. However, conventional predictive modeling paradigms are largely incompatible with the most important complexities recognized in SSNRD systems: heterogeneous actors, the contingent nature of capacities and decision-making, and the dynamic social-ecological interactions and feedbacks underpinning the process of adaptation [81].

Based on CAS principles, cellular automata and agent-based models (ABMs) simulate and track the dynamics of each individual heterogeneous agent in a system through time [82]. Agents are typically spatial grid cells in cellular automata, and individuals or organizations in ABM. As a model simulation runs, each agent's attributes and behaviors can change, depending on internal, proximal, and system-wide conditions, as specified in sets of (often probabilistic) 'rules' that simulate human decision-making processes [83, 84] or ecological dynamics [85, 86]. As they do so, agents change and adapt, and system-level patterns and behaviors emerge. The emergent attributes are typically the focus of analysis, thus ABMs are often called 'bottom-up' models, but the micro-macro level influences can be bidirectional and form feedbacks.

Unlike other modeling approaches for HES (e.g. systems dynamics modeling [87]), ABMs can readily simulate complex feedbacks for heterogeneous agents in a spatially explicit system, and are increasingly used as an exploratory tool to study social phenomena [88], ecological processes [89], and the behavior of HES systems [90, 91]. Models that couple a human behavior (HB) ABM, with a land use change (LUC) cellular automata model that tracks environmental variables in a heterogeneous landscape, have recently proliferated in the study of SSNRD systems [see 22, 84, 92–97 for reviews and discussions]. HB + LUC models are uniquely able to simulate human perceptions, decisions and behaviors at a fully disaggregated level [98, 99] and according to different theories of behavior [100], as well as adaptation as a result of dynamic feedbacks between agents and a changing environment [90, 101].

ABMs are particularly valuable for studying SSNRD systems in transition because they provide a means to study systems that have heterogeneous components and nonlinear cross-scale interactions, and

change structurally over time, without using analytical or numerical modeling to specify and generate those phenomena, which may be prohibitively complex [94, 95, 102]. One tradeoff is that, while interactions may be structurally and dynamically complex, the rules governing behavior are usually highly simplified and simulation experiments typically explore only a few variables to facilitate interpretation of simulation results [103]. Although models may generate empirically observed emergent patterns, the chosen rule set is not necessarily the only possible way those patterns could arise. Thus, ABM models generate hypotheses for why systems behaviors emerge, but do not verify those hypotheses [104]. Instead, the methodology of pattern-oriented modeling is increasingly used as a confirmatory process for rule sets and model parameterization, by comparing model outputs to multiple observed empirical patterns, which model rules cannot generate directly [105]. Because there are rarely independent predictions or replicated empirical outcomes to validate HB + LUC ABM simulation runs, they are less appropriate for generating specific quantitative predictions, but instead explore system behaviors that may rise under ranges of conditions [106]. In effect, empirical studies tend to focus on ‘what is?’ while ABM studies can be used to explore pressing, but otherwise unapproachable questions of ‘what if?’

3. The ESLA framework

The ESLA framework is a dynamic representation of livelihood adaptation and human-environmental feedbacks experienced at the household-level in SSNRD systems (figure 3). It incorporates key components and processes that ES, LA, and SES adaptation studies have shown to be pivotally important factors in livelihood adaptation, capitalizing on their complementarities to forge novel linkages and alignment among them. ESLA has heuristic value for policy and practice; it provides an organized structure for thinking about livelihood adaptation as an ongoing process, focusing attention on often-overlooked factors and heterogeneities that influence outcomes and tradeoffs for different segments of society. ESLA was developed specifically to guide complementary empirical and modeling research. It provides a generic yet operationalizable template for choosing and constructing empirical research questions in a way that permits their holistic integration. ESLA is cast at the household-level to capture the local environmental contexts and heterogeneous livelihood dynamics experienced by different members or segments of society. It is important to note that studying a whole SSNRD system entails multiple instantiations of the framework’s causal loops to describe those dynamics and conditions for different households or for different segments of society. Having this localized level of organization makes the framework directly implementable through

