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Reframing the payments for ecosystem services framework in a coupled human and natural systems context: strengthening the integration between ecological and human dimensions

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ABSTRACT

Introduction: As challenges to biodiversity mount, land-use policies have been implemented to balance human needs and the integrity of ecological systems. One such program, Payments for Ecosystem Services (PES), incentivizes resource users to protect ecosystem services and has been implemented around the world to reduce soil erosion, create or improve wildlife habitats, and improve water quality and other environmental goals. The PES policy, at its core, is a concept that aims to capture the reciprocal relationships between human systems and ecological function and process. As such, PES epistemologically embodies a coupled human and natural systems approach.

Outcomes: Yet, despite this conceptual alignment, the on-the-ground implementation or evaluation of PES typically does not adopt this coupled approach and PES programs have little integration between socioeconomic, sociocultural, human demographic, and ecological elements. To advance the evolution of PES, we consider what and how socioeconomic and ecological factors have been incorporated into PES program implementation and evaluation. We also present a conceptual model to articulate how PES research can capture the reciprocal relationships among socioeconomic, demography, and ecology and discuss the quantitative modeling approaches that can support this conceptual development, i.e., structural equation and agent-based modeling, and latent trajectory models.

Conclusions: By strengthening the conceptual framework for PES within a coupled human and natural systems approach and identifying analytical approaches that can be used to quantify and characterize these complex cross-disciplinary relationships, we aim to support the evolution and advancement of PES, in service of more meaningful and positive outcomes for human well-being and ecological sustainability.

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Agent-based modeling; disciplinary integration; ecological responses; human socioeconomics; latent trajectory models; structural equation modeling

Introduction

Ecosystems and their corresponding services are degrading worldwide at an unprecedented manner (Ferraro and Kiss 2002). Ecosystem services, defined as positive benefits, direct or indirect, that wild organisms or ecosystems provide to people, have been identified as necessary for human survival and well-being (MA 2005; Harrison et al. 2010). In response to widespread environmental degradation, governments, private sector, and other actors have allocated billions of dollars to programs which provide payments to protect ecosystem services, termed payments for ecosystem services (PES) programs. PES programs provide incentives directly to resource users that engage in environmentally desirable actions or to refrain from undesirable actions to bolster ecosystem services, which are typically categorized as provisioning, regulating, supporting, or sociocultural services (Ferraro and Kiss 2002; Wunder 2007). Most PES programs are geared to improve provisioning (e.g., timber) or regulating (e.g., air or water quality) services.

PES programs have been adopted in many countries as a response to many critical global environmental challenges. For example, climate-smart PES programs have been established to reduce carbon emissions from deforestation and forest degradation through carbon market mechanisms (Kanninen et al. 2007). In the United States, PES has also been implemented through the Conservation Reserve Program to reduce agriculture-induced soil erosion, create wildlife habitats, improve habitat quality, control crop supply, and transfer income to farmers (Smith 1995; Johnson, Misra, and Ervin 1997), with farmers receiving conservation payments for converting highly erodible or environmentally sensitive cropland to grass, woodland, or other conservation uses. Several other countries have also implemented ambitious PES programs, such as the Permanent Cover Program in Canada and the conservation payment programs in European Union countries in the 1990s (OECD 1997). PES has also been adopted in developing countries, including

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Mexico, Costa Rica, Nepal, and China (Miteva, Pattanayak, and Ferraro 2012). One of the largest national PES programs is China's Grain-to-Green program (GTGP). GTGP, which aims to reduce soil erosion and increase vegetation cover through tree planting in steep farmland areas where farmers are compensated through cash, wheat or rice (Bennet 2008; Liu et al. 2008) was first implemented in 1999 and, in 2008, was extended for another cycle (Liu and Diamond 2005).

