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The global status and trends of Payments for Ecosystem Services

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Recent decades have witnessed a considerable increase in Payments for Ecosystem Services (PES)—programmes that exchange value for land management practices intended to provide or ensure ecosystem services—with over 550 active programmes around the globe and an estimated US$36–42 billion in annual transactions. PES represent a recent policy instrument with often very different programmes operating at local, regional and national levels. Despite the growth of these programmes, comprehensive and reliable data have proven difficult to find. This Analysis provides an assessment of the trends and current status of PES mechanisms—user-financed, government-financed and compliance—across the domains of water, biodiversity, and forest and land-use carbon around the world. We report the various dimensions of growth over the past decade (number of programmes, geographical spread, dollar value) to understand better the range of PES mechanisms over time and to examine which factors have contributed to or hindered growth. Four key features stand out for scaling up PES: motivated buyers, motivated sellers, metrics and low-transaction-cost institutions.

Just two decades ago, Payments for Ecosystem Services (PES) was an obscure term, with only three PES journal references in 1995 (according to a Google Scholar search, see details in Methods). There are now over 550 PES programmes around the world, with combined annual payments over US$36 billion. PES has been featured on the cover of *The Economist* magazine and become a central component of China's nationwide environmental protection strategy[1,2]. In 2016 (according to the same Google Scholar search), there were over 1,900 PES journal references, reflecting the breadth of scholarship that has emerged.

These numbers show growth but tell us little about the details and evolution of particular payment mechanisms. Because PES represents such a recent environmental policy instrument with disparate practices at local, regional and national levels, comprehensive and reliable data have proven difficult to find. This article provides an empirical assessment of the state of PES mechanisms—user-finance, government-finance and compliance—across the domains of water, biodiversity and forest carbon around the world. Using data collected by the Ecosystem Marketplace—an initiative of the non-profit Forest Trends focused on tracking market-based mechanisms for conservation around the globe—since 2005, we assess the various dimensions of growth (number of programmes, geographical spread and dollar value not adjusted for inflation). These data provide insights into which factors have influenced growth and effectiveness.

In economic terms, PES seeks to internalize the positive externalities (that is, the third-party benefits) generated by natural systems, creating incentives for landholder behaviour that ensure service provision. In some circumstances, PES can create additional revenue streams for conservation and has been described as "making trees worth more standing than cut down"[3]. It is important to recognize, however, that PES captures only a fraction of the values provided by natural systems. Existence values, option values and many public goods benefits often remain outside the scope of PES mechanisms.

Wunder identifies nine different definitions of PES[4]. We take a broad view, defining it as the exchange of value for land management practices intended to provide or ensure ecosystem services. Researchers have also proposed different categorizations for the various types of PES[5,6]. Building on a framework developed previously[6], we group PES mechanisms into three broad categories:

- User-financed PES. Users of ecosystem services agree to compensate landholders for activities that maintain or enhance the delivery of ecosystem services. Users may be individuals, companies, non-governmental organizations (NGOs) or public actors that are direct beneficiaries of ecosystem services protection, enhancement or re-establishment. This includes payments by hydroelectric companies to landholders in the upper watershed for maintenance of forests and their ecosystem service of erosion control.
- Government-financed PES. Third parties acting on behalf of users compensate landholders for activities that maintain or enhance ecosystem services delivery. The buyer is a public or private entity (such as a conservation group) that does not directly use the ecosystem service. This includes government programmes in Costa Rica and China that pay landholders for reduced deforestation or afforestation activities that enhance flood protection, water quality or other ecosystem services.
- Compliance PES. Parties facing regulatory obligations compensate other parties for activities that maintain or enhance comparable ecosystem services or goods in exchange for a standardized credit or offset that satisfies their mitigation requirements. This includes water quality trading, wetlands mitigation banking and the European Union's emissions trading scheme for greenhouse gases.

Given the broad range of PES approaches, some programmes do not fit neatly into these categories and represent a hybrid approach[6].

Watershed PES

The watershed PES sector is the most mature in terms of transaction value and and geographical distribution (US$24.7 billion in 62 countries in 2015). There are currently 387 watershed PES

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programmes: 153 user-financed, 203 government-financed and 31 compliance. The evident connection between land management in an upper watershed and threats of poor water quality and flooding to downstream users makes it easier to gain support for payments from beneficiaries to providers. Transaction costs can be low because existing institutions collect funds from diffuse beneficiaries, whether through water utilities or government taxation power. Compliance is easy to confirm because nearly all programmes pay for 'practice' (implementing a particular management activity on a specified area of land, such as installing fencing to keep livestock away from riparian areas) rather than performance (such as improvements in water quality). Table 1 sets out each watershed PES mechanism and broad category, its definition, an illustrative example, market size, number of programmes and geographical reach. The following text then briefly explains the data highlights.

Chinese dominance. China dominates government-financed payments for watershed PES. A series of major floods and droughts in the late 1990s made it clear to the Chinese government that deforestation posed serious threats to water quality and flooding. China's unique political and centralized authority has allowed it to put in place PES strategies at a scale and speed simply not possible in other countries, reshaping the country's policy and ecological landscape in a very short period of time[7].