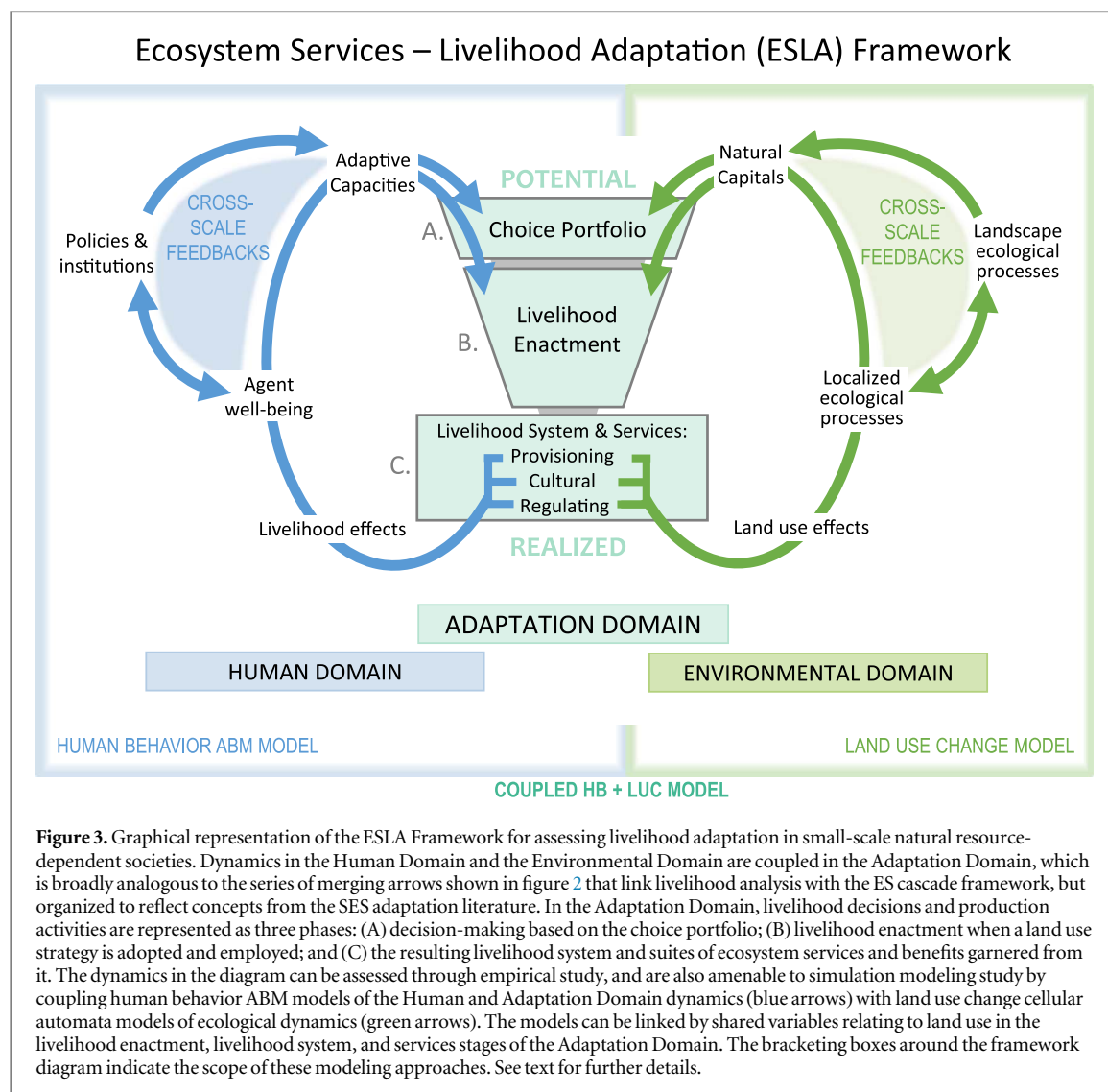
agent-based modeling using HB + LUC approaches to study dynamics at multiple levels, from highly localized to system-wide [106, 107].