PES programs aim to reduce human impacts on ecosystems by changing human behavior in consideration of the corresponding socioeconomic, demographic, and cultural conditions (Zbinden and Lee 2005; Wunder 2008). Given this structure, PES is, at its core, a concept that captures the reciprocal (i.e., bidirectional) relationships between human activities and ecological function and processes. As such, PES epistemologically adopts an approach of coupled human and natural systems (CHANS; Liu et al. 2007). Yet, despite the interdisciplinary and coupled nature of the PES concept, the systematic integration of human and ecological processes in PES-related research or program evaluation remains limited (Brouwer, Tesfaye, and Pauw 2011; Scullion et al. 2011; Miteva, Pattanayak, and Ferraro 2012). Some of these gaps in cross-disciplinary integration are likely the result of the genesis of PES. At its inception, PES was largely viewed as an economic construct (Farley and Costanza 2010) and early descriptions of PES by Engel, Pagiola, and Wunder (2008) prioritized the economic efficiency and ecosystem services of PES largely within a market model. More recent descriptions of PES (Muradian et al. 2010) have broadened to include ecological sustainability, both in a market and nonmarket context.

Another challenge to an integrated or CHANS approach in PES programs is that the underlying framework assumes a positive relationship between ecosystem quality and human economic or sociocultural well-being. This conceptual foundation has received considerable attention in the broader ecosystem services literature (Balvanera et al. 2014; Schröter et al. 2014; Harrison et al. 2014), with the criticism that many studies that relate human well-being to ecological changes are typically correlational, lacking direct empirical evidence (Mertz et al. 2007; McNally, Uchida, and Gold 2011; de Groot et al. 2010). Ecosystems can be assessed by many metrics, including metrics that measure ecosystem function, process, or composition. To date, most empirical ecosystem services research has focused on the links between changes in ecosystem composition, i.e., species richness, and ecosystem services (Balvanera et al. 2016). Even within this limited scope, the relationship between ecosystem services and ecosystems composition is complex (Cardinale et al. 2012; Harrison et al.

2014; Balvanera et al. 2016; Daw et al. 2016). In some systems, at shorter time scales, metrics of human well-being have increased as environmental conditions have degraded (Raudsepp-Hearne, Peterson, and Bennett 2010). Ecosystem disservice describes an inverse relationship in which an improved ecological process or function harms local people (Woodroffe, Thirgood, and Rabinowitz 2005). The term ecosystem service elasticity (Daw et al. 2016) has been used to describe the complex relationship between human well-being and different ecosystem metrics, complexity affirmed by recent research (Schröter et al. 2014; Harrison et al. 2014; Balvanera et al. 2014).

Nonetheless, in light of the pressing challenges to global ecosystems, the need for sustainability policies and strategies that support both human well-being and ecological viability is paramount. While PES policies have been identified as a solution to balancing human and ecological priorities, long-term, sustainable improvement of ecosystem features and of social and economic benefits from PES programs has not been clearly demonstrated in all but a few cases (McMaster and Davis 2001; Sierra and Russman 2006; Asquith, Vargas, and Wunder 2008). In this paper, we consider what and how socioeconomic and ecological system elements have been incorporated into PES program evaluation to consider the extent to which current PES research captures the reciprocal relationships between the sociocultural or economic and ecological dimensions. Through this review, we identify areas where and how stronger connections or bridges can be made between largely disparate disciplinary approaches to PES research.

Socioeconomics of PES

What socioeconomic factors are considered in PES?

PES schemes aim to affect change in human behavior and patterns of resource use by providing economic incentives to encourage compliance with resource regulations that reduce human impacts on ecosystems. A wide range of factors are often considered in PES program development and implementation including income sources and levels (Cooper and Osborn 1998; Chen et al. 2009b), land productivity (Zbinden and Lee 2005), alternative livelihoods (Cooper and Osborn 1998), distance from household to land enrolled in the program, land plot slope, age of contract holders, household labor supply, and social norms (Chen et al. 2009a, 2009b). The existence of a PES program, itself, may affect socioeconomic factors. For instance, China's Natural Forest Conservation Program (NFCP) has substantially reduced fuelwood consumption of PES participants (Chen et al. 2014). In addition to the direct impact of PES on the contracted land, PES may also indirectly

affect land-use decisions in larger areas due to increased regulations, changed social norms, and alternative opportunities to produce spillover effects or lead to increased degradation elsewhere to produce leakage effects when harmful human actions are moved to places not under contracts (Andam et al. 2008).

How have social and economic factors responded to PES programs?

