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Uncertainties in demonstrating environmental benefits of payments for ecosystem services

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ABSTRACT

Payments for Ecosystem Services (PES) have become the flagship of conservation organizations in recent years. However, PES schemes are as much criticized as they are acclaimed in the literature. Researchers have pointed that many PES schemes, particularly water-related ones, are based on unreliable assumptions and lack strong causal links between land use and ecosystem services. Evidence of outcomes is hardly demonstrated. This uncertainty in PES schemes arises not only from practical difficulties, but from the complexity of the human-environment systems (HES), and the limits of current knowledge about HES. Many scientists and practitioners have proposed that more research is needed to improve the scientific basis of PES. Here we argue that this research should be complemented with a deeper understanding of the uncertainties involved in PES, an explicit treatment of these in the whole process of PES negotiation, design and monitoring, and clear uncertainty communication among the actors involved. Neglecting uncertainties could lead to unfounded expectations and poor assessments of PES outcomes. If recognizing and accounting for uncertainties are to threaten the success of PES, then uncertainty can be seen as an opportunity to open up the dialogue to alternative ways of achieving the desired conservation goals.

1. Introduction

Ecosystem Services (ES) have been considered one of the most prominent approaches towards conservation nowadays (Kull et al., 2015). With roots in the late 1970s and strong influence from neoclassical economics (Barnaud and Antona, 2014; Gómez-Baggethun et al., 2010), the concept has travelled in the hands of economists and ecologists and reached policy spheres by means of concrete practices (Costanza et al., 1997; Costanza and Daly, 1992; Daily, 1997; de Groot, 1992; Millenium Ecosystem Assessment, 2003). Accordingly, mechanisms derived from the ES concept – like Payments for Ecosystem Services (PES) – have become the flagship of many conservation organizations and have been pitched, among other things, as solutions for lack of funding and inefficiency (Ferraro and Simpson, 2002; Postel and Thompson, 2005).

While, on the one hand, PES schemes have been positioned as an alternative solution for conservation, on the other hand, increasing criticism ranging from the very conceptual roots of ES to the social and environmental trade-offs found in practice has paralleled the increasing trend of implementation of PES projects (Dempsey and Robertson, 2012; Kosoy and Corbera, 2010; Kull et al., 2015; Muradian et al., 2010; Norgaard, 2010; Peterson et al., 2010). The criticism rests in part on the observation that many PES schemes are based on untested assumptions, e.g. related to the role of vegetation on hydrological services (Lele, 2009; Ponette-González et al., 2014), and have critical information gaps, such as baseline data and definition of the target ecosystem service (Carpenter et al., 2009; Martin-Ortega et al., 2013; Naeem et al., 2015; Ojea and Martin-Ortega, 2015). PES projects have also been criticized for a lack of robust monitoring and evaluation processes (Echavarria et al., 2004; Muradian et al., 2010; Porras et al., 2008; Postel and Thompson, 2005).

In sum, there are considerable uncertainties in demonstrating the environmental benefits of PES promised on paper. Uncertainty is here understood as "any deviation from the unachievable ideal of completely deterministic knowledge of the relevant system" (Walker et al., 2003, p.5). If, as a consequence, environmental benefits fall short of expectations or are not even detected, then this

Abbreviations: ES, ecosystem services; PES, payments for ecosystem services; HES, human-environment systems; PWS, payments for watershed services.

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puts under risk the trusting relationships among the actors built to support the PES schemes, the reputations of the organizations involved, and the long term conservation efforts (Fisher and Brown, 2014; Muradian et al., 2010).

To some, the solution to uncertainty is straightforward: More scientific research (Kaimowitz, 2005; Kosoy et al., 2007; Naeem et al., 2015). Accordingly, Naeem et al. (2015) have written a set of guidelines to "get the science right" in PES schemes; baseline data to document initial conditions and a monitoring system are among its fundamental principles. However, uncertainty will not disappear with more science, and we might even create uncertainty as we discover new limits to our knowledge or leave whole research strands unexamined by focusing narrowly on the "right science" (Brown, 2010; Gross, 2010; Stirling, 2010; Wynne, 1992). The transaction costs of "getting the science right" may also prove prohibitive for a scheme to work properly (Muradian et al., 2010; Wunder, 2008).

PES schemes will thus have to "live with uncertainty", and a thorough evaluation and communication of uncertainty seems mandatory (Hamel and Bryant, 2017). With this paper we take a step towards these goals with respect to water related PES by inventorying the sources and types of uncertainty according to three fundamental uncertainty factors (Norgaard, 2010; Muradian et al., 2010; Barnaud and Antona, 2014): (a) the *complexity* of human-environment systems (HES); (b) the *limits of knowledge* about these systems; and (c) *practical constraints*, such as the high cost of measuring and monitoring system variables. We thereby complement the existing political economy/political ecology critiques of ES governance by bringing in literature on uncertainty in Hydrology and more general ignorance studies, and draw on a case study in Colombia to illustrate our points.

The article proceeds as follows: Section 2 discusses how HES complexity may preclude evidence of environmental benefits of PES; Section 3 reviews the limits of available scientific knowledge regarding the links between land cover and hydrological services, and explores the sources of uncertainty in knowledge production itself; Section 4 details several practical constraints of PES schemes; Section 5 presents the illustrative case study; and in Sections 6 and 7 we discuss the previous points and conclude with some propositions on how to consider uncertainty in PES schemes and the prospects of adaptive approaches.

2. Complexity

PES schemes are part of complex HES that are composed of a myriad of elements and subsystems interacting dynamically and exhibiting non-linear and emergent properties that can only be properly observed and understood when taking into consideration the system as a whole (Liu et al., 2007; Ostrom, 2009). HES are constantly evolving through exchanges of energy, matter, and information (Liu et al., 2015). They are open, multidimensional, dynamic, multi-scalar, spatially distributed, multi-agent, multi-causal, and therefore exhibit conditions that are very site-specific (Biggs et al., 2009; Brown, 2010; Liu et al., 2015, 2007; Ostrom, 2009). All these features render HES predictions inherently uncertain and make PES schemes, like other conservation initiatives, difficult to be designed, implemented and successfully managed in practice.