The Sloping Land Conservation Program (SLCP, focused on converting steep croplands to forest and grassland) and the Natural Forest Conservation Program (focused on logging bans and afforestation) represent the largest PES programmes in the world, investing over US$50 billion from 2000 to 2009[8]. The SLCP alone paid 32 million farmers and 120 million households[8]. These programmes, like many other government-financed PES programmes, also have an explicit additional purpose of rural development[9]. Assessments have found that all ecosystem services increased from 2000 to 2010 (except for biodiversity habitat) with mostly positive socioeconomic benefits[8].

Growth in South America. Water funds in South America have experienced the most rapid growth in number of watershed PES programmes. In a PES water fund, an institution combines resources from multiple water users (including private parties, NGOs or government bodies) to pay upstream landowners for management actions that provide water quality and other benefits. At least 57 funds have been created in the past decade, with a wide range of approaches in programme size, participants, funding strategies and forms of compensation. Much of this is due to the Latin American Water Funds Partnership (LAWFP). Launched in 2011 by a consortium of funders led by The Nature Conservancy, LAWFP has directed an estimated US$27 million in leveraged start-up capital and now has 16 operating funds. The Brazilian National Water Agency has also been active, expanding its Water Producer programme to 19 programmes across Brazil from 2007 to 2015[10].

Table 1 | Watershed PES

PES mechanism (category)	Definition	Example	Market size 2009 → 2015	Programmes 2005 → 2015	Distribution (number of countries)
Subsidy watershed PES (government-financed)	Public finance rewards land managers for enhancing or protecting ecosystem services. The funders do not directly benefit from the management activities.	Chinese government's Sloping Lands Conversion Program pays farmers to stop cultivating on steep slopes. Roughly 53 million farmers receive compensation to improve water quality and flood control.	$6.3 billion → $23.7 billion (US$12.98 billion in China)	17 → 139, with 69 in China	39
Collective action watershed PES (user- and government-financed)	An institution pools resources from multiple water users (private parties, NGOs, government bodies) to pay upstream landowners for management actions that provide water quality and other benefits.	Quito's Water Conservation Fund relies on a 1% surcharge on monthly water bills and monies from local electrical utility and beer company directed to finance projects protecting forests and grasslands in the watershed.	US$402 million → US$564 million	16 → 86	22
Bilateral watershed PES (user- and government-financed)	A single water user compensates one or more parties for activities that deliver hydrological benefits to the payer or serves to mitigate impacts from their activities.	In the 1990s, New York City raised a bond to pay for land-use changes in the Catskills and Delaware watersheds to ensure the quality of their drinking water at much lower cost than installing a treatment plant.	US$13 million → US$93 million	19 → 111	27
Instream buybacks (user- and government-financed)	Water rights are purchased or leased from historic rights holders and retired, which leaves the water in-stream to deliver water-quality benefits and ensure healthy ecological flows.	In Australia, the Restoring the Balance programme committed over $3 billion over a ten-year period to purchase water entitlements from farmers to ensure instream flows in the Murray–Darling Basin.	US$25 million → US$60.7 million	15 → 20, with 18 in the United States	3
Quality trading and offsets (compliance)	Water service providers comply with regulations by paying landowners for activities that improve a measure of water quality (such as nutrients, salinity or temperature) in exchange for credits.	In the Hunter River Salinity Trading Scheme, salt credits are traded among mines and power stations based on river conditions to control the salinity.	US$8.3 million → US$22.2 million	10 → 31, with 29 in the United States	3

The participation of both public and private actors can make these funds a hybrid of user-financed and government-financed PES. This combined support of first movers—government, private sector and NGOs—has driven the rapid increase by developing the institutions, expertise and market infrastructure for watershed payments[11]. It also introduces more stakeholders into the governance process, thereby identifying local champions and creating a broad base of political support. Continuity of funding, especially when a sufficiently large endowment is established, allows those managing the funds to sign contracts and plan ahead while covering operating expenses, in contrast to many other watershed PES programmes that need to secure funding every year.

Limited reach for instream waters. Instream water and quality trading remain limited in geographical reach. Legal authority for protecting instream flows and water quality is in place in many countries, yet trading programmes operate only in the United States, Mexico and Australia. These countries' consistent and credible enforcement of laws mandating pollution reduction from non-point sources (in the case of water quality trades) or aquatic ecosystem protection (in the case of instream flows) creates a demand for trades. Trading systems need robust institutions to provide clear and enforceable rights as well as an accurate and accessible recording system.

Biodiversity and habitat

The biodiversity and habitat PES sector uses offsets to ensure no net loss. This sector remains the least developed in terms of geographical scope and is most challenging for countries to put in place. There are currently 120 biodiversity and habitat PES programmes: 16 user-financed and 104 compliance. Unlike in water PES for which the beneficiaries of clean water and flood protection are straightforward and local, the beneficiaries of biodiversity are often widespread and the specific benefits indirect or non-material. Institutions comparable to water utilities that can collect fees on behalf of many beneficiaries do not exist, and common metrics are difficult to determine. As a result, biodiversity PES programmes in the field remain limited to 36 countries, and the most successful initiatives rely on regulatory drivers (we do not include conservation easements or traditional conservation finance such as land purchase, because many of these are made to ensure open space rather than provision of a specific service). The very practice of offsets remains controversial, with strong opposition from NGOs worried about endorsing habitat destruction[12].

