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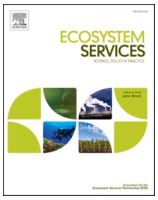

Payments for forest-based ecosystem services in the United States: Magnitudes and trends

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ABSTRACT

This manuscript reports on an effort to account, estimate, and document, to the fullest extent possible, direct payments for ecosystem services to private forest landowners in the United States. This includes payments derived from markets, subsidies, and hybrid approaches, from both governmental and non-governmental sources. Data were compiled from government agencies, public registries, and surveys of market participants. In some cases full reporting of program/market payments and forest area enrolled was possible. In other cases estimation was necessary, including averaging and interpolation by state and year, to create a conservative and comprehensive understanding of the nature, magnitude, and trends of programs and markets that provide payments for forest-based ecosystem services (PFES). Programs and markets were classified by categories of ecosystem services supported (carbon sequestration and storage, water quality and watershed protection, wildlife habitat, and bundled services), as well as payment mechanism (public payments, compliance transactions, and voluntary transactions). Findings show that estimated total PFES averaged $3.3 billion per year (2015 dollars), or about $17.69 per hectare of private forest per year over the decade 2010–19. This includes an average of $176 million per year for carbon, $889 million per year for water, $1529 million per year for wildlife habitat, and $754 million per year for bundled services. Hunting leases in particular are the largest payment source for private forest landowners, and have grown substantially up to $1.6 billion in 2016. At the same time, compliance and voluntary markets for carbon and water have also grown. In particular, the establishment of a market for carbon offsets within California's cap-and-trade program has increased the size of forest carbon offset markets by two orders of magnitude from $3 million in 2010 to $326 million in 2019. However, public programs connected to PFES have steadily decreased in real dollar terms over time, as has participating land area. Various states and regions in the U.S. have higher or lower level of PFES connected to different service categories, for various apparent reasons. Results suggest that some small, highly-urban states received high levels of payments for conservation easements. Other states with a large agricultural land base relative to forestry received relatively high levels of public conservation program payments. Some states with both large private forest area and large urban centers had high values of payments for recreational access, such as hunting and wildlife viewing.

1. Introduction

Forest ecosystems in the United States provide a large number of socially-valuable ecosystem services including water quality regulation, air quality regulation, wildlife habitat, and carbon sequestration and storage (MEA 2005; Warnell et al. 2020). While production of many ecosystem services are potentially complementary with income-generating activities such as timber harvest, these traditional income streams from forests are often lower than from alternative land uses such as agriculture or urban development (Cubbage et al. 2020). In the absence of economic compensation to landowners for the production of ecosystem services, they are "externalities" whose production will be lower than the socially-optimal level that would be available if there were a functioning, competitive market for them (Baumol & Oates 1988).

Over multiple decades, numerous public and private mechanisms have become established to compensate fully or partially some private landowners for production of ecosystem services, thus potentially

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getting closer to socially-optimal production. Broadly, these mechanisms can be called "payments for ecosystem [or environmental] services" (PES), although they operate through a variety of approaches. At the outset, the concept of PES was narrowly tailored to include market-based mechanisms with well-defined property rights, largely based on the theoretical work of Ronald Coase (1960; Muradian et al. 2010). However, an alternate approach is for government to tax a negative externality or subsidize a positive externality (Pigou 1920). Over time, the term "PES" came to include strategies using both markets, subsidies, and hybrid approaches (Diswandi 2017; Muradian et al. 2010; Wunder 2015). Examples in the United States include voluntary markets for hunting leases, government conservation programs that share costs of implementation and rent farmland for establishment or protection of trees,[1] and compliance markets for carbon credits (Mercer et al. 2011). The conditions for participating in these mechanisms, including eligibility requirements, participation procedures, approaches for measuring and monitoring production of services (if they are measured at all), and other formal and informal rules and preferences, vary widely, as do compensation rates and formulas (Wunder 2015).