Evaluation of the effects of PES on human livelihoods is an ongoing, active field of research. PES effects are often nonuniform, i.e., different for different PES participants and beneficiaries (Daw et al. 2011). PES socioeconomic or cultural effects are also context-dependent, influenced by factors such as social relationships, institutional arrangements, property rights, capabilities, and various capitals (Pagiola, Arcenas, and Platais 2005; Zilberman, Lipper, and McCarthy 2008). However, empirically-based quantitative evaluations of the socioeconomic benefits of PES programs remain rare in the literature.

Studies on the impacts of PES on human livelihoods have mainly focused on poverty alleviation (Pattanayak, Wunder, and Ferraro 2010), which is partially because environmentally significant land often coincides in areas of poverty (Wunder 2008). Although poor landholders may not have extensive human, financial, or technical capitals, poor landholders are often able to participate in PES because they have eligible land and property rights for compliance to PES contracts (Pagiola, Arcenas, and Platais 2005). Because poor landholders often have lower opportunity costs, they tend to receive higher economic benefits in PES programs with a flat payment scheme. However, in PES programs where the payment rate is determined in competitive auctions, poor landholders often bid less, resulting in less economic gains than others. Further, the impacts of PES on the poor can also be quite different due to heterogeneities in the size of land holdings (which determines the transactional costs of PES) and wealth (which is correlated to the capitals and techniques) among poor landholders (Zilberman, Lipper, and McCarthy 2008). In general, the efforts on monitoring PES impacts are largely focused on supporting compliance rather than sanctioning non-compliance as sanctions can be politically and logistically costly especially for government-coordinated PES programs (Pattanayak, Wunder, and Ferraro 2010).

PES has been found to have mixed impacts on the economy of local stakeholders. On one hand, many logging-related jobs may be terminated due to the implementation of PES programs (e.g., NFCP). On the other hand, PES may create new employment opportunities in artificial tree plantation (e.g.,

Costa Rica's Environmental Services Payment program), park guards, tourism development, and monitoring for compliance to PES contracts, leading to more stable and diversified incomes (Grieg-Gran, Porras, and Wunder 2005). In a few Latin American cases, studies have found that PES has increased small landholders' land-tenure security as property rights are often required for PES participation and increased human and social capitals from improved internal organization for PES implementation (Grieg-Gran, Porras, and Wunder 2005). PES may also have impacts on land and labor market when the land is contracted to PES programs and labor is released from agricultural sectors (Wunder 2008). Conservation payments from China's GTGP have facilitated the shifting of rural labor from agricultural sector to off-farm employment in urban regions (Uchida, Rozelle, and Xu 2009). Further, food security has been a concern for PES programs that remove land from agriculture; however, this concern is also context dependent. A study on China's GTGP suggested that food security has not been significantly compromised by the PES program because most of the lands that have been enrolled in the program are marginal land with low yield of crops (Xu et al. 2006).

Ecology of PES

What ecological factors are considered in PES?

The PES framework assumes that the relationship between ecosystem services and ecological responses is a positive one – e.g., improved forest cover or increased species richness would lead to improved services. While the broader field of ecosystem services research considers an extremely wide range of ecosystem services (e.g., Figure 3 in Harrison et al. 2014), within the PES realm, the most commonly measured ecosystem service in PES programs is land use and land cover (LULC). LULC measures floristic changes, primarily in vegetation structure rather than composition, most often of forests, and can often be measured using remotely sensed satellite imagery. Satellite remote sensing provides a tractable means to analyze change in forest cover over broad scales and several modeling approaches to estimating the fraction of forest cover based on Landsat multispectral imagery have been tested and implemented (e.g., Asner et al. 2005; Rogan et al. 2008; Hansen et al. 2013). These approaches primarily fall within the categories of image classification (cover interval classes), spectral mixture analysis, and continuous value machine-learning routines. Far fewer PES programs and program evaluations have included faunal as well as more detailed floral responses to PES programs (but see Liu et al. 2008; Tuanmu et al. 2016). Few studies consider cover quality, structural

complexity, and vegetation or other associated faunal characteristics (Tuanmu et al. 2016).

How have ecological factors responded to PES programs?