The compliance mitigation programmes that restore stream and wetland habitat benefit from strong regulations backed by credible enforcement and common agreement on currencies of exchange (such as wetland acreage)[13]. This sector is the least transparent in terms of availability of data on transactions or project implementation. Global transactions are estimated to be US$2.5–8.4 billion per annum, a wide range indicative of the difficulties in tracking payments. The calculation of range is explained in the Methods and the Supplementary Information.

Mitigation credits. Mitigation credit banks are growing but primarily in developed countries. With transactions estimated at US$3.6 billion per annum, compensatory mitigation banking continues to grow. It has not spread geographically, however; almost all the growth has occurred in the United States, Australia, Canada and Germany (where wetlands are the largest habitat type offset). Mitigation banking has been introduced on a voluntary basis in Malaysia and for compliance purposes in the Northern Mariana Islands, and is in the process of being piloted in Colombia; otherwise, it is found only in developed countries. In developing countries, mitigation carried out directly by the party producing the impact or by a subcontractor, known as 'permittee-responsible mitigation', is the most commonly found option for compliance, although many countries (including Brazil, Cameroon, China, Colombia, Egypt, India, Mozambique and South Africa) allow developers to pay a compensation fee in lieu of an offset, which is generally used to fund conservation projects carried out by the public sector or an NGO.

Mitigation banks take on from developers the risks and complexity of undertaking an offset. From an efficiency and ecological perspective, large mitigation banks can achieve economies of scale in design, maintenance and monitoring, enabling them to protect larger contiguous areas that offer better ecological outcomes than smaller, isolated permittee-responsible mitigation projects. An effective mitigation system requires strong laws, effective monitoring compliance and credible enforcement. Transparency, however, remains a persistent problem. Despite the market's size, data on credit prices remain difficult to obtain, and relatively little market infrastructure has emerged (brokerages, accounting services, standards) compared with newer markets such as carbon. There are also concerns over whether the currency of exchange adequately reflects ecosystem service values and can meaningfully ensure no net loss[14,15].

Voluntary offsets. Voluntary biodiversity offsets are a recent policy development and remain small. They generally take the form of one-off projects undertaken by companies for reasons ranging from social corporate responsibility to risk management. This approach rests on developing a persuasive business case for voluntary offsets. Many 'voluntary' offsets have in actuality been 'pre-compliance' offsets, where a developer has sought to develop offsets in advance of expected regulation or to demonstrate sufficient conservation to preclude regulation. Just 16 projects have been reported, and even fewer have independent verification.

Forest and land-use carbon

The forest and land-use carbon market has received the most attention of any PES sector. A policy instrument to combat climate change, US$2.8 billion has been spent since 2009 for forestry and land use practices that sequester carbon and quantify carbon benefits in the form of a standardized offset. There are currently 48 forest and land-use carbon PES programmes: 31 government-financed and 17 compliance. Over the past 20 years, markets and funding mechanisms for climate mitigation have emerged all over the globe—from purely voluntary exchanges (CCX) to international funding mechanisms (BioCarbon Fund), state mandates (California's AB-32) and international treaty flexibility mechanisms (CDM). The Paris Agreement endorsed continued market development, introducing the term "Internationally Transferred Mitigation Outcomes". The four main sources for forest and land-use carbon offsets include afforestation/reforestation, improved forest management (IFM), sustainable agricultural land management, and reduced emissions from land use and forest degradation (REDD), which may include afforestation/reforestation, IFM or agricultural interventions (Table 3).

Supply far exceeding demand for voluntary forest carbon. The number of voluntary projects marketing offsets to buyers motivated by corporate social responsibility (CSR) or in anticipation of future compliance obligations has continued to grow, with forest carbon the dominant project type on the voluntary market for the past 2 years, surpassing renewable energy-based project types in market value. Nonetheless, demand from philanthropy and private sector programmes satisfies only a small fraction of the available supply for carbon offsets. There is no obvious prospect for significantly increased demand.

Limited impact of compliance carbon markets. Neither the Clean Development Mechanism nor the European Union Emissions Trading Scheme has directed large investment flows to forest conservation. California's Air Resources Board has been more receptive to

Table 2 | Biodiversity/habitat PES

PES mechanism (category)	Definition	Example	Market size 2008 → 2016	Number of programmes	Distribution (countries)
Wetlands and stream mitigation (compliance)	To compensate for filling wetlands or streams, developers purchase credits for comparable wetlands and streams created offsite that have been certified by a government agency.	Under the US Clean Water Act, a permit for development of wetlands can require the purchase of mitigation credits from an offsite bank of created wetlands.	US$1.3–2.2 billion → US$1.4–6.7 billion	5	1
Compliance biodiversity (compliance)	To comply with regulatory requirements that mitigate impacts on biodiversity, developers can purchase credits for a specific habitat type that has already been created by a third party as an offset, purchase biodiversity credits created in a similar manner or pay into a general offset fund.	The Biodiversity Offsets and Banking Scheme (BioBanking) was launched by the state of New South Wales in 2007 to offset habitat impacts from development. Developers can purchase credits from conservation management activities such as managing grazing, removing invasive species or creating habitat corridors, for trades that match 'like for like' credits and impact according to the habitat type.	US.5 billion → US$1.1–1.7 billion	99	33
Voluntary biodiversity offsets (government-financed)	Developers choose to mitigate the impacts of projects through measurable conservation outcomes intended to achieve no net loss, or preferably a net gain, of biodiversity with respect to species composition, habitat structure, ecosystem function, and people's use and cultural values associated with biodiversity.	In Sabah, Malaysia, the Malua BioBank contains one of the world's highest concentrations of orangutans. The government of Saba worked with private parties to invest in the restoration and maintenance of 34,000 hectares of rainforest. The BioBank sells 'biodiversity conservation certificates', with each certificate representing 100 square metres of forest restoration and protection for at least 50 years.	US$20 million → US$10.5 million	16 implemented project sites	11