As HES are *open* systems, any boundaries established to study and manage HES are artificial. Drawing these boundaries is informed by the perceived problems and solutions and will, in turn, reinforce these very same problems and solutions (Brown, 2010). Examples of such artificial boundaries are the "area of influence" of PES schemes (theoretically, the area in which both service users and providers are located), and even economic boundaries like "ES provider" and "ES user". As designing conservation interventions inevitably draws boundaries, schemes like PES will always face external influences or surprises due to unexpected system behavior or neglected processes.

HES involve interacting processes in a *multidimensional* setting. Groundwater flows are connected to surface water flows, conditioned by climate inputs and controls in the form of precipitation, wind, temperature, and other factors. These flows are mediated by soil conditions and land cover, subject to human influence. Land use is a product of social-cultural, institutional and economic conditions together with geomorphology and soil characteristics, like fertility and porosity. PES schemes may fail if these dimensions are not considered together.

Because HES are *multi-scalar*, i.e. they are *temporally dynamic* and *spatially distributed* (Liu et al., 2015, 2007), PES schemes are subject to the timing, frequency, amplitude, and nested scales of processes in these systems. It is often difficult to detect and investigate environmental changes at the scale of interest (Biggs et al., 2009). For instance, in a watershed context, river discharge and its sediment load are products of cumulative processes involving the entire watershed as well as the climate system, which means the ES in this case cannot be framed in terms of land units like farms (Barnaud and Antona, 2014). It will be difficult to assess the overall impact of conservation if only part of the land owners in a watershed engages in the conservation practices. In a voluntary scheme, those land owners whose properties contribute most sediment or contaminant loads to the streams might be completely missed. And if monitoring is only carried out at the mouth of the main river in the watershed, it is difficult to isolate the effect of conservation practices from other human interventions or natural effects taking place in the different tributaries.

As HES are *multi-agent* systems, different types of individuals, groups and social networks interact with each other and change the system through competition, cooperation, hierarchies, association, etc. (Barnaud and Antona, 2014). Not accounting for the social networks, power relations and conflicts in place can negatively influence PES effectiveness. For instance, the conservation practices of farmers may not be effective in guaranteeing water quality if local industries, even acting as payers for on-farm schemes, continue to act as a source of water pollutants (e.g. Rodriguez-de-Francisco and Budds, 2015). In some cases, the dichotomy "provider-payer" may create unbalanced power relations, with payers or intermediaries defining rules disregarding providers' standpoints, which may be used for short term gains, e.g. political power or green marketing, rather than improving ES.

As most of the processes occurring in HES are *multi-causal* and not all the causes are controlled by human intervention, it does not make sense to assess causes in isolation (Biggs et al., 2009). For instance, high levels of arsenic in water can be a result of geochemical site characteristics (Nordstrom, 2002). And certain river basins can produce impressive amounts of sediment purely as a result of their geomorphology and precipitation patterns (e.g. Restrepo et al., 2006). If causal links are not well understood, especially biophysical processes generating ES (Palmer and Filoso, 2009), PES schemes may propose solutions based on processes that are not actually under human control and, therefore, end up being considered ineffective and mistrusted (Ponette-González et al., 2014).

The aspects of HES complexity discussed in this section make ES provision extremely *site-specific* (Biggs et al., 2009). We now proceed by exploring how the limits of our current understanding of HES and the uncertainties related to knowledge production may affect our ability to predict and verify environmental outcomes of PES in particular places.

3. Limits of knowledge

3.1. PES step-by-step and perceptual models

A *typical* PES scheme would be implemented in five major steps usually performed linearly (Fig. 1): (1) Proposition; (2) Studies; (3) Design; (4) Execution; and (5) Monitoring (Calvache et al., 2012; Engel et al., 2008; Ruiz-Agudelo et al., 2013; Salzman, 2009; Wunder, 2005). Negotiation, Evaluation and Reporting would go alongside steps (1) to (5) and support adjustments needed along the way, although frequently in a limited form.

The proposition of a PES scheme (Fig. 1, item 1) frames an environmental issue together with the causes of that issue. Hence, from the beginning, there is an idea of the HES in question and how it works, a "perceptual model" in the terminology of Beven (2009) or a "mental model" as referred to by Ostrom (2005) and others. Proposing a PES scheme also indicates that a specific problem-solving mindset is present, since other solutions for the same environmental issue could have been proposed instead. The studies conducted to characterize the system in question (Fig. 1, item 2) are conditioned by this perceptual model, which dictates how and with what focus the system should be studied (Brown, 2010). The conservation activities proposed for the PES scheme (Fig. 1, item 3.A) then are equally based on assumptions about how the system will behave under new conditions. In sum, the way we understand and conceive the HES, i.e. our perceptual model, shapes the way we "see" environmental issues and conduct decisions to solve them (Bardwell, 1991).

Our perceptual model is the product of a particular cultural, political and economic context, including the prevalent knowledge about the HES in question or, vice versa, what is not known (Krueger et al., 2016; Ostrom, 2005). Hence, some reflection upon the uncertainties of the HES will be helpful (not expecting that all of the following questions can be answered directly):

(a) What do we know? – referring to the current state of knowledge about the system
(b) What do we not know? – referring to lack of knowledge, unknowns, and scientific knowledge gaps; if we can answer this question, then we are in the domain of perceived non-knowledge or, as expressed by Gross (2010, p. 9), "acknowledgment of ignorance"
(c) What do we think we do not need to know? – asking if we consciously leave a knowledge gap, called "negative knowledge" by Gross (2010)
(d) What can be known? – referring to the perceived potential to know and the limits of knowledge
(e) How much time, effort and resources does something require to be known? – referring to the practical feasibility of coming to know
(f) What do we not know that we do not know? – referring to what Gross (2010) calls "nescience", unawareness of unknowns, a pre-condition for total surprise

The process of learning that is behind any decision-making process, therefore, ideally extends in several directions: towards surprises; towards perceived non-knowledge; and towards reviewing current knowledge to check for errors not detected previously. We learn when surprises turn nescience into new knowledge and perceived non-knowledge (Gross, 2010). We look at past experiences and take lessons from our previous unawareness. While using current knowledge we can also face situations in which what was consciously left unknown (negative knowledge) turns out to be an important part to be taken into account in the future. The limits of knowledge that bound the way we perceive HES are a major source of uncertainty in PES schemes.