PES programs typically evaluate and report program performance based on the level of program participation, or actions or behaviors of program participants, e.g., cessation of logging, acres left fallow, or number of trees planted. When ecological results or outcomes of PES programs are included, LULC is reported (Miteva, Pattanayak, and Ferraro 2012; Kroeger 2013). For example, in a review of primary literature on nine PES programs in Costa Rica and Mexico (see Table 3 in Miteva, Pattanayak, and Ferraro 2012), the authors find that LULC is the only ecological parameter or outcome monitored for the PES programs. Other PES meta-analyses have drawn similar conclusions. Brouwer, Tesfaye, and Pauw (2011) found that quantitative, empirical information on environmental performance of existing PES schemes was lacking and that quantitative data on environmental objectives were reported by less than 50% of the PES programs reviewed. Scullion et al. (2011) concluded that evidence of environmental benefits from PES programs remains limited. Even the relationship with LULC is nonuniform. For example, an increase in forest area and LULC was not found to lead to an increase in ecological performance (Hall et al. 2012), in part because an increase in forest cover can lead to lower species richness, particularly if a monoculture is being planted. The need for more ecologically relevant metrics has been flagged as a key ingredient to PES program development (Yin et al. 2013). Several authors have suggested other ecological variables or indicators of interest to monitor, including spatial configuration or connectivity of the landscape, structural complexity, faunal responses, changes to physical soil properties or erosion (Liu et al. 2008; Liu and Yang 2013; Tuanmu et al. 2016). This can include documenting changes in abundance, distribution, or occupancy of umbrella or indicator species (Liu and Yang 2013), capturing changes in floral or faunal species richness (Tuanmu et al. 2016) as well as the structural complexity and connectivity of the landscape (Zheng et al. 2013).

PES as a CHANS construct – continuing the evolution of the PES framework

The PES literature continues to track PES program participation and the impacts on human socioeconomics and demography to evaluate the ability of PES programs to lead to permanent and positive changes in environmental and human conditions, i.e., assessing the sustainability of PES programs. However, these efforts have not led to an in-depth

understanding of reciprocal linkages (i.e., bidirectional) between PES and the associated human–natural systems over space and time. Nor has this research answered a key question: how do changes in the social and economic variable(s) of interest lead to changes in ecological responses and vice versa? To answer this question, the PES community will need to consider feedback loops and complex, dynamic reciprocal relationships that change over space and time and often give rise to emergent properties at macro-spatial or temporal scales, an approach that is captured by the CHANS construct.

The CHANS framework

The CHANS framework is largely equivalent to the similarly titled social–ecological systems (Ostrom 2009), human–environment systems (Turner et al. 2003), or social–environmental systems (Eakin and Luers 2006). Despite their many different contexts and settings, CHANS have been found to share common complex phenomena. For instance, a comparative analysis of CHANS systems (Liu et al. 2007) revealed analogous complex features (e.g., feedback, nonlinearity and thresholds, heterogeneity, time lags) in six CHANS systems across the globe. Study of other CHANS systems in the Amazon (Malanson, Zeng, and Walsh 2006a, 2006b), southern Yucatán (Manson 2005), Wolong Nature Reserve of China (An et al. 2005, 2006), and Northern Ecuador (Walsh et al. 2008) has identified similar features. CHANS research also adopts multi-scalar and cross-disciplinary approaches (e.g., Bian 1997; Phillips 1999; Walsh et al. 1999; Manson 2008).

The CHANS framework has a large part of its intellectual origin in complexity science. Originating, in part, from general systems theory (von Bertalanffy 1968; Warren, Franklin, and Streeter 1998), the study of complex systems focuses on heterogeneous subsystems, autonomous entities, nonlinear relationships, and multiple interactions such as feedback, learning, and adaptation (Arthur 1999; Axelrod and Cohen 1999; Manson 2001; Crawford et al. 2005; Levin et al. 2013). Complexity can be manifested or measured in many forms, including path-dependence, self-organization, difficulty of prediction, and emergence of qualities not analytically tractable from system components and their attributes alone (Manson 2001; Bankes 2002; An et al. 2014; National Research Council 2014).