The ESLA framework represents SSNRD system dynamics as a sequential process that is iterated through time, with each loop through the framework occurring on the time scale (typically seasonal or yearly) at which livelihood practices are undertaken. The Human Domain represents the variables and cross-scale interactions typically encompassed and analyzed in LA research [24, 108]. The Environmental Domain includes the capital-to-services cascade of ES frameworks, and also dynamic cross-scale feedbacks of land use onto subsequent stocks of natural capital [109], which is captured in some [e.g. 110–112] but not all ES analytical approaches [113]. The key structural novelties of the ESLA model occur as a sequential process in the Adaptation Domain, where household-level livelihood strategy decisions are made and then enacted, to co-produce services and benefits.

3.1. Adaptation domain

The Adaptation Domain is the nexus where the benefits cascade (from ES studies), the influence of capitals on service co-production (from LA studies), and sequential stages of adaptation (from SES adaptation studies) are integrated. The process begins with potentials, comprised of adaptive capacities and natural capitals accessible to a household, of which only a subset are utilized through livelihood enactment. In the first phase (figure 3(A)), households must make decisions about the type of livelihood to pursue. The term *range of choice* refers to the Universe of social and ecological potentials available within a particular population or society [114]. The ESLA framework’s *choice portfolio* describes the narrowed subset of the full range of choice, which is available to a particular household. It is limited by the individual’s specific assets and capabilities, including access to, and quality of, natural capitals. Importantly, the choice portfolio includes only potentials that people perceive as possible or desirable. Cultural, social, political, and technological contexts can change people’s perception of their own capability to adapt their livelihood strategy [24, 115]. Furthermore, possible livelihood options depend on perceiving appropriate matches between multiple environmental and human-domain capacities [116]. The interdependence of multiple forms of potentials further reduces the set of possibilities in the choice portfolio. From the winnowed choice portfolio, households make decisions as to which livelihood activities to pursue.

In the second phase (figure 3(B)), households enact their decisions, which takes place over time. The enactment process requires additional social and natural capacities to be matched and mobilized [117, 118]. For example, although pastoralists may have the financial capital to choose to switch to the



more drought-resilient practice of camel husbandry, their success and realized benefits depend on access to additional capacities during enactment, like social networks with other camel owners and veterinary knowledge [119] (see box 1). The temporal sequentiality of decision-making and enactment in ESLA emphasizes the need for policies to consider at the outset which capacities people will need to successfully navigate both stages of adaptation [56]. Policy interventions that incentivize decisions, while households lack the needed capacities to enact decisions over time, can in fact increase livelihood vulnerability [120].

In development practice, aggregate assessments of range of choice are commonly used to inform adaptation policies, with little acknowledgement that households actually experience much narrower—and unequal—choice portfolios [121–123]. For example, a rural agricultural assistance program may identify a potentially lucrative farming practice based on environmental and market conditions, yet in spite of economic subsidies offered, the targeted participants may lack other critical capacities that would enable participation, or afford success if they did (see box 2). ESLA's

Adaptation Domain disaggregates the adaptation process socially, according household capacities, and processually, by recognizing decision-making and enactment phases. This key feature of ESLA affords a much more realistic evaluation of different capacities that constrain adaptation. The heterogeneous, narrowed choice portfolios so identified can be scrutinized and compared to aggregate ranges of choice to reveal how and where inequalities arise and may be propagated or mitigated.

3.2. Outcomes and feedbacks

The livelihood system and services phase (figure 3(C)) represents the outcomes of the Adaptation Domain, where co-produced services, and their social and spatial distributions, are tracked. In the Human Domain, livelihood effects are subsequently assessed using any household-level variables that are causally influenced by the livelihood practiced, the broader mosaic of livelihood activities, and/or other services garnered. Livelihood effects feedback through the Human Domain to influence subsequent decision-making, as examined using LA. ESLA's generic

Box 1. Camel husbandry adoption in Kenyan drylands: a prospective analysis.