3.2. Scientific knowledge gaps

Arguably, assumptions connecting conservation practices and desired outcomes in PES schemes should be in accordance with available scientific knowledge (Palmer and Filoso, 2009). However, current scientific knowledge gaps may prevent some assumptions from being validated. Palmer and Filoso (2009, p. 575) argued that the "flurry of interest in ecosystem markets supplied by restoration" are "out of step with the science and practice of ecological restoration". In practice, many PES schemes have been implemented without clear causal relationships between land use practices and ES (Barnaud and Antona, 2014; Kosoy et al., 2007; Lele, 2009; Muradian et al., 2010). Instead, proxies such as "total forest

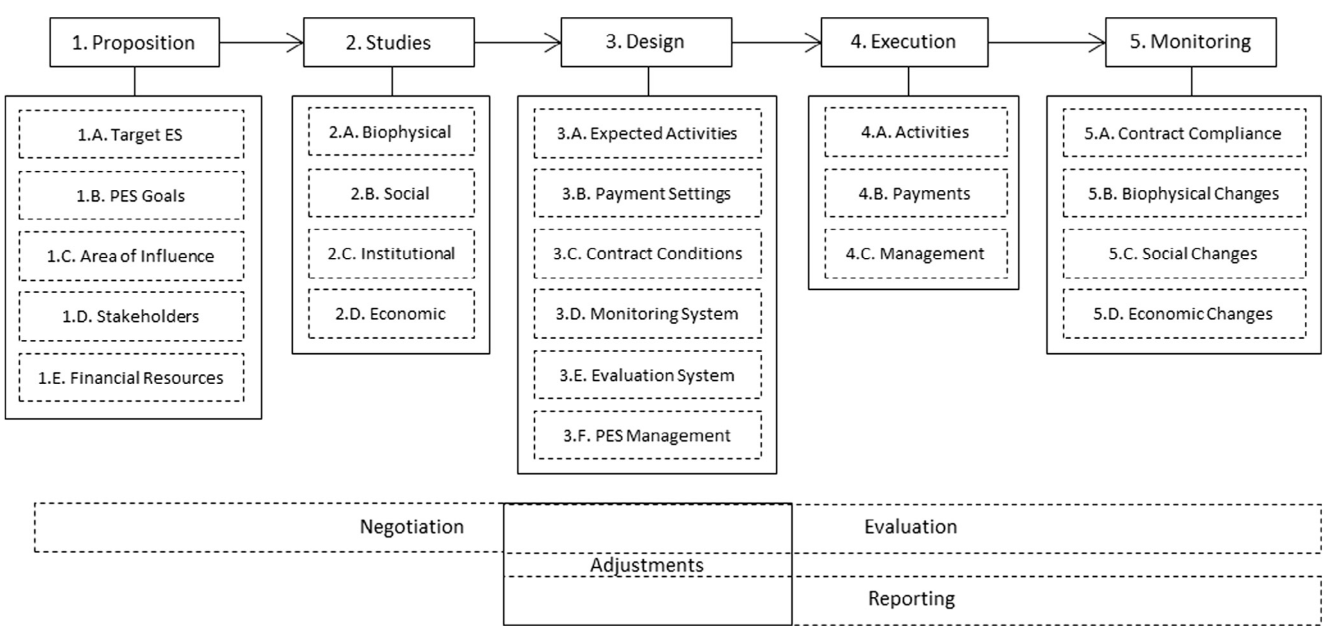

Fig. 1. Steps and components of implementing a *typical* PES scheme performed linearly with limited feedback through evaluation and adjustments. Source: elaborated by the authors.

area under protection" or "number of trees planted" have been used by practitioners to provide some evidence of environmental benefits (Ponette-González et al., 2014; Porras et al., 2008; Quintero et al., 2009; Wunder, 2005). For instance, it is common to see conservation projects based on the assumption that "a tree-dominated land cover will provide similar hydrologic services regardless of its structural or ecological properties" (Ponette-González et al., 2014, p. 4). Hydrological service provision, however, will depend critically on the hydrological properties of the system such as the extent of surface vs. groundwater catchment, hydrogeology, soil properties, geomorphology, microclimatology, etc. As Kosoy et al., 2007; Tallis et al., 2008; and Wunder, 2007 noted, the lack of demonstrable foundations made many PES schemes – especially water-related ones – based more on "faith" than on empirical knowledge.

Kosoy et al. (2007) compared common perceptions among PES payers regarding the links between land cover and hydrological services with the correspondent scientific positions. They found a frequent mismatch in the evaluations of forest cover effects on water quantity and regulation (when it came to the role of forest cover in water quality the payer and scientist positions where more aligned). Beyond this mismatch between public and scientific understanding, the science itself is far from settled. For instance, Lele (2009) emphasized the knowledge gaps regarding the forest-soil-water link and the related misconceptions behind ES related schemes, like PES. The author referred to lasting controversies in Hydrology regarding the effects of land use change on river discharge, floods, dry seasons, erosion, and sedimentation as discussed by Bruijnzeel (2004) and Calder (2004). As summarized by Montanari et al. (2009, p.1), "Hydrology is a science that is highly uncertain. The main reason for this uncertainty is that we still do not know the intrinsic dynamics of many hydrological and water quality processes".

Under-researched components and processes, controversies over concepts, and clashing frameworks may interfere with the contributions science can make to support PES schemes and hence must be taken into account. However, not only knowledge gaps as such are potential sources of uncertainty, but also the practice of *knowledge production* itself.

3.3. Knowledge production underpinning PES and uncertainty sources

Because there is an increasing trend towards supposedly "science-based" projects and policies, like PES schemes, it is of extreme importance to consider the constraints of scientific methods and the sources of uncertainty inherent in the knowledge production process, e.g. in modelling, measurement and data analysis (Fig. 2).