Table 3 | Forest and land-use carbon PES

PES mechanism (category)	Definition	Example	Market size	Programmes	Distribution (countries)
Voluntary forest and land-use carbon market (user-financed)	Buyers willingly purchase offsets outside government regulation—although 'pre-compliance' demand anticipating regulation counts as voluntary.	Companies such as Microsoft, Disney and Natura Cosméticos voluntarily purchase forest carbon offsets to meet corporate social responsibility commitments.	US$46 million (2009) → US$74.2 million (2016)	n/a	67
Compliance forest carbon market (compliance)	Regulation on greenhouse gas emissions, typically through cap-and-trade, allows forest carbon sequestration or avoided deforestation to provide offsets for emissions.	California's cap-and-trade programme, launched in 2013, includes US forestry as one of its offset protocols.	US$5 million (2009) → US$551.4 million (2016)	4 (2009) → 17 (2016)	8
REDD readiness finance (government-financed)	Mechanism under the United Nations Framework Convention on Climate Change in which developing tropical forest countries receive payments from countries for implementing activities that avoid deforestation and maintain carbon stocks in standing forests.	The World Bank Forest Carbon Partnership Facility Readiness Fund provides support to countries preparing to receive REDD+ payments, including development of national REDD+ strategies, systems for monitoring, reporting and verification, and reference emission levels.	US$3.2 billion (2009) → US$8.1 billion (2014)	28 (2014)	28 (2014)
Public sector payments for performance (government-financed)	Developed countries may agree to pay developing countries for reducing deforestation (REDD), with payments flowing once results are achieved.	Norway pledged US$1 billion to Brazil's Amazon Fund to reduce the deforestation rate in Brazil. Because Brazil has reduced deforestation more than 80% since 2004, most of the money has been disbursed.	US$2.9 billion committed, US$218 million disbursed (2014)	3 disbursed funds (2014)	3 disbursed, 23 pending (2014)

these project types: 65% of all offsets issued by the Board as of 2017 were from forestry and land-use projects. However, volumes transacted in 2016 (4.1 million tonnes CO_2 equivalent) were still small compared with overall offsets markets activity, and the requirement that all offset projects must be based in the United States (excluding Hawaii and only for certain regions in Alaska) limits potential for scale. The Paris Agreement explicitly recognized the importance of forests in mitigating climate change, but subsequent negotiations have not yet resulted in agreement on the role for forest and land-use carbon offsets in meeting emissions reduction targets.

Uncertain future of REDD+. Funding for REDD+ and REDD Readiness (building capacity to accept payments for performance) has dominated the PES carbon sector. Developed countries have pledged over US$8 billion in funds for REDD Readiness through 2020 (46% from Norway) to 67 tropical forest countries and almost US$3 billion for payments for actual emissions reductions. Although $8.1 billion has been documented in Readiness funds disbursement, progress in making payments for actual performance has been slow: as of 2017, only US$218 million had been paid out to countries for emissions reductions. Without REDD+, the prospects for forest carbon PES are much diminished. The Paris Agreement endorsed the REDD+ approach, but the focus on Nationally Determined Contributions creates considerable uncertainty over how many national and subnational programmes will accept REDD+ credits from other countries for compliance obligations.

Assessing the effectiveness of PES

The data in the preceding sections on geographical coverage, number of programmes and value of transactions reveal much about PES growth. Importantly, however, these data cannot measure the effectiveness of PES in terms of service provision (a biophysical measure), efficiency (an economic measure) or improvement of social welfare (such as poverty reduction, gender equity or securing property rights). A literature review of the effectiveness of PES reveals that spending money, in and of itself, does not guarantee provision of valuable ecosystem services. For the vast majority of programmes, we simply do not know their effectiveness[16–18]. Research has provided very mixed results when examining the effectiveness of forest PES[19–26] and watershed PES[17,27], as well the programmes' impacts on social welfare[16,24,28,29–37].

Like most conservation programmes, PES schemes are rarely established with a rigorous evaluation of effectiveness in mind[38,39]. Researchers studying them at a later date have often lacked baseline data, control areas or randomized design, making it difficult to evaluate counter-factuals—what would have happened without a PES programme[18,40]? Moreover, much of the literature has relied on case studies, introducing problems of selection bias[16]. The scant impact evaluation of PES in the field prevents meaningful analysis of the programmes' effectiveness or efficiency, hinders comparisons across programmes and frustrates understanding the trade-offs between environmental, economic and social/political goals that are particularly important in PES programmes that promote multiple benefits.

Discussion

Although there is considerable heterogeneity, a few PES mechanisms account for most of the growth in number, volume of transactions, size of transactions and geographical spread. The key question is why. In studying these programmes over the past decade, the Ecosystem Marketplace has found that focusing on the specific attributes of buyers, sellers, metrics and low-transaction-cost institutions explains well the trajectories of individual PES programmes.