The Maa-speaking pastoralists of the Laikipia Plateau in north-central Kenya customarily kept mixed herds of cattle, goats and sheep for milk and meat as the basis of their livelihood system. The social-ecological system relied on herd mobility to access grazing across an extensive landscape. Over the last century, these communities have lost access to more than 90% of their customary grazing lands, resulting in increased year-round grazing pressure within the group ranches. These pressures have led to decreased forage productivity, extensive soil erosion, and shrub encroachment. Rainfall in the region has become significantly more erratic over the last 40 years, with more frequent droughts leading to devastating herd losses. Only about ¼ of households surveyed in 2009 reported that their livestock were sufficient to meet household needs [143].

Over the last 35 years, a small proportion of residents have explored camel husbandry as a potential pathway to adapt their pastoralist production system. The changes in climate and vegetation structure are increasingly favorable for camels versus customary species, and, unlike cattle and small stock, camels can provide copious milk yields even in dry seasons. For these reasons, camels may provide a more steady and sustainable stream of provisioning services given the current state of natural capital, and thus would appear to be a ‘win-win’ adaptation strategy from the perspective of ecological sustainability and benefits for human well-being. Volpato and King (2019) used the ESLA framework prospectively to design ethnographic research which sought to understand why only about 10% of households had adopted camel husbandry (figure 4) [108].

Adoption of camel husbandry is a broadly transformative livelihood change. In this tightly coupled SES, livestock care, ownership, and reciprocal exchanges are governed by, and reinforce, social and political relations within the society. Camels are not part of those exchanges, they require specialized veterinary and herd management knowledge, and novel allocations of household labor. Camels are expensive to purchase, yet present opportunities to engage in emerging animal and milk sale markets. LA studies and cognitive mapping identified the Human and Environmental Domain assets and capacities that influenced each stage of the adaptation domain, revealing that environmental conditions, purchase prices, access to cash, social connections to camel owners, and personal dislike of camels largely governed decisions to adopt camels, while the livelihood enactment challenges were largely related to husbandry knowledge and household labor. Thus, despite common access to favorable forage as natural capital, livelihood outcomes and well-being garnered from the same adaptation strategy within a single community were highly contingent on multiple additional capacities, only some of which related to financial wealth.

Already there were signs of adaptation within the system that could reduce these barriers for more households. Camels may become part of cultural livestock exchanges, many children are now growing up drinking camel milk shared with them by camel-keeping families, and social learning and labor allocation are improving herd husbandry. These findings, along with an ecohydrological ABM of vegetation dynamics [81], pave the way for further implementation of ESLA through empirical and modeling studies to address questions such as, ‘Which of these factors would accelerate the spread of camel adoption?’ and, ‘What would be the ecological consequences if all families adopted camels?’

framing of livelihood effects can thereby accommodate any criteria by which outcomes are valued, such as changes in income or other capacities, nutritional intake, relative contribution to well-being, etc.

Box 2. Castor oil production in northeast Brazil: a retrospective analysis.

The Brazilian National Program for the Production and Use of Bio-fuels was established in 2004 to stimulate demand for renewable fuels [144]. Although energy concerns were a major driver of the program, a central component was the requirement for social development and the inclusion of family farms. A key mechanism was the creation of marketing agreements between farmers and refineries in order to ensure fair pricing and a minimum market share for family farmers [145, 146]. In Brazil’s semi-arid Northeast, castor beans (*Ricinus communis* L) were promoted as the ideal biofuel crop, in part because the region has a history of castor bean production. By 2016 however, the program did not achieve its desired objectives of social inclusion, and the parastatal Petrobras began shuttering refineries in the Northeast.