3.3.1. Modelling

Knowledge production always involves some sort of modelling and, in general, qualitative and/or quantitative data analysis (Fig. 2). Here we refer to models as *any representation of human-environment processes*; every attempt to describe a system or frame a specific problem is, fundamentally, a modelling exercise. The first level of modelling, here called a "perceptual model" (Beven, 2009) (Fig. 2, item i.M), would be a conceptual representation, i.e. a qualitative description we create when we try to conceptualize processes. At this first level, uncertainty sources relate to framing, perception, understanding and reasoning, and, therefore, potential error, non-knowledge, nescience and negative knowledge. Our perceptual models are constrained by the previous theoretical frameworks, mindsets or beliefs we carry, be they scientific or otherwise (Krueger et al., 2016; Ostrom, 2005). In general, there will be multiple ways to model a given system, i.e. there will always be model structural uncertainty (Beven, 2005). Model structural uncertainty is modulated in a conscious manner through negative knowledge, i.e. what we consider can be left out from the model for the purposes of a given study. When we establish the boundaries of our perceptual model we are creating uncertainty by actively ignoring parts of the system (Beven, 2009; Brown, 2010).

At the second level of modelling, in the "formal model" (Fig. 2, item ii.M), representations acquire a more systematized description, leading to mathematical formulations of the system/processes under study (Beven, 2009). Of course, not all knowledge production will lead to this step – some will remain at the first level of model abstraction, i.M., and others will use data types not intended for mathematical processing. Once processes are being represented in mathematical terms, however, the formal model can be influenced not only by model structural uncertainty, but also by negative knowledge and parameter uncertainty: mathematical formulations can constrain what aspects of the system/processes are left in or out; and precise values for all system parameters will, in general, be impossible to obtain by estimation or measurement.

The third level of modelling refers to the implementation of the "procedural model" (Fig. 2, item iii.M) using computational

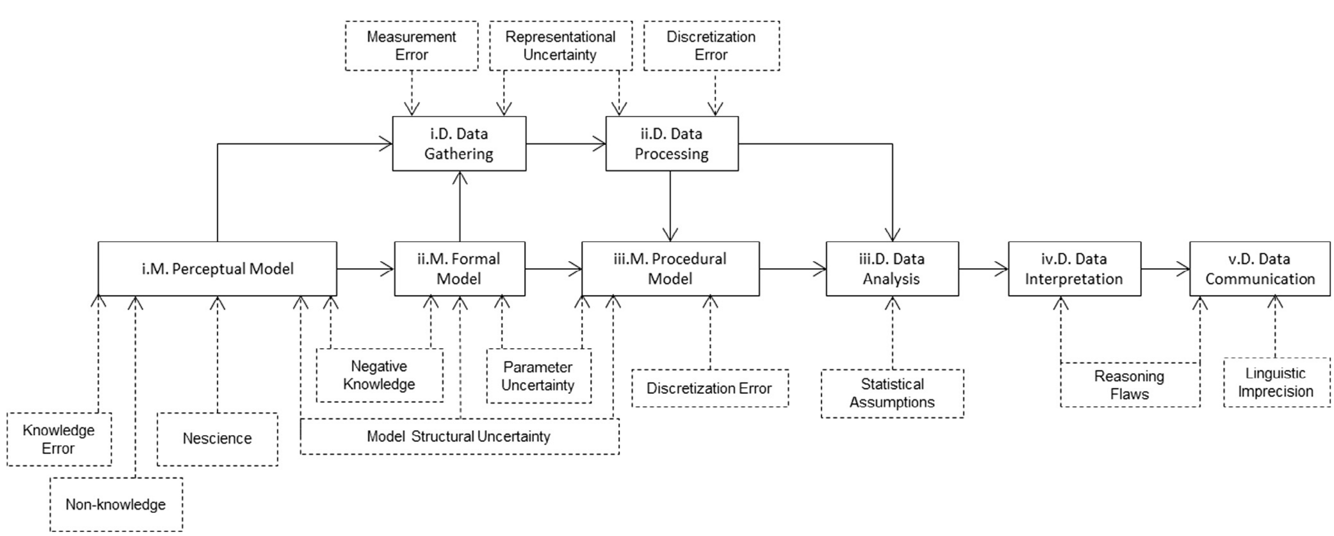

Fig. 2. The production of knowledge underpinning PES with related sources and types of uncertainty. Perceptual models constrain the way we design data gathering and modelling. Several technical sources of uncertainty are present in the process of producing knowledge in addition to sources related to cognitive processes. Source: elaborated by the authors.

resources (Beven, 2009). The procedural model can be influenced by the previous sources of uncertainty and two additional ones related to data: representational and discretization errors. The first is linked to how representative the data used are with respect to the processes of interest. The second is linked to the fact that hardware and software have numerical precision limits so that numbers may be truncated while performing calculations. In addition, many problems cannot be solved analytically, requiring so called numerical methods, the choice of which can strongly influence the final results of a model and thus is an important source of uncertainty (Kavetski et al., 2006; Seppelt and Richter, 2005).

3.3.2. Measurement and data analysis

Data uncertainty refers to a set of potential errors affecting the data used to represent the processes of interest, either directly or via input into models. Whenever data are used to drive or evaluate a procedural model or to test a hypothesis (derived from a perceptual model), another chain of analysis will usually be performed (Fig. 2): data gathering (item i. D), processing (item ii. D), analysis (item iii. D), interpretation (item iv. D), and communication (item v. D). Any output from a procedural model will also constitute new data and may follow the same path. In each of these steps, additional sources of uncertainty matter.

Data gathering (Fig. 2, item i. D) will be subject to the uncertainties of the perceptual and formal models used to define what and how much data to gather, and where and when to obtain it. In addition, data gathering is always subject to measurement error (McMillan et al., 2012). This error has a variety of components: sampling technique used, transport (e.g. water samples, microorganisms), handling (material loss, microbial or other decay, audio recording noise, unreadable field notes, and instrument damage), laboratory preparation (e.g. contamination of samples), instrument error (intrinsic precision, calibration error, and systematic error), and operation (e.g. human mistakes). Precision and sampling design, including spatial and temporal coverage, are linked to what is called representational error. This source of uncertainty is prevalent, for instance, in gridded spatial data based on the interpolation of sample points (Eigenbrod et al., 2010; Heritage et al., 2009; Phillips and Marks, 1996; Robinson and Metternicht, 2006; Sun et al., 2009), or in water sampling schemes sought to represent spatially and temporally aggregated processes (Gentine et al., 2012; Krueger, 2017; McMillan et al., 2012), or when a survey has a high nonresponse rate (Groves, 2006).