Motivated buyers. As with all exchanges, PES is driven by demand: by the perceived scarcity of ecosystem services. The scarcity may concern water quality, flood protection, climate stability or loss of biodiversity. If a service is not scarce (or is scarce but taken for granted), there is no evident need to pay for it. Because many services are public goods, demand can be created through regulation or subsidies. This prevents free-riding and overcomes the collective action costs of organizing diffuse beneficiaries. It is thus no surprise that the largest PES programmes are all based on transactions mandated by compliance PES driven by regulation (such as mitigation banking) or government-financed PES (such as watershed PES financed through water utility bills or government payments). This also explains why the PES mechanisms of compliance biodiversity, instream flow and water quality markets remain limited to a small number of countries. The necessary governance capacity of laws and institutions to create regulatory demand is absent in many countries.

Motivated sellers. If PES payments are to provide or ensure service provision, then landowners need to be paid, and their behaviour must be sufficient to provide the desired service. Moreover, the size of the payment to landowners must be competitive with the opportunity costs. Put another way, PES on its own will make trees worth more standing than cut down only if the service payments to economically motivated landowners are as attractive as, for example, the extractive values of timber. In many settings, the revenue streams from PES will be inadequate on their own to change landowners' behaviour and may need to operate in tandem with regulation or other strategies. A key challenge for subsidy programmes lies in identifying those landholders that are most important for service provision. This requires an assessment mechanism to ensure the funds are spent most efficiently. Many subsidy programmes, however, do not condition payments on service provision capacity, either because of the transaction costs or concern over achieving a dual goal of poverty alleviation.

Metrics. Because PES is, by definition, an exchange of value for services, how the service should be measured is of prime importance. Most PES transactions do not operate as markets, in the sense of competing buyers and sellers. PES markets are only feasible where metrics are easily assessed and services are fungible, such as the carbon compliance market in California which trades in offset credits equivalent to one tonne of CO_2-equivalent emissions. Wetland and stream mitigation programmes also provide low-cost metrics, defining credits in terms of area of wetland and linear stream habitat lost/restored, often with additional quality weightings. These are proxies, however, and it remains contested how accurately they capture provision of services[13]. Metrics become ever more problematic in terms of definition and exchange once one moves to biodiversity and habitat, as seen by the difficulty in establishing the practical meaning of no net loss[41].

The choice of metrics presents a tension: easily assessed metrics reduce transaction costs and aid in exchanges, but they risk missing what really matters and may not, in fact, align with conservation goals. More rigorous metrics, by contrast, may accurately capture service values but be so unwieldy that transaction costs become prohibitive[13].

Low-transaction-cost institutions. As a practical matter, a PES programme requires a set of discrete buyers to pay for the service and a set of discrete sellers to be paid. Equally, there must be an efficient means of exchange to collect and distribute funds. This is fundamental to the success of many watershed PES programmes. Water utilities already exist to collect fees from beneficiaries. No individual negotiation is necessary, so the transaction costs are greatly reduced.

Once one moves away from services with clear and localized benefits, such as water purification and flood protection,

two institutional problems loom large. First, ecosystem services often span across the domains of different agencies and political jurisdictions, creating high transaction costs to mediate the different regimes. Second is the problem of diffuse beneficiaries. If everyone benefits from a public good such as biodiversity or carbon sequestration, then effectively no one can be charged. Philanthropic institutions such as the World Wildlife Fund or the Norwegian government's foreign aid for REDD can overcome these hurdles by aggregating demand on behalf of the public, but free-riding remains problematic.

With these factors in mind, it becomes obvious why government-financed watershed PES has scaled up as a successful strategy in terms of value, growth and geographical reach. The apparent relationship between watershed protection and water quality motivates buyers. Upper-watershed landowners are easily identified and can be paid to change their management practices. The clear metrics for implementation are based on development restrictions and subject to low-cost monitoring. Additionally, water utilities are already in place to collect fees from beneficiaries and pay suppliers. User-financed biodiversity PES, at the other extreme, generally lacks all of these attributes.

This does not mean, however, that simply because certain types of PES are unlikely to scale up they should be regarded as failures. In many parts of the world where conservation is most under threat, alternatives to PES may be infeasible and the preconditions for large-scale PES absent. As a result of weak governance capacity, regulation and credible enforcement may not be options. In those settings, PES mechanisms, even if operating at small scale, may represent the most promising 'second-best' conservation strategy.

Methods

The use trends of Payments for Ecosystem Services were obtained by searching in Google Scholar for articlescontaining either terms 'payments for environmental services' or 'payments for ecosystem services', using filters toscreen multiple versions of the same article. The trends from Google Scholar data were confirmed by the samesearch on Web of Science, which only has relevant data from 2005.

Overview of methodology. The Ecosystem Marketplace's launch in 2005 (ecosystemmarketplace.com) marked the first attempt to collect comprehensive data on PES programmes globally. As a first mover, the Ecosystem Marketplace was opportunistic, relying on a mixed methods approach to collect as much relevant information from PES programmes around the world as possible. Their strategies included semi-structured interviews, surveys, secondary literature reviews and analyses of registries. Surveys collected data on programme transactions, design, financing, seller characteristics, buyer characteristics, monitoring and evaluation activities, programme developers' expectations for future market outlook, and co-benefits (such as ancillary ecosystem services co-benefits or benefits to local communities). Surveys were provided to respondents in web-based and spreadsheet form. Interviews and desk research sought to collect identical data.