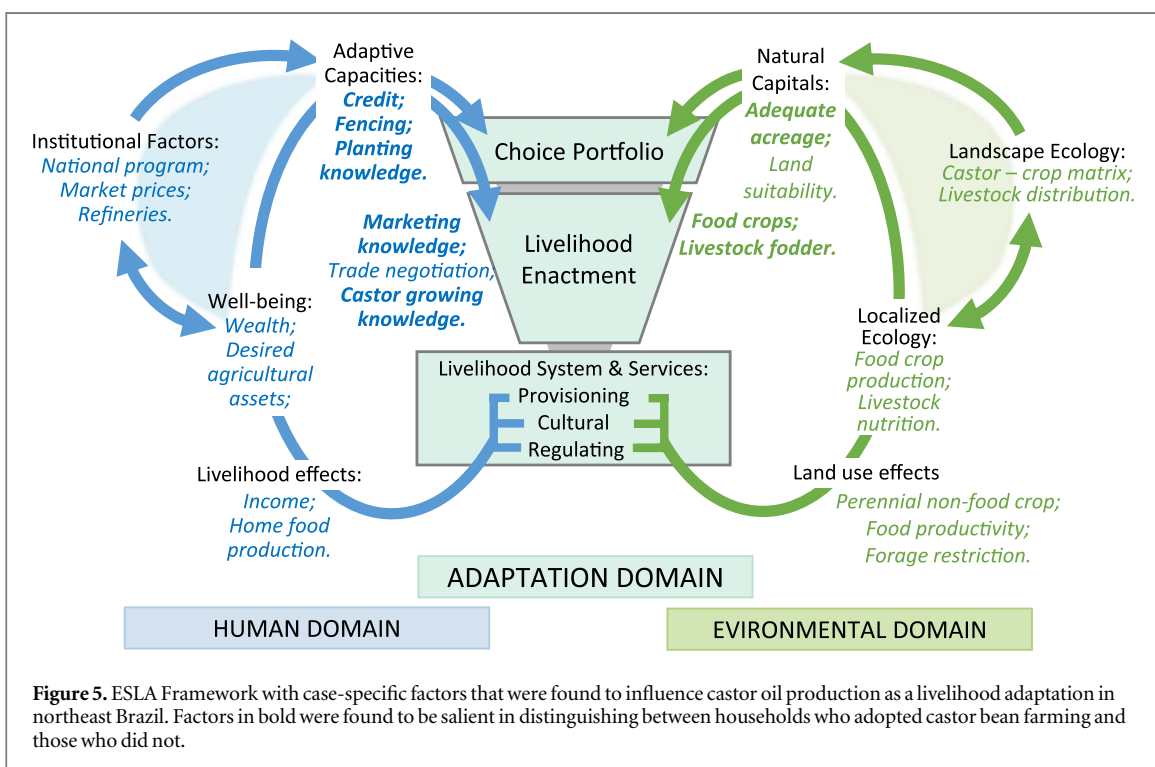
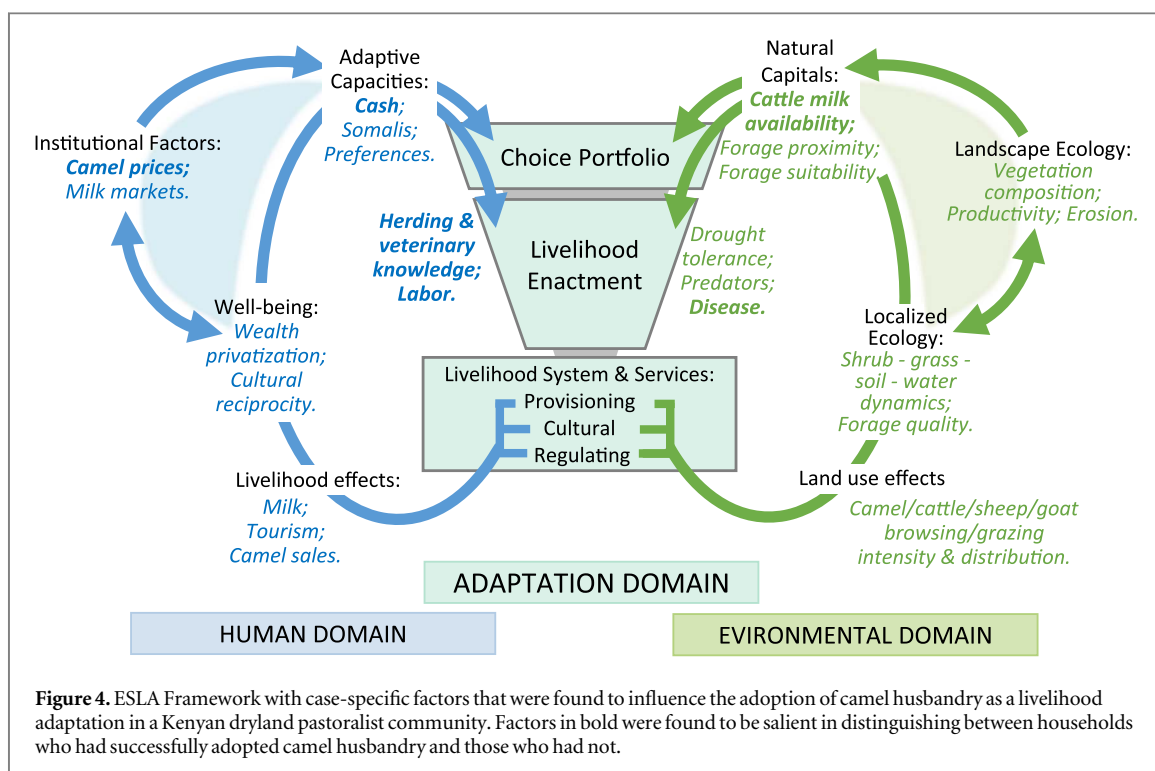
Suitability analyzes used to support the policy factored in climate, soil, and water analyzes. From a natural capital perspective, the region has significant potential for castor bean production [147]. Most analyzes of the program’s failure focus on the changing regulatory framework, a weak production chain, and low market prices [145]. These evaluations implicitly assume that if they could get the market design ‘right’, farmers would see the potential benefits, adopt castor bean production, and begin realizing the provisioning ecosystem service benefits. In addition to demand side failures, the program also had only a small impact on social inclusion and development. By retrospectively mapping the known dynamics of the program onto the ESLA framework (figure 5), it becomes evident that the failure to account for the capacities and choice portfolios of the population contributed to the limited impact of the program on the development of small scale farms [148].