Data processing (Fig. 2, item ii. D) is needed when raw data are in a format that is not suitable for analysis or to feed procedural models. Data processing would include conversion to different data formats, mixing different data sources, filling data gaps, classifying and eliminating outliers, transcribing interviews, coding texts, rearranging numerical data in spreadsheets, resampling raster maps, etc. Errors derived from these procedures are of a variety of types and a large literature has been devoted to their analysis in different disciplines (Biemer, 2010; Hunter et al., 1995; Kim and Ahn, 2009; Lunetta et al., 1991; Teegavarapu and Chandramouli, 2005).

Data analysis (Fig. 2, item iii. D), in turn, refers to the choices made when using statistical procedures and methods to assemble, organize and present the data. Basic statistical metrics (e.g. mean and standard deviation), distributions and intervals are used to organize large amounts of observations and corresponding uncertainties, and graphics and formal statistical tests are used to compare values. The statistical assumptions are a common source of uncertainty in this step (Cooper et al., 2014; Zuur et al., 2010).

Data analysis is followed by data interpretation (Fig. 2, item iv. D) and communication (Fig. 2, item v. D). Both steps are subject to uncertainty due to flaws in reasoning, cognitive bias, and misuse of scientific information, which may include: overgeneralization, unsupported claims, oversimplification, deriving causation from correlation, strategically selecting information to support arguments, etc. (Brown, 2010). Data communication in particular is subject to an additional source of uncertainty, linguistic imprecision (Carey and Burgman, 2008). Examples of the effects of the uncertainty sources mentioned in this section on a PES scheme are discussed in Section 6.

4. Practical constraints

The final uncertainty factor we explore in this paper is the practical constraints that may prevent environmental outcomes from PES to be proven. Here we refer to specific difficulties that may arise while implementing projects in the field. These difficulties permeate every step of a PES scheme (Fig. 1) and may also be one of the drivers of model and data uncertainty (Fig. 2). They are well known by practitioners, although frequently disregarded by theorists and decision makers proposing top-down policies. Here we discuss difficulties related to time resources, field accessibility, trained staff, data availability and accessibility, and transaction costs.

PES schemes are *time* consuming for the intermediaries in charge. Developing ES research for the scheme, negotiating with different actors, gaining acceptance in the field, building a network of trust, getting funds from payers, installing monitoring instruments, verifying contract compliance, and regularly monitoring indicators of PES impacts; all of these tasks require a lot of time. How much time is *available* to perform them effectively depends on the commitments made by the intermediaries towards both providers and payers. For instance, when a government body or public company is engaged as payer they may pressure intermediaries with deadlines to deliver results in order to match the timing of political or business processes. Development agencies may also require schemes to be adapted to a set of progress indicators to be reported annually. Providers, on the other hand, may demand implementation of activities to be in time as agreed on contract. Conservation projects are also subject to the difficulties of matching the delivery of expectations with the timing of natural processes as the latter might be much slower, e.g. the release of legacy pollutants from the system long after inputs have stooped (Powers et al., 2016).

Accessibility issues in the field may further decrease the chances of providing evidence of environmental outcomes of PES. These issues include physical difficulties, e.g. inaccessibility due to topography, difficulties in the installation and manipulation of monitoring instruments due to river morphology or seasonal floods, instrument damage by natural events, etc. They may also include social aspects, e.g. practitioners not being accepted in the field by locals, closed communities, presence of armed conflicts, etc. Although not regularly cited as obstacles, these issues can make field work unsafe or impede it completely.

When designing a PES scheme, stakeholders must be aware that it is not only a matter of time and funds, but also of having *trained technical staff* available to keep track of the changes in the field and be able to monitor and detect the desired outcomes. Although it may sound simple in theory, in practice designing and managing a monitoring system to provide rigorous ES data usually require experts and well trained staff.

Another common practical constraint is the *availability of secondary data* managed by government bodies, local associations, companies and universities. With the need to prove PES outcomes, there is a need for a baseline (Naeem et al., 2015). However, developing countries, where most PES projects take place, often do not have enough environmental data to properly characterize the initial conditions of the system upon which to detect the effects of the conservation practices. As pointed out by Ponette-González et al. (2014, p. 2) for the case of water-related ES, "the opportunity to measure water flows often arises simultaneously with the opportunity for intervention".

In addition to data availability issues, there is the *data accessibility* issue. Secondary data are seldom easily accessible as they may not be organized, or in a proper format, or open for public use. Authorities or other data holders might not want to share their data due to conflicts of interest. For instance, a water supply company could consider providing data to third parties a business risk. A government authority may not want to share data due to a perceived risk to sovereignty over natural resources. Local research centers, if they are privately owned, may consider that data gathering had a cost for them, and may thus refuse to share data free of charge. Lastly, academics may not want to share their data due to publication issues and authorship.

Most of the practical constraints reported here can be translated into different types of *transaction costs*: (a) information search; (b) negotiation; (c) contract enforcement (Dahlman, 1979). These costs are present in all steps of PES design and implementation (Fig. 1) (Phan et al., 2017; Vatn, 2010); there are costs behind every data gathering effort, every contact made, every trust relationship built, every repair of a monitoring instrument (Jack et al., 2008). All of these demand time, money and expertise, and they must not be ignored (Muradian et al., 2010). However, payers may be willing to pay for conservation practices that can be measured and reported, e.g. number of trees planted, but they may not want to pay for research and monitoring systems. Monitoring is often the first function to be cut down under budget limits (Williams and Brown, 2016).