Although the goal was to be comprehensive, data availability or transparency and the limits of survey instruments were a challenge. Unless otherwise indicated, Ecosystem Marketplace does not extrapolate or report projects that we cannot verify. As a result, our findings should be considered a conservative or low-end estimate of actual activity. Description of the scope, criteria for inclusion, methods and response rates are provided below for watershed investments, forest and land-use carbon, and biodiversity offsets and compensation.

Scope of watershed PES. The study's scope encompassed any programmes using a transaction mechanism linking a buyer and seller, or buyer and intermediary party, in which the exchanges are intended to ensure the supplier's provision of watershed services (or some proxy indicator). We consider transactions to occur at the point of exchange between a buyer and a programme administrator or a buyer and seller directly. For compliance credits, we count transaction values toward the compliance year of the credit when it will actually be retired. A 'forward' credit sold in 2012 for the 2013 compliance year would thus be included in 2013 transaction values.

Programmes were classified as watershed investments for which transactions were linked to preservation, restoration, or enhancement of hydrological services as a primary goal of the programme. Thus PES for which hydrological benefits could be ancillary but are not the basis of payment, such as payments for achieved emissions reductions from avoided deforestation, were not considered to fall in our scope.

Data collection was designed to be as inclusive as possible in the interest of providing a comprehensive review of PES mechanisms for watershed protection, restoration or rehabilitation.

Criteria for inclusion in the report's scope were as follows:

Programmes must involve a transaction between two parties involving either money or in-kind compensation (such as agri-environmental inputs)
Programmes must have been active in at least the past 3 years (for example, made a transaction).
Preservation, restoration, or enhancement of hydrological services were identified as a primary goal of the programme. For example, a tree-planting programme driven by climate mitigation motives with ancillary hydrological benefits would not be considered within the report's scope. Nor would trading of water-use rights, which uses a market mechanism for allocation of a natural resource but does not necessarily result in a benefit for hydrological services.
The basis of payment must have been a land-use-based activity, such as agricultural management, forest conservation or ecological restoration. Thus payments for engineered infrastructure such as a pipeline or a well are not in scope. Nor are activities such as scientific research.

Costa Rica's national Payments for Environmental Services programme, which targets a bundle of ecosystem services including climate mitigation, watershed services, biodiversity and landscape beauty, proved challenging to categorize. The programme does not break out payments explicitly for every ecosystem service and therefore could equally be classified as carbon or biodiversity benefits. The buyer (Costa Rica's National Forest Financing Fund) explicitly identifies watershed services as a core component of the bundle of ecosystem services paid for and channels payments funded by water tariffs directly toward watershed restoration/conservation projects, so it was included in the watershed category to avoid double-counting. The programme had US$1.8 million in investments in 2015. It should be noted that true 'bundled' payments as seen in Costa Rica's programme are rare, so this issue did not arise with other programmes. The programme also serves as a useful reminder that the boundaries between user-financed and government-financed programmes can be blurred in practice: as noted, a portion of the programme's funding comes from water users themselves in the form of water tariffs.

Sampling strategy for watershed PES. As noted above, data collection was intentionally inclusive and systematic. Ecosystem Marketplace gathered data on watershed investment programmes from a wide variety of sources, including a global survey of programme administrators, ongoing desk tracking through programme reports, donor reports and databases, statistical yearbooks, credit registries, and interviews with programme administrators and market intermediaries.

A review of grey literature and other sources including news articles and programme websites was also conducted via an online search to identify programmes potentially fitting our scope. Search terms included: payments for watershed services; payments for ecosystem services; watershed incentives; catchment management incentives; reciprocal agreements for water; water fund; agri-environmental subsidies; eco-compensation; water quality trading; water quality offsets; environmental water acquisition and leases; instream buybacks; stormwater offsets; and stormwater trading.

Programmes identified in the scoping exercise were contacted with a request to complete the survey or participate in a semi-structured interview to share information about their programmes. Where individuals did not respond to this request, data were gathered from secondary sources to construct a programme profile. These profiles were shared with the programme administrator along with a request that they verify the information and supply any missing data.

For national or jurisdictional subsidy programmes making payments to landowners for agri-environmental or watershed management measures, data were collected from national statistical databases, statistical yearbooks or government reports. In cases where programmes were administered at subnational levels but used national government funding, national funding figures were used and subnational figures were discarded in order to avoid double-counting of transactions. In cases where funding figures were available only for multiple-year periods, the total budget for payments to landowners was prorated evenly across the overall time period to obtain annual estimated transaction values. Funds for administration or non-monetary support (such as budget for technical advice to landowners on implementing land management activities) were not included in transaction figures. Programmes that had begun before 2005 but with regular disbursements in the 2005–14 period are included in our analysis.

Response rates and quality checks for watershed investments. Overall, the data collection rate was 407 programmes, or 83% of the 488 programmes identified in a scoping exercise. We received survey data from 167 programme administrators overseeing active or developing watershed investment programmes in 2013 and gathered data on another 240 programmes through desk research and interviews with market actors. With respect to geographical distribution, the data collection rate was highest for North America (99%) and lowest for Latin America and the Caribbean (53%). External reviewers active in project development, policy or academia with expertise in particular regions or programme types (such as water

quality trading) were asked to review the draft text of the report to identify any major missing programmes or developments.