Application of the CHANS framework in PES research

The CHANS framework recognizes the coupled nature of human and natural systems with consideration of many complexity features (Liu et al. 2007; An 2012; An et al. 2014). The CHANS framework reinforces a complex systems approach that has the

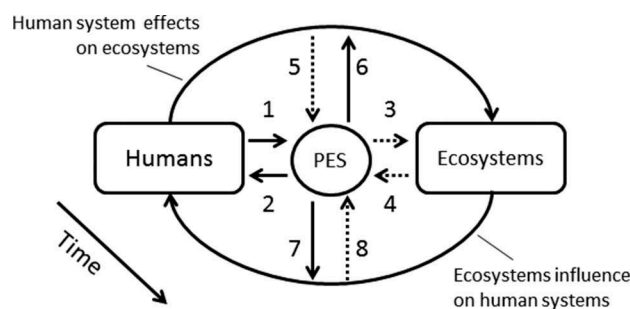
capacity to synthesize and integrate data and models from various disciplines, scale up findings across spatial and temporal scales through approaches including interpolation or extrapolation, and simulate emergent systems dynamics that are difficult to obtain through empirical studies alone. Conceptually, PES embodies the CHANS construct by the very nature of its design. However, in practice, more meaningful integrations of socioeconomic and ecological factors are needed to answer critical questions that are integral to PES evaluation, e.g., how does human demography change as a function of ecological responses and how do changes in human activity affect ecological structure, function, and process? To date, relatively little attention has been paid to the complex interrelationships among PES components: human livelihood decisions, socioeconomic status and changing demographics, and the associated ecological responses.

To what can we attribute the lack of integration among the socioeconomic and ecological elements within PES research and literature? We posit that the lack of integration is due, largely, to the fact that coupled human–natural systems have mostly been studied separately, and many of the existing analytical methods are disciplinary and less suited to cross-disciplinary explorations (An 2012). Despite numerous and repeated calls for meaningful integration of human and natural elements in coupled complex systems (Ostrom 2007), the PES literature, as with other related areas of study, remains largely

canalized between natural and social sciences. The absence of ecological factors or processes within the PES research has been found to stem, in part, from the lack of interdisciplinary dialogue (Vogt et al. 2015). A history of division between natural and social sciences, along with postulated unidirectional exploration of connections between natural and human systems, has hindered understanding of complexity in CHANS (Liu et al. 2007; An 2012). Another notable challenge to engaging in or catalyzing trans-disciplinary PES research is the need for a robust and multifaceted data set that captures sociocultural, demographic, economic, and ecological data. Although beyond the scope of this paper, this topic is explored in recent literature (Leavey 2016) and warrants attention.

To support the continued evolution of the CHANS concept in PES and continued or improved efficacy of PES programs, a more direct integration of socioeconomic and ecological responses is imperative. In this context, we propose a new CHANS-based framework for PES research (Figure 1).

This illustration captures the human and ecological subsystems (rectangular boxes) and the reciprocal linkages that connect each subsystem, denoted by the two curved arrows that link from humans to ecosystems (top) and ecosystems to humans (bottom). Considerable literature has documented how humans, i.e., through various resource extraction or land-use actions, have affected corresponding ecosystem features and processes, e.g., land cover, forest



Line #	Describes the relationship between
1	Demographic and other human systems effects on PES program
2	PES effects on human systems
3	PES affect change in ecosystem structure, function /process or composition
4	Ecosystem features change PES implementation, compliance or success
5	Changes to PES program based on human effects on ecosystems
6	PES program influences how human systems affect ecosystems
7	PES program changes how ecosystems influence human systems
8	Ecosystem influence on human system affects PES program

Figure 1. An illustration of a CHANS framework for PES research. Solid arrows represent recognized impacts, while dotted arrows represent unstudied or understudied relationships. The legend provides a description of the reciprocal relationships among PES programs, human systems, and ecosystems. The diagonal time line captures the temporal dimension which is essential in PES research as all elements in this CHANS will change and evolve over time. Lines shown here can include nonlinear, synergistic, or lagged effects that may occur on different temporal and spatial scales.

composition, soil erosion, and biodiversity (e.g., Matson et al. 1997; Vitousek et al. 1997; Tschardt et al. 2005; Johnson, Edwards, and Erhardt 2007; Kadafa 2012; Nakayama and Shankman 2013). Another body of literature, although less populated, has documented the opposite relationship of how changes in ecosystem features have influenced socioeconomic parameters (e.g., Schuster and Highland 2007; Antwi-Agyei et al. 2012; Dikgang and Muchapondwa 2012).