5. Illustrative case study

In order to illustrate the points made in the previous sections, we explore the case of the Bolo River watershed (Valle del Cauca department, Colombia), focusing on conservation practices carried out in one of its tributaries, Aguaclara (Pradera and Palmira municipalities). This case was one of four cases studied during a 6-months doctoral research stay of the first author in Colombia from January to June 2016. The study aimed at understanding how uncertainty regarding environmental benefits of water related PES schemes were perceived and assessed by PES practitioners. The study was based on key informant interviews, informal interviews, questionnaires, participant observation, and review of reports and related documents from the organizations managing directly and indirectly the scheme (e.g. Calvache et al., 2012; Moreno-Padilla, 2016; Munoz Escobar et al., 2013; Uribe et al., 2009). In total, 12 key informant interviews were recorded, transcribed and coded for qualitative analysis using *NVivo* (QSR International Pty Ltd.). Fieldwork notes were processed through the same system. Participant observation was conducted while following the practitioners in their daily work, during hydrological monitoring campaigns and while negotiating with local actors. This study also includes information collected during a regional conference of water funds held in Bogotá, Colombia, in June 2016.

Interviewees were approached by the researcher by phone and email upon which the context of the doctoral project in which the collected information would be used was introduced. Most interviews were undertaken face-to-face, a few used teleconferencing. Questions started with topics related to the origins of the scheme; the main actors involved in the initial design and their motivations; and the status of the scheme in number of providers, activities performed, and total area committed for conservation so far. Subsequent questions were focused on the assessment of the effectiveness of the scheme and related methods. Topics such as practical constraints in the field and institutional problems were covered.

5.1. Description of the Bolo River watershed case

Public-private partnerships aiming at the protection of water resources through conservation practices became common in Colombia in the early 1990s with the creation of water user associations in several tributaries of the Cauca River (Echavarria, 2002). Conservation projects carried out by these associations have been regarded in the literature as PES or "PES-like" projects (Goldman et al., 2010; Grima et al., 2016; Munoz Escobar et al., 2013; Rodriguez-de-Francisco and Budds, 2015): water users from the downstream area of the watersheds, mainly sugarcane producers, pay a voluntary fee to fund conservation practices in the upper watersheds in order to protect the water resources upon which the downstream users depend. The associations are the intermediary entities between the payers and the providers and they have established voluntary conservation agreements directly with landowners upstream (Munoz Escobar et al., 2013).

The Bolo River water users association (ASOBOLO) is one of these cases, established in 1993 with the support of the local environmental authority (Munoz Escobar et al., 2013). Its main remit is to improve and maintain water flow regulation, and at the same time avoid sediment overloads to water bodies. Funding has been provided by water users, local companies, the local environmental authority, non-governmental organizations and international cooperation agencies. Engaged landowners receive in-kind payments, e.g. through improvements of the farm systems and through materials and resources to implement the conservation activities. River fencing, protection of springs, small-scale biodiversity corridors, and agrosilvopastoral systems are among the main conservation interventions in upstream areas.

In 2008, the Colombian sugarcane production sector boosted the creation of a *water fund* (Goldman et al., 2010; Bremer et al. 2016) called "Fondo Agua por la Vida y Sostenibilidad" (FAVS) aimed at supporting the ongoing conservation activities by water users associations (Moreno-Padilla, 2016). The fund was launched in 2009 through a cooperation agreement involving the sugarcane production sector, The Nature Conservancy (TNC) as the main promoter of water funds (Calvache et al., 2012), two local companies, and 13 local water user associations. FAVS provides the funding and technical support, while relying on the water user associations like ASOBOLO carrying out the conservation interventions. TNC had an important role in the design and implementation of FAVS and has been influencing the water fund to work towards a more scientific approach.

5.2. Challenges in producing evidence of environmental benefits

When FAVS came into force, ASOBOLO was asked to follow new technical guidelines promoted by TNC, such as monitoring guidelines (e.g., Higgins and Zimmerling, 2013) and hydrological studies to define priority areas for conservation (e.g., Ruckelshaus et al., 2015). For instance, TNC arranged modelling studies for the FAVS watersheds through consultancy with a local research center (Uribe et al., 2009) and received funding from United States Agency for International Development (USAID) in 2010 to support the design and implemention of a hydrological monitoring system in one of the watersheds. A successful monitoring scheme would allow TNC and partners to communicate results to payers, attract new potential funders and support the expansion of the water fund model to other regions (Hoyos-Villada et al., 2016).

The science-based approach encouraged by TNC through the water fund model brought funding and technical assistance for the water user association; however it brought new challenges too. The hydrological modelling study arrived at ASOBOLO in the form of a report suggesting priority areas for ES conservation. It turned out that most of the priority areas identified by the report coincided with the higher lands of the watershed which had been strongly affected by armed conflicts since the 1990s and were still unsafe for fieldwork due to remnants of mistrust among the different actors (a similar situation was reported in Ruckelshaus et al., 2015). It was clear for the association that the prioritization defined by a model based solely on biophysical variables was not useful.

The presence of armed conflicts in the region also affected the possibilities for hydrological monitoring. Technicians looked for different watersheds to install the monitoring system but struggled to find one that was safe enough to work in. Eventually, the Aguaclara watershed (tributary of the Bolo River) was chosen. ASOBOLO made it clear that they did not have any technical staff available to maintain the sophisticated and expensive monitoring system that was going to be installed. So FAVS made an agreement with CENICAÑA, the Colombian research center for sugarcane production, to get their technical support. Since 2014, CENICAÑA has run the monitoring system consisting of several climatological stations, pluviometers, river stations with automated water level recorders and suspended solids measurements (Hoyos-Villada et al., 2016). The total implementation costs were USD 194,319 and the total annual operating costs were USD 46,880 between 2013 and 2014 (Hoyos-Villada et al., 2016). To date, this is the best case of a monitored water related PES scheme in Colombia ever documented. Still, a number of technical challenges exist.

Before the installation of the new hydrological monitoring system, the Bolo River watershed had practically no local data on river discharge besides two stations managed by the local environmental authority in the lowest part of the watershed. The downstream location of the available stations makes them unsuitable for measuring any impact of conservation practices implemented along the middle to upper reaches. Climatological data relied on old stations from neighboring watersheds, although the high elevation gradient in the Bolo River watershed would require local stations to properly capture spatial precipitation variability. No data related to groundwater were available in the watershed apart from wells located in the downstream part. No extensive soil characterization was available apart from a soil classification map for the whole Valle del Cauca department made on a 1:500,000 scale (Uribe et al., 2009). In sum, it was practically impossible to establish an adequate baseline of the climatic, hydrologic and edaphic conditions prior to the commencement of the PES scheme.