Scope and definitions for forest and land-use carbon PES. Our forest and land-use carbon market reports track global transactions of offsets generated from the sequestration or avoidance of carbon emissions from forestry projects (carrying out such activities as improved forest management, tree planting or avoided deforestation) and other land-use projects (such as restoration of wetlands).

The study was primarily based on data collected from forest carbon project developers. It investigated both compliance carbon markets and voluntary transactions of forest carbon offsets not driven by an existing regulatory compliance obligation. This includes transactions of offsets created specifically for voluntary buyers as well as regulatory market offsets or allowances that buyers voluntarily purchase to offset their emissions. It also includes transactions of offsets to prepare for compliance obligations.

We considered 'transactions' to occur at one of three points: when the offsets are contracted; when suppliers otherwise agree to deliver offsets immediately or in the future; or when suppliers agree to retire an offset on someone's behalf based on a donation model. Payment and delivery of offsets can occur simultaneously ('spot' transaction); payment can occur in advance of delivery ('pre-pay') or upon delivery ('pay on delivery') of offsets that will be generated from future emissions reductions. Contracts may define a specific volume of offsets to deliver ('firm' or 'fixed' delivery) or specify that delivery and payment are based on the volume of offsets that are actually generated by the project in the future ('unit contingent').

Buyers of forest and land-use carbon offsets are sometimes equally or more motivated by co-benefits generated by offset projects (such as biodiversity conservation or local economic development) than they are by the carbon sequestration or avoidance which offsets represent. However, because carbon is the basis of payment, these transactions fall within our scope and are considered payments for carbon rather than for other ecosystem services.

Our tracking of carbon transactions included both offset transactions in compliance and voluntary carbon markets, and results-based payments for emissions reductions through bilateral or multilateral agreements.

Sampling strategy for forest and land-use carbon PES. Data on offsets transactions in compliance voluntary markets were collected through an online survey designed for organizations developing forest carbon offset projects or acting as an intermediary (broker or retailer) supplying forest carbon offsets to buyers. The survey was conducted each spring between 2009 and 2017, with the exception of 2010 when no survey was conducted. The most recent survey in 2017 was disseminated to approximately 1,100 organizations identified as possible forest offset suppliers or retailers. The survey was available between 14 February and 15 August 2017.

We complemented the annual survey with data and insights provided by major registries, brokerages and exchanges, including: APX, Australia's Clean Energy Regulator Registry of Offsets Projects, BlueRegistry, Carbon Trade Exchange (CTX), the Chicago Climate Exchange Offsets Registry Program, CDC Climat, CF Partners, Climex, Evolution Markets, GHG Clean Projects Registry, Japan Verified Emission Reduction (J-VER) Registry, Korea GHG Reduction Registry Center, Markit Environmental Registry, Numerco and TFS Green.

Our analysis examined the volume of carbon offsets transacted to chart the size of the global marketplace in terms of carbon offsetting and future project investment. We did not track the individual 'lives' of offsets as they pass through the value chain. For example, if a project developer sold an offset to an offset retailer and then the retailer sold the same offset to a final buyer, we counted each transaction to derive the volume and value of transactions in the overall market. This methodology is consistent with most other marketplace analysis, such as the World Bank's annual reports on carbon pricing mechanisms.

Response rates and quality checks for forest and land-use carbon PES. As an example, in 2017, 199 organizations developing or actively marketing forest and land-use carbon offsets responded to the online survey, reporting a total of 259 unique transactions. Detailed data on land tenure, project-level finance and co-benefits were provided by 145 projects. It is critical to note that because of the fragmented nature of the market and confidentiality issues surrounding transaction data, it is impossible to capture all projects and transactions. In 2017, we received the largest number of responses from North American suppliers[32], followed by Europe[30], Latin America[28], Oceania[10], Africa[8] and Asia[7].

To minimize the occurrence of 'double-counting' volumes reported by offset suppliers and brokers, we asked respondents to specify the volume of offsets transacted through a broker or exchange. When we identified an overlap, the transaction was counted only once.

Because the aim of the study was to account for all voluntary and compliance payments for emissions reductions, we did not apply quality criteria screens for offsets included in calculations. However, we did follow up with dozens of respondents to clarify survey responses that were incomplete or raised a red flag. This included any responses that varied much from 'typical' market behaviours and thus would significantly influence analysis. In a few cases where we were unable to confirm that transactions occurred, responses were omitted.

Scope and definitions for biodiversity offsets and compensation. Data on biodiversity offsets and compensation come from Ecosystem Marketplace's *State of Biodiversity Markets 2010*[42], *State of Biodiversity Markets 2011 Update*[43] and *State of Biodiversity Mitigation 2017*[44] reports. These reports focused specifically on compensatory mitigation carried out within the framework of the 'mitigation hierarchy' (avoid, minimize, restore and then offset impacts to biodiversity). A scoping exercise conducted through online research used the following terms to identify and gather information on compensatory mitigation projects for the report: biodiversity offsets, mitigation banking, conservation banking, habitat credit trading, fish habitat compensation, BioBanking, compensation fund programmes, conservation certificates and Environmental Impact Assessment offsets.