Farmers derive livelihoods from a mix of strategies, including subsistence and market-oriented agriculture, livestock production, small business, off-farm employment, a federal retirement program and more recently, conditional cash transfers. Just under half of farmers are landowners and most practice low-tech agriculture [149]. To effectively adopt castor bean farming as a livelihood strategy, the decision is first predicated on producers having access to sufficient land for castor beans as well as crops and livestock to satisfy household preferences and needs, sufficient capital for fencing to keep their livestock away from toxic castor bean plants, access to credit, and knowledge of how to sow castor beans. Livelihood enactment further requires knowledge of castor bean care and replanting cycles, crop marketing knowledge and networks, and the ability to negotiate contracts with commodity brokers.

Each capacity requirement forces a winnowing of choice portfolios for many farmers, with the end result that, practically, only landowners with sufficiently large farms, additional financial capital, and multiple knowledge forms can enter into castor bean production. The program design favored individuals with particular sets of capacities and choice portfolios, and unintentionally excluded many farmers that were intended beneficiaries of the program.

An analysis of choice portfolios reveals many of the shortcomings of the project design, which was born out of a limited focus on the environmental and market-related potential to extract productive ecosystem services.

ESLA dynamically represents feedbacks from adaptation outcomes onto subsequent natural capital in the Environmental Domain. A multitude of dynamic, spatially explicit models are available to study land use change, agricultural systems, hydrological processes,



etc at various spatial scales [112, 124, 125], increasingly employing CA principles to capture nonlinearities that arise from landscape heterogeneity, connectivity, spatial flows, and cross-scale feedbacks [126–129]. For ESLA, models that track heterogeneity of environmental resources at spatial resolutions commensurate with SSNRD households' differential access to them are most appropriate. Those models that account for spatial heterogeneity, but generate aggregate estimates

of ES potentials, may not reveal the variation in access to environmental assets in households' choice portfolios.

3.3. Implementing the ESLA framework

ESLA defines general classes of variables and interactions to guide the selection of context-specific variables for analysis and integration. ESLA can be implemented prospectively to help elucidate key

variables and interactions, or retrospectively to integrate known dynamics in a given context. Box 1 illustrates a prospective implementation of ESLA in a Kenyan pastoralist SSNRD system, wherein the ESLA framework was used to design and structure empirical inquiry into the dynamics of the Human Domain and Adaptation Domain [108]. Thus far, the ESLA approach has revealed key cross-scale dynamics in the Human Domain, and also effectively teased apart decision-making, enactment, and outcomes stages in the Adaptation Domain by identifying the assets and capacities that influenced each stage. Box 2 illustrates a retrospective application of ESLA in a Brazilian dryland SSNRD system, in which the ESLA framework was used to re-evaluate existing knowledge in order to identify and explain the significance of household-level adaptive capacities in a failed agricultural development policy.

Specific variables and interactions for a given context should reflect what is expected to matter most to the behavior of the system as well as to stakeholders, thereby increasing both research relevance and legitimacy [130]. Participatory engagement, concept mapping, and co-production of the research agenda, particularly with a diversity of SSNRD livelihood practitioners, can help researchers build the pluralistic understanding necessary to achieve this dual aim [131, 132]. Building cross-disciplinary understanding among contributing researchers in the specification process is equally important for meaningful integration [133, 134].

Empirical research to explore selected dynamics can employ established qualitative and quantitative methods from ES, LA, and SES adaptation research, with the salient requisite to address social and environmental heterogeneities. Empirical research typically considers more variables and relationships than is practical or desirable to include in an ABM [95]. Yet simulation modeling is a useful complement because it can explore a broader range of values and hypothetical conditions involving a subset of key variables, beyond what may be present in the system. Within ESLA-based modeling, empirical research and theoretical questions should guide the formulation of research questions around a subset of interesting interactions that can be explored through simulation experiments. For developing an ABM of human decision-making to simulate the adaptation domain, qualitative research is especially useful for understanding how motivations, perceived capacities and constraints affect livelihood decisions and outcomes [135, 136], while well-being effects and feedbacks may involve quantitative as well as qualitative methods [84, 137]. Qualitative and quantitative assessments can be merged used to construct cognitive maps [138, 139], decision trees [140], or Bayesian belief networks [141], from which ABM decision rules can be derived [142] to simulate the successive phases of the adaption domain. Sequential rules that depend on different sets

of conditions and capacities are typically complex relative to existing HB + LUC models, yet capturing this complexity is central to ESLA's premise that heterogeneous livelihood outcomes are often rooted—yet undetected—in heterogeneous choice portfolios.

There is an inevitable tradeoff between developing a framework that is methodologically easy to implement, and the ability of that framework to represent complex cross-scale and cross-domain dynamics and feedbacks in a SES in transition. We argue that achieving the latter necessitates a synthesis of methods, which is, by its nature, challenging. However, because ESLA combines approaches with established research methodologies already used in sustainability research, ESLA is feasible to implement and logically robust, though admittedly challenging because the contributing methods in themselves are quite sophisticated analytical approaches.