The Aguaclara monitoring system was intended to be a pairwise watershed study; one watershed was taken as the control case while conservation practices were implemented in another (Hoyos-Villada et al., 2016). However, there was no way to guarantee that the control watershed would remain under any expected land use, since it was not owned by FAVS or its associates. Meanwhile, in the other watershed where conservation agreements had been made, the CENICAÑA monitoring staff found that external influences could have had an impact on their data analysis: an unexpected point contamination by a local chicken slaughterhouse happened to interfere with the suspended solids sensor creating odd patterns in recorded data; unexpected suspended solids spikes were misinterpreted until the staff found out that a local farmer was crossing his cows in the creek every day; flash floods were continuously bringing debris and sediments to the gauging station making it impossible to record the water level during such events; a local landowner who took part in the project decided to open the area he had set aside for conservation to his horses releasing a considerable amount of sediments close to the monitoring station. In addition, the strong 2015 El Niño event affected several conservation schemes in the region, including another water fund close to Bogotá. There was a high percentage of mortality among seedlings and young trees planted and several forest patches set aside for recovery were taking much more time than expected to regain strength.

5.3. Uncertainty sources in the Bolo River watershed case

For more than 20 years, ASOBOLO has worked in the Bolo River watershed based on trust and reputation built over time. Landowners upstream were engaged largely thanks to the environmental awareness created during those two decades. The payers, in turn, demanded a report with indicators related to the activities performed with their money, like total number of trees planted, total area under recovery, and so on. Most of them were not expecting concrete numbers related to the effects of those activities on river discharge, sediment load, nutrient concentration, etc. However, evidence of ES improvement became important with the implementation of the water fund model, and uncertainties suddenly started to play a bigger role.

As described previously, the Bolo River watershed did not have enough environmental data to characterize its hydrological and ES baseline (non-knowledge), a common case in many Latin-American watersheds. Without this information, it is very hard to describe the initial conditions of the biophysical system with confidence and to calibrate a model capable of representing its behavior (leading to model structural/parameter uncertainty). Local information on specific vegetation-soil-water dynamics is not available, and neither are studies of these dynamics under varied land cover/land use categories or vegetation types/stages of recovery (parameter uncertainty). Effects of land use change on hydrology are usually extremely site-specific and general assumptions can be misleading (non-knowledge/knowledge error) (Bruijnzeel, 2004; Calder, 2002; Porras et al., 2008). Therefore, without local data it is difficult to predict to which extent farm conservation practices or forest recovery would affect water flow during dry and wet seasons, and sediment transport and loads. Even with this information at hand, it would still be difficult to extrapolate point information to the entire watershed (representational error). Land use and cover maps, regularly used in models for ES valuation, are known to have significant representational and discretization errors (Dong et al., 2015).

In addition to data issues, defining conservation priority areas solely by biophysical factors and disregarding social ones can lead to irrelevant results. In the presented case, as social conditions were not integrated in the prioritization model, it turned out impossible to target the indicated areas due to the presence of armed conflicts (negative knowledge). Social factors also influence many other aspects of a PES scheme, for instance: social norms behind farm lease, tenure and irregular occupation trends influence the degree of engagement of actors (leading to high transaction costs of negotiation); lack of trust and confidence among actors due to the armed conflict legacy may constrain field studies (model structural uncertainty); local behavioral patterns influence the risk of having monitoring equipment stolen or damaged (leading to measurement errors).

The influence of external variables on the PES scheme (consequence of an open system) in the form of omitted processes is associated with nescience or non-knowledge that may lead to several measurement errors, e.g.: the El Niño influence on the rate of mortality of planted trees; non-compliance by landowners and its effect on monitoring signals; intense rainstorms generating floods that damage monitoring equipment; unexpected influence of chicken tissue contamination on the sediment sensor.

Lastly, uncertainty in the administrative domain, including legal and financial uncertainty, is a common practical constraint associated with high transaction costs. In this case, by being a voluntary initiative with budgets calculated on an annual basis, it has been unfeasible for the association to offer continuous payment and even pay farmers proportionally to their opportunity cost. The same uncertain financial future did not allow the association to afford the sophisticated monitoring system or to pay the technical staff to manage it. The possibility of implementing one in Aguaclara watershed only became reality through a development agency grant and the partnership with TNC and local research centers, which are favorable conditions not found in most other cases.

6. Propositions for uncertainty management in PES

As a conservation mechanism that deals with complex HES and is, at least in theory, subject to evidence of "service provision" (Wunder, 2005), PES are highly demanding in terms of data and models, and hence vulnerable to the associated uncertainties. Even the "simple yet rigorous" scientific principles and guidelines proposed by Naeem et al. (2015) are, in practice, not so simple if uncertainty and transaction costs are taken into account.

Specifically, if stakeholders frame their expectation of PES as improvements of ES in terms of supposedly "factual numbers", then uncertainty affecting data gathering, processing, analysis and interpretation should be a major concern for PES effectiveness. In practice, procedural models, like hydrological and sediment transport models, have been used in PES schemes to define where, when, what types of and how much conservation interventions will be needed to achieve some environmental outcome (Crossman et al., 2013; Quintero and Estrada, 2006; Ruckelshaus et al., 2015; Tallis and Polasky, 2009). If practitioners then expect to achieve the numbers provided by the models and manage to convince potential payers based upon them, then model uncertainty may compromise the effectiveness of the schemes.

In order to manage uncertainty, we propose a modification of the *typical* step-by-step PES process (Fig. 1) towards an adaptive management cycle (Haasnoot et al., 2013; Murray and Marmorek, 2004; Smith and Porter, 2010; Williams and Brown, 2016) including considerations of how to tackle uncertainty issues (Fig. 3).