Projects carrying out compensatory mitigation for impacts to biodiversity, habitats and species through either permittee-responsible offsets, mitigation banking or habitat crediting, or a financial compensation mechanism were included in our scope. Government-mediated payments for biodiversity, payments for ecosystem services and other market mechanisms such as certifications for biodiversity were not tracked. Payments for protected areas were also excluded from this study.

Sampling strategy for biodiversity offsets and compensation. Data were collected through three methods in 2017:

1. A survey collecting data on the size, scope and characteristics of biodiversity offsets and compensation mechanisms in 2016 worldwide. The survey was disseminated online during April and May 2017 to programme administrators, project developers and other market actors;
2. Personal communications via semi-structured phone and email interviews collecting identical data as the survey; and
3. Desk research investigating programme reports, donor reports and databases, academic journal articles, project registries and other primary and secondary sources. Additionally, a Freedom of Information Act request was submitted to the US Army Corps of Engineers (ACE) for data on Clean Water Act section 404 permits issued that had triggered compensatory mitigation requirements.

For the 2010 and 2011 studies, much less information was available from online databases and registries. Research depended on primary data obtained from regulators and project developers through a questionnaire or semi-structured interviews. A key reference for US-based offsets and compensation projects was the Environmental Law Institute's 2005 report[45]. Ecosystem Marketplace spent over 250 hours from October 2008 to July 2009 searching and requesting information on wetland mitigation banking to update the Environmental Law Institute's 2005 study. Data on offsets and compensation for species and habitats were collected in January–July 2009, June 2010 and March–April 2011.

Additional information was collected through online research reviewing US ACE District websites, state agency wetland mitigation banking websites, databases of peer-reviewed literature, grey literature, project websites, and interviews with academics.

Following this initial effort, we undertook another data collection effort from October 2010 to January 2011 (~200 hours), with a brief follow-up data collection in June 2011 (~15 hours). Corrections were made based on the 'District Mitigation Summary' reporting query function within the US ACE's RIBITS (Regional In-Lieu Fee and Bank Information Tracking System) wetland mitigation banking database.

Ecosystem Marketplace also made over 30 formal and informal information requests to US ACE headquarters, US ACE District offices, US Fish and Wildlife Service, and the California Department of Fish and Game offices. National-level and US ACE District-level information on area of mitigation, losses of wetlands, and categories of suppliers of offsets and categories of types of offset creation were obtained from the US ACE headquarters ORM database via a Freedom of Information Act request made in 2009 and again in early 2011.

For offsets and compensation projects outside of the United States, lists of approved projects were provided directly by regulators in Australia, Canada and the United Kingdom. In Canada, France, Germany and Malaysia, project developers completed a questionnaire. For German compensatory mitigation projects, project websites and personal correspondence with several experts in academia were used to check the completeness of our data.

Response rates and quality for biodiversity offsets and compensation. In total, data were collected on 3,769 projects in 2017: 2,135 mitigation banks, 1,223 projects carried out by compensation funds, and 341 permittee-responsible offsets projects. Most projects (3,117) projects were in North America, followed by Oceania (463), Europe (132), Africa & the Middle East[22], Latin America and the Caribbean[16], and Asia[9].

This geographical imbalance is largely explained by actual distribution of compensatory mitigation activity: strong regulatory drivers and enforcement capacity exist in North America, Oceania and Europe. However, transparency is also an important issue in this market segment. In the United States and Australia, publicly available data on compensatory mitigation projects and transactions are generally good and easily accessible via online databases and registries. In other countries, regulators make far less information readily available or up to date. Considerable efforts were expended to ensure good geographical representation,

including conducting interviews and desk research in multiple languages (French, Germany, Spanish, Italian and Chinese).

The complete dataset in 2011 included 1,137 banks or sites. Given a lack of transparency around offsets and compensation implementation during the time period when research took place, Ecosystem Marketplace was fully aware that there might have been many programmes that were not captured. As well, although we made every attempt to access quantitative figures for each programme to give a sense of its scale, many of the offset programmes covered either did not track national payment or area figures, or could not provide them.

Price data (in the form of prices associated with specific transactions, or average annual ranges) were provided anonymously by mitigation bankers and In-Lieu Fee programmes in interviews in 2010, 2011 and 2017. Price data on In-Lieu Fee programme price ranges were also provided by the US ACE and found through online research on secondary sources such as news articles, public agency meeting minutes, and annual reports or public datasets of major buyers such as state-level departments of transportation. A total of 191 price points were collected for the 2005–2009 period. A total of 384 price points were collected for the 2015–2016 period.

Analysis of biodiversity offsets and compensation. With the exception of the US Aquatic Resources Compensatory Mitigation and Conservation Banking programmes, transactions reported by programmes were simply summed to estimate annual transaction value. For the two programmes mentioned above, a different approach was taken. Price data were normalized to price per acre or linear foot, and used with data on bank transactions obtained from the RIBITS to estimate low-end and high-end values for total market annual transactions in 2016. See the Supplementary Information for a detailed explanation of this methodology.

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

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Author contributions

J.S. conceived the project, analysed the data and wrote the paper. G.B. performed data collection and analysis and wrote the paper. N.C. and A.G. performed data collection and analysis. M.J. edited the paper.

Competing interests

The authors declare no competing interests.

Additional information

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