Private lands account for 58% of the forest cover in the United States, and significantly higher percentages in some states and regions such as the southeast and northeast (Oswalt et al., 2014). With such a high percentage of forest-based ecosystem services that support human populations coming from private lands, there is significant interest in the United States in using payment mechanisms to provide financial incentives for private forest landowners to maintain and increase these services (Mason et al. 2020). An ideal PES program, whether market or subsidy, would be based on perfect knowledge of quantities of ecosystem services produced, and the aggregate utilities of consumers and producers of the services. There has been substantial recent effort devoted to ecosystem service/natural capital accounting and mapping in the United States (Hein et al. 2020; Keeler et al. 2019; Mason et al. 2020; Warnell et al. 2020). Parallel to this effort, significant progress has been made in estimating the economic value of various types of ecosystem services (Hellerstein & Lohr 2020; Johnston & Bauer 2020; Sills et al. 2017). Still, PES markets, policies, and programs generally rely on proxy measures or cost of implementation, rather than known service quantities or economic values.

Despite the disconnect between existing PES programs and economic valuation, private forest landowners remain interested in these financial incentives (Andrejczyk et al. 2016; Ruseva et al. 2015), and such incentives have been shown to impact their behavior positively (Lee et al. 1992; Song et al. 2014). However, the magnitude of the impact that financial incentives have on forest landowner behavior is often considered to be relatively weak, with many of the financial incentives going to those who might have undertaken the action anyway (Kilgore et al. 2007). In this context of disconnect, uncertainty, and public interest, it is important to understand the magnitude of existing programs and track them over time. Various past publications have explored the size and extent of portions of the PES programs markets at various scales and points in time. Mercer et al. (2011) conducted an accounting and compilation of payments for forest-based ecosystem services (PFES) in the United States. To our knowledge, no other published literature has comprehensively documented PFES within the United States, or tracked them temporally or geographically. They found payments averaging $1.80 billion (2005 dollars) per year during 2005–07, the equivalent to about $9.36 per hectare of private forestland per year, based on an estimated 192 million hectares of private forestland in 2006 (USDA Forest Service 2021). Of that total, about 21% came from governmental and 79% from non-governmental sources. A few further studies have estimated the size of voluntary and compliance markets for ecosystem service credits at different scales, representing a subset of services, or for a different set of ecosystems (e.g., Bennett et al. 2017; Donofrio et al. 2019; Salzman et al. 2018).

This manuscript reports on an effort to account, estimate, and document, to the fullest extent possible, direct payments to private forest landowners for ecosystem services in the United States. The objective of this research was to achieve the most robust and complete accounting of PFES possible, in order to provide a comprehensive understanding of the nature, magnitude, and trends of these programs and markets. We discuss broad spatial and temporal trends, as well as limitations and opportunities of PFES policies and markets. This includes payments derived from markets, subsidies, and hybrid approaches, from both governmental and non-governmental sources. It updates and expands upon the previous work by Mercer et al. (2011), and complements work by others on ecosystem service accounting, mapping, and valuation.

2. Methods

We compiled, processed, and analyzed data to compare payment amounts and forest land areas receiving PFES from various sources, across time and space within the United States. Data sources included government agencies, public registries, and surveys of market participants. The data upon which this manuscript is based are stored in a publicly-available database with time series from 2005-2019, along with a comprehensive description of methods used for data acquisition, processing, and estimation (where necessary), and assessments of completeness and accuracy for each data source and overall (Frey et al. 2021). A brief summary of this research will be published in the 2020 U. S. National Report on Sustainable Forests (Robertson, In press); this article relates a more comprehensive description.

The scope of this work is to focus on revenue sources, other than traditional forest product markets, for private forest landowners in the United States, which compensate them for providing ecosystem services. Private landowners include individuals, corporations, and non-governmental organizations. Payers can be (federal, state, and local) government agencies, non-governmental organizations, private individuals, or corporations. We do not include payments or expenditures related to activities on public forestlands.[2]

Since the focus is on revenues other than those for traditional forest products, we do not include revenues for timber and other wood products, such as sawtimber, pulpwood, woodchips, or fuelwood, nor do we include revenues for non-timber/non-wood forest products such as plants or fungi used for medicinal, edible, artisanal, decorative, or landscaping purposes. Following Mercer et al. (2011) and based on Wunder (2005),[3] we accounted revenue streams for forest landowners in exchange for the following categories of ecosystem services:

1. Carbon sequestration and storage
2. Water quality and watershed protection
3. Wildlife habitat

[1] Several federal and state programs follow this model, the most well-known of which may be the Conservation Reserve Program (CRP) administered by the U.S. Department of Agriculture (USDA) Farm Service Agency, as well as others including the Environmental Quality Incentives Program (EQIP) administered by the USDA Natural Resources Conservation Service.