Moving from a linear model of a typical PES (Fig. 1) to an adaptive version (Fig. 3) requires stakeholders to be committed to a transparent and participatory process. In this adaptive model, tackling the environmental issue at hand is recognized as a loop that is continuously permeable to new information and surprises shared among the stakeholders. Whenever possible, there is an explicit assessment of uncertainty sources and an emphasis on a collective project evaluation. This adaptive model implies that PES goals and therefore contracts can be re-negotiated in a participatory manner according to new knowledge about the HES.

If environmental monitoring is feasible, it should be done in tandem with PES implementation. However, relevant knowledge about the HES is produced not only by scientific methods, but also by non-scientific knowledge through participation of those who actually live in the area under management (Krueger et al., 2012). For instance, there are several explanations for environmental events in a watershed that could be easily understood through communication with locals instead of obtaining data from sophisticated monitoring equipment. In our illustrative case, a local land owner was the one who found out that the turbidity peaks observed at the monitoring point was being caused by the cows crossing one of the tributary streams every afternoon. Involving the local community in the actual environmental monitoring can also increase the sense of participation and ownership of the process which could in turn increment the chances of acceptance and long-term survival of the scheme. An adaptive approach to PES that accounts for uncertainty through an open dialogue with stakeholders and integrates providers' standpoints, instead of a top-down measure set up among only intermediaries and payers, may produce a more legitimate process (Kwayu et al., 2014; Petheram and Campbell, 2010; Ruckelshaus et al., 2015).

Assessing uncertainty can be challenging (Hamel and Bryant, 2017). Taking uncertainty seriously means that expectations of PES schemes should be balanced against the costs of monitoring and predicting the outcomes. There is a need to discuss among the stakeholders the "value of information" (Williams and Brown, 2016), i.e. how much we gain from investment in getting more information about the system under management. Still, uncertainty assessment can even reduce costs in natural resources management (e.g., McMillan et al., 2017). In this context it is important to recognize that adaptive management would imply other types of transaction costs related to participatory and negotiation processes and frequent reviewing cycles.

A potential risk of the uncertainty-inclusive PES management strategy outlined so far is that the uncertainties exposed become so large that payers would not be willing to pay for such uncertain services anymore. If this is the case, then perhaps uncertainty can be used as an opportunity to open up discussion about alternative conservation strategies. However, we should not forget that payers may not engage in PES schemes only to see proof of environmental benefits, but following other motivations or preferences. For

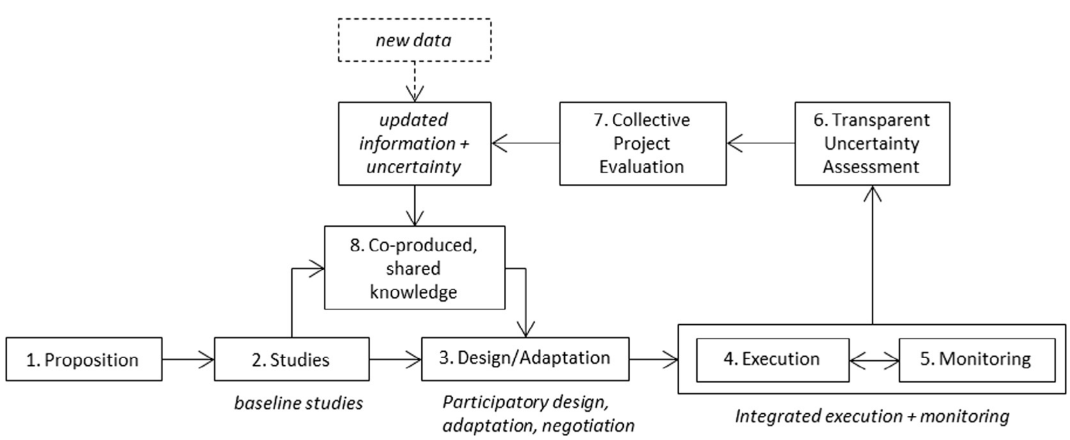

Fig. 3. A modification of the typical step-by-step PES management (Fig. 1) taking into consideration uncertainty and adaptation strategies. Step 1 and 2 follow descriptions made for Fig. 1; entering the loop of management, step 3 refers to the design of strategies, negotiation and project adaptation stressing the need for greater stakeholder participation; steps 4 and 5 emphasize that execution ideally should be done in parallel with monitoring; step 6 stresses the importance of an assessment of uncertainty sources in a transparent way among stakeholders; step 7 refers to a general evaluation of the scheme ideally by stakeholders; new sources of external data are continuously feeding the loop and should be incorporated to update information about the system; step 8 stresses the importance of a co-produced and shared knowledge base as input for adaptation of plans as needed. Source: elaborated by the authors.

instance, companies could engage just to fulfill their corporate socio-environmental policies. Citizens acting as payers may participate motivated by a sense of community belonging. Governments might engage just to be seen to be "doing something" about environmental issues. Nevertheless, in these cases too, being explicit about uncertainty will help to expose alternative motivations and lend transparency to the conservation debate in those particular places (see Hamel and Bryant, 2017 for more on transparency about uncertainty).

7. Conclusion

Conceptualizing PES as transactions of "units of service" is unrealistic; the complexities of HES defy such simple compartmentalization. Nevertheless, the ES paradigm led to the privileging of PES schemes over other conservation strategies, while the considerable uncertainties related to demonstrating environmental benefits have been downplayed. But there is no escape from uncertainty, with the potential for losses, harm or undesired consequences when outcomes are not as expected. In designing PES schemes, we should therefore explicitly address uncertainty in order to have a clearer picture of potential ways to progress, cope with and adapt to unforeseen circumstances, and eventually ensure the long term viability of the conservation projects. However, we must not forget that uncertainty may be used selectively, downplayed or amplified in politics to suit vested interests or keep unequal power relations.

We propose that PES stakeholders should invest time and effort in understanding and exchanging knowledge about the complexity of the HES they are dealing with, and make uncertainties openly explicit in the process of proposing, bargaining and designing PES mechanisms. Arguably, transparent treatment of uncertainty is fundamental to managing expectations, build trust among actors and maintain credibility of PES practitioners. If recognizing and accounting for uncertainty is to threaten the success of PES schemes, then uncertainty can be seen as an opportunity to open up dialogue about alternative ways of achieving the conservation goals.

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