When PES programs are implemented, i.e., oval in the center of Figure 1, the programs first directly affect and are affected by the human subsystem as represented by lines 1 and 2. In this model, the human subsystem refers to local people or communities that reside in the CHANS system, as opposed to policy makers or government agencies. Numerous studies have documented demographic factors that impact PES participation (Chen et al. 2009a, 2009b), and how local people's well-being or demographics may change due to PES (Grieg-Gran, Porras, and Wunder 2005; Pattanayak, Wunder, and Ferraro 2010). PES programs also directly affect and are affected by, ecosystems. These relationships are represented by dotted lines 3 and 4 as they are less studied or poorly understood. The line that links PES to ecosystems (line 3) is not meant to imply that a PES program would directly alter ecosystem structure or function without going through humans. What we emphasize here is the often longer term, nonlinear, or lagged ecological processes or interactions (e.g., succession, prey–predator relationships, and biological competition) induced or triggered by the PES program that are related to human actions. Likewise, the relationship that links ecosystems to PES (line 4) has also been rarely studied, i.e., how changes in species richness or ecological structural or compositional complexity have influenced PES program development, implementation, or effectiveness.

PES programs likely change, and are changed, by the way that humans affect ecosystems (lines 5 and 6), although these relationships are also not well studied and understood. Ongoing research at two protected areas in China is addressing this knowledge gap. For instance, indigenous people in Wolong Nature Reserve and Fanjingshan National Nature Reserve traditionally extract fuelwood and medicinal plants directly from the reserves (An et al. 2005; Wandersee et al. 2012). With the implementation of the aforementioned PES programs, NFCP, and GTGP, local people have changed resource use patterns, illustrating how PES may affect the way humans make use of or rely on local ecosystems, represented by line 6. In Wolong, local people reduced the amount of fuelwood extracted from local forests after NFCP initiation (Chen et al. 2014; Tuanmu et al. 2016). Household

surveys in 2014 and 2015 in Fanjingshan suggest that local villagers made fewer forest visits for mushroom and medicinal plant collection post-PES initiation (An et al. unpublished data). Some households which received direct income from PES invested the money on public infrastructure (e.g., road construction). These changes in resource use and income may, in turn, affect ecosystems (the top curved arrow) which can have substantial influence on PES program success (line 5).

Likewise, we expect that PES programs would change, and be changed by, the bottom curved arrow which represents how ecosystems changes affect humans. For example, more widespread availability of primary forest post-PES implementation at Fanjingshan might account for the reported decline in medicinal herb extraction, found in the understory layer of primary canopy forests. Since GTGP implementation, local people tend to spend income and associated time from PES participation on other more lucrative, less financially tenuous activities such as running local businesses (e.g., restaurant, hotel). This example shows that the PES programs at Fanjingshan may trigger local people to shift from more resource-dependent to a more market-dependent lifestyle.

Methodological applications of the CHANS framework for PES

Developing an integrated CHANS framework for PES is more than a change in a conceptual paradigm. Adopting a CHANS framework, along with its complex systems approach, will allow PES programs to continue to develop conceptually and in practice. The current gaps in the CHANS framework for PES also highlight the need for more advanced analytical approaches. As Figure 1 depicts, PES includes various looped or coupled processes, where factors affect or are affected by one another and each could be a driver and a consequence simultaneously or at different stages. Traditional regression-based approaches, where dependent and independent variables are easily identifiable, may not adequately address a complex system of this nature. One modeling approach that has been used to address complex system analyses is called structural equation modeling (SEM). SEM is widely used in the social sciences to study complex interdependent relationships between different latent variables, often represented as various paths, such as the ones as shown in Figure 1. SEM uniquely estimates coefficients of various causal relationships (paths) by choosing the most fitted model whose estimated covariance structure best match the empirical covariance matrices (An et al. 2003; Bollen and Curran 2006; Weeks et al. 2004; Santibáñez-Andrade et al. 2015).