[2] Excluded also are payments to public agencies for mitigation banking or similar programs on public lands. Although mitigation banks have been built on public lands, there are no known cases of federal land agencies requiring payments for use of public land to create mitigation banks (Doyle et al. 2020).

[3] Wunder (2005) also includes a category for "Landscape beauty;" although some U.S. programs' stated justifications have components of payments for this service, they are almost always are bundled together with other types of services.

4. Bundled services[4]

In general, we included any type of direct financial payment to a private landowner for them to do something, refrain from doing something, or allow access to forests, which is justified by providing, increasing, or maintaining forest-based ecosystem services. This includes public programs that provide payments for forest- or tree-related conservation practices; purchase of ecosystem service credits or offsets; conservation easements; and leases and access fees. In-kind benefits were not included as no funds change hands, and payments related to technical assistance (e.g., to hire a forester to create a forest management plan) were not included since they are not directly related to a forest management activity. Revenues were grouped by the payment mechanism under which the financial transaction took place, including public payments, compliance transactions, and voluntary transactions.

2.1. Data

2.1.1. Public payments

Public payments are revenues received by private forest landowners from federal, state, and local government agencies. These payments generally take one of two forms: a cost-sharing payment in which the government agency reimburses a landowner for a portion of the costs of completing a conservation practice, and/or a temporary rental payment in which the government pays the landowner to maintain or conserve the land in some state.

We obtained administrative data for the largest and most well-known conservation payment programs for the years 2005–2019 where available, from four federal government agencies: U.S. Department of Agriculture's (USDA) Natural Resources Conservation Service (NRCS), USDA Farm Service Agency (FSA), USDA Forest Service (FS), and U.S. Department of the Interior's Fish and Wildlife Service (FWS). Most of these programs operate as cost-sharing programs, or as a of combination cost-sharing and rental (Table 1).

To obtain information on state-implemented programs, we contacted state forestry agencies in each of the fifty states. We asked for basic information on the purpose, activities funded, and method of payment for each qualifying program, and aggregate land area and landowner payment data for the period 2005–19.

2.1.2. Compliance transactions

Compliance transactions are payments within market mechanisms developed in response to mandatory government regulation. Buyers pay sellers for credits which offset or mitigate some environmental impact or damage that the buyer created (and in some cases includes banking credits in the present to offset some potential future damage). Typically, the seller has to have created the credit by doing some land-management practice that would not have taken place otherwise, such as building a wetland where there wasn't one previously or planting trees on cropland.

In order to avoid a single seller selling credits that do not meet appropriate standards, or selling the same credits to multiple buyers, projects must be registered and verified, and sales transactions tracked in public databases. When a credit is "retired," it has been sold to the buyer to offset their environmental impact, and removed from markets so that the same credit cannot be traded again.

Carbon compliance transactions include those which fall under California's cap-and-trade program. Data on retired forest carbon compliance credits were obtained from the California Air Resources Board's Offset Credit Issuance Table (ARB 2020). Water quality compliance transactions include payments for wetland and stream credits to meet requirements under the Clean Water Act, as well as other federal or state-level policies. Conservation banks include creation of habitat for specific species protected under the Endangered Species Act, as well as other federal or state-level programs. Data on retired water and wildlife habitat compliance credits were obtained from the U.S. Army Corps of Engineers' Regional In-lieu Fee and Bank Information Tracking System (RIBITS) (Martin & Brumbaugh 2011; USACE 2020) (Table 1).

In order to know the amount of the payment to a forest landowner, one must multiply the credits retired times a price per credit. Credit tracking systems such as RIBITS do not track prices. Forest Trend's Ecosystem Marketplace tracks average credit prices through surveys, some details of which are published in various reports (Bennett et al. 2017; Donofrio et al. 2019; US EPA 2020), and additional data was made available by the organization.