4. Discussion and conclusion

4.1. The elusive connection between natural capital, ecosystem services, and well-being

The notion that enhancing natural capital will enhance human well-being was an early argument in the history of the ES concept, based on the general idea that we all depend on Earth's life support systems, and they contribute to our aggregate well-being [47, 50]. This is a sound supposition for those services that can be classified as public goods, such as atmospheric regulation. When services and benefits are rivalrous, or locally co-produced according to beneficiaries' capacities, or when they contribute variably to different people's livelihoods, conserving or enhancing natural capital does not necessarily enhance well-being for everyone [55, 56]. This is a major source of discrepancy between well-intentioned interventions and the realities that materialize for rural poor [54, 150]. Integrated, disaggregated approaches are needed to assess the connection between conserving natural capital and enhancing human well-being [50, 151], and its contingencies on capacities and stages of co-production [52].

4.2. Reflexivity and responsibility

Researchers whose work informs policy are also co-producers of ES benefits and livelihoods; their motivations and values affect the choice portfolios of SSNRD households via the options and incentives they choose to analyze and the findings they make available to policymakers [152]. ESLA permits, and the authors encourage, the explicit evaluation of the system-level effects of prioritizing different research questions and policymaking values. For instance, ESLA-based analyzes and modeling can ask, 'Which livelihood options do residents identify as the most *culturally appropriate* and *desirable*', 'What are the *most environmentally sustainable* livelihood options?' and can also ask, 'What

livelihood adaptations are likely to generate the *most equitable* outcomes under the broadest range of possible future conditions? Researchers should recognize that their own choices of research questions and methodologies are normative. When their findings influence available knowledge, policy, and narratives, they can have real tangible implications for creating or limiting equity and justice in the systems they study [52]. Thus an important reflexive question that researchers should consider is, ‘Which segments of society will be most impacted by the options we chose to explore?’ As knowledge producers and brokers, researchers are also not external to the power dynamics in SSNRD systems in transition. Co-producing the orientation of research questions with SSNRD households themselves is a way to responsibly share that power. Seeking out and eliciting the diversity of objectives and values held by different rural households as well as policymakers, and also reflecting on how and why they differ from researchers’ preconceptions, can be a revelatory and trajectory-shifting experience for researchers as well [153, 154].

4.3. Equity in sustainable development

Promoting a resilient planet and addressing rising inequities are two key challenges of sustainability science [144] and the Sustainable Development Goals of Agenda 2030 [2]. While much of the attention is focused the global and national levels, CAS theory makes clear that sustainability and equity are emergent outcomes of multi-scalar processes, with localized dynamics being of particular importance in SSNRD systems. ESLA provides the space to derive empirically-informed models and conduct controlled simulation experiments that get to the heart of fundamental equity-sustainability questions in SSNRD. For example: What is the relationship between equitable distribution of resources and sustainability? Are SSNRD systems more resilient when they are more equitable? Does equity in resource access between households lead to more sustainable landscapes, or is diversity in household-level assets a more important characteristic for sustainability? Which environmental, social, or decision-related factors are most influential in modulating equity in an SSNRD system? What kinds of pro-poor interventions are likely to become self-reinforcing and thus lead to sustained improvements in equity? Despite the tremendous advances in complexity-based studies of HES, we do not know the answers to those questions. ESLA offers a tool for making further progress by complementing place-based research with modeling studies of system behaviors.

As the Sustainable Development Goals seek to enhance multiple benefits that people derive from nature, we must contend with the challenge of aggregate tradeoffs between goals, and there are increasingly productive research approaches for doing

so [155, 156]. But we must also contend with the implications of those tradeoffs in terms of equity [157]. Today we see rapid methodological advances emerging in this arena [51, 52, 60, 121, 151, 158–160], and the ESLA framework advances this critical endeavor by combining existing strengths, embracing dynamism, facilitating coupled empirical-modeling research, and adopting a bottom-up approach that recognizes that in SSNRD systems, sustainability and equity ultimately depend on the way that individuals, households and communities experience and navigate the challenges of livelihood adaptation.

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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