When developing conservation strategies for the forests of the Magdalena river basin in Mexico City, Santibáñez-Andrade et al. (2015) applied SEM to evaluate complex relationships among ecosystem composition, structure, and function (measures of the current quality and quantity of natural resources, stressors from human activities, such as presence of rubbish, grazing, visitors, and fire, and environmental measures, e.g., relative humidity, environmental temperature, soil temperature, altitude, and slope). With data from 75 plots of 25 × 25 m at Magdalena river basin, they explore the relationship among coupled factors. Their SEM analyses suggest that plant regeneration, a measure of ecosystem function, is only significantly predicted by human activities, rather than other ecosystem metrics or abiotic factors indicators.

A second methodology that can support a complex systems approach is digital simulation models. One such simulation approach is agent-based modeling (ABM). ABM is an object-oriented program that represents all related entities and subsystems as agents at various, often hierarchical levels. Model components, including agents, follow flexible rules to mimic complex and often nonlinear relationships and interactions. ABM approaches have been used to understand system structure and function and can support the development of relevant actions to effectively manage complex systems (Axelrod and Cohen 1999). For example, local households or individual people can be modeled as spatially explicit agents at specific locations with associated behaviors at/near ecosystems, which in turn can be modeled as a dynamic, updatable, pixelized world. All the resource or land-use activities (e.g., farming, extraction of fuelwood) are simulated in the local ecosystems, providing an opportunity to monitor changes in local ecosystems or social systems to capture nature of the reciprocal relationships denoted in Figure 1.

Recent studies have used ABM to explore human–environment interactions that are shaped by PES programs and evaluate the effectiveness of PES (Sun and Müller 2013). For instance, Smajgl et al. (2015) use ABMs to consider PES programs success without monitoring or regulatory mechanisms; they found that PES schemes may not achieve the expected objectives if appropriate monitoring and regulatory mechanisms are not enforced. In evaluating China's NFCP, Chen et al. (2014) use ABM to consider how electricity payments, rather than cash payments, would impact the NFCP and found that if the cash payment can be replaced with an electricity payment, the effectiveness can be improved by 39%. ABM has also been used to understand the alternative design and implementation of PES schemes. In another example, Chen et al. (2012) simulated the evolution and impacts of social norms on the PES participation. They found

that more than 15% additional land can be enrolled at the same price in China's GTGP due to the effects of social norms if repeated interactions among landholders regarding their land-use decisions are allowed.

Finally, the CHANS framework can account for a temporal dimension which is essential in PES research. Due to data limitation, researchers use cross-sectional data to explore various relationships in the above diagram. But without longitudinal data and observations, many of the putative relationships cannot be tested and established (Guo and Hippo 2004). There is a clear need in PES-related research for integrated socio-ecological data collection, monitoring, and evaluation over relatively longer time scales. Once longitudinal data have been collected in a PES system, latent trajectory models (LTMs) can be used to support an exploration of coupled socio-ecological temporal patterns, i.e., how does slope of land parcels influence PES participation and how successful are PES programs in reducing erosion, retain topsoil, or improving water quality of areas of high slopes (An et al. 2016)?

Conclusions

As threats to human and ecological sustainability mount, the need for programs and policies that are designed to simultaneously support human well-being and ecological composition, process, and function intensifies. Conceptually, PES embodies a CHANS approach by recognizing the fundamental reciprocal relationships among human activities, human well-being, and ecological conditions. Despite this, the research and implementation of PES continues to focus largely on socioeconomic or demographic and ecological factors independently, with limited research on the complex, interrelationship among socioeconomic, demography, and ecological metrics, as represented in Figure 1. Ecosystem services within PES program evaluation are largely limited to LULC as a proxy for ecosystem services (but see Tuanmu et al. 2016). To resolve these conceptual and empirical gaps will require study of a more representative range of ecological responses to PES, building on and drawing from the rich ES literature (Harrison et al. 2014; Schröter et al. 2014; Balvanera et al. 2016). Continued exploration of ES elasticity (Daw et al. 2016) and how ES elasticity changes over space and time will also be needed to support the evolution of PES both in terms of conceptual development and empirical application. From an analytical perspective, adopting a more integrated CHANS framework for PES programs would provide field practitioners with tools and information that can support PES program relevance to context-dependent management needs. With a more comprehensive understanding of the complex linkages among social,

cultural, demographic, and ecological dimensions, PES programs may be improved and fine tuned to adapt to inherent dynamics that govern both social and ecological subsystems.

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