2.1.3. Voluntary transactions

Voluntary transactions include sales of credits, access rights, leases, or easements in unregulated markets. Voluntary carbon offset sales operate similarly to compliance transactions, which include offset purchases by individuals and corporations trying to meet sustainability goals and in some cases include early actions of buyers to offset limits in a potential future compliance market (Galik & Olander 2018). Since the buyer has an interest in ensuring their funds are allocated to the intended purpose, the offset is real, and the seller does not sell the credit multiple times to different buyers, verification and registration mechanisms are used to track credits. Three primary carbon registries have emerged in the U.S.: American Carbon Registry (ACR), Climate Action Reserve (CAR), and Verra. We downloaded data on retired credits from their publicly-available databases (ACR 2020; CAR 2020; Verra 2020). Price data was obtained from similar sources as described in the section on compliance transactions.

Relatively large markets do exist in many states for wildlife habitat services, in the form of leases and entrance fees for hunting and wildlife viewing on private properties. The U.S. Census Bureau and FWS jointly administer a national survey of hunters, wildlife-viewers, and anglers every five years (FWS, 2006, 2011, 2016) which details expenditures on these activities, including leases and entrance fees.

A final category of voluntary transactions is the purchase of conservation easements on forested land, which permanently place certain restrictions on the owners' rights to use the land. In the case of forest easements, the owner would not be able to convert the land to agriculture, residential, commercial, or similar uses. Easements can either be sold or donated. We included only the former, since those are the type that involved direct monetary payment (donated easements can generate tax incentives, but those are not considered here). Forest conservation easements are frequently justified by multiple ecosystem services, so they are categorized in the "bundled services" class. Information on conservation easements was obtained from the Trust for Public Land (TPL) and Ducks Unlimited, which survey and compile easement data from national, regional and local land trusts and conservation non-profits (DU & TPL, 2020; TPL, 2020).

2.1.4. Data limitations

Unfortunately, piecing together information from numerous sources has inherent limits and precludes the possibility of providing a complete accounting. Due to the time and resources required, we limited our search of public payments to the largest federal programs and a direct inquiry to state agencies. Not all states provided information on their existing PFES programs. Voluntary and compliance transactions were based on existing data from registries and previously-conducted surveys. One-off contracts that do not fit into the registries or programs outlined above, and some local or small programs are not included. Also, additional categories such as tax incentives, price premiums paid by

[4] The latter category, "bundled services," represents payments for production of a suite of forest-based services or those for which no clearly-defined, specific service is designated. They may include a combination of the previous three services, or others not specified here. Timber and non-timber forest products are not included.

Table 1
Payment for forest-based ecosystem service (PFES) programs and markets in the United States, for which data were acquired, and sources of uncertainty for the final estimates of total payments.

Type/ category	Program(s) or market(s)	Payment meth. [a]	Agency [b]	Data source	Uncertainty source [c]
A. Public					
A1. Carbon	None recorded	N/A	N/A	N/A	N/A
A2. Water	Agricultural Management Assistance Program (AMA)	C-S/R	NRCS	FPAC-BC (2020b)	1
	Agricultural Water Enhancement Program (AWEP)	C-S/R	NRCS	FPAC-BC (2020b)	1
	Chesapeake Bay Watershed Initiative (CBWI)	C-S/R	NRCS	FPAC-BC (2020b)	1
	State programs	Varies [d]	State	[e]	7
A3. Wildlife habitat	Wildlife Habitat Incentive Program (WHIP)	C-S/R	NRCS	FPAC-BC (2020b)	1
	Partners for Fish & Wildlife (PFW)	C-S/R	FWS	FWS (2020d)	1
	North American Wetlands Conservation Act (NAWCA)	C-S/R	FWS	FWS (2020c)	4; 5 (08–09)
	National Coastal Wetlands Conservation Grant (NCWCG)	C-S/R	FWS	FWS (2020a, 2020b)	4; 6 (18–19)
	Landowner Incentive Program (LIP)	C-S/R	FWS	Mercer et al. (2011)	4
	State programs	Varies [d]	State	[e]	7
A4. Bundled	Conservation Reserve Program (CRP)	C-S/R	FSA	FPAC-BC (2020a)	1 (13–19); 4 (05–12); 6 (05–12)
	Conservation Reserve Enhancement Program (CREP)	C-S/R	FSA	FPAC-BC (2020a)	1 (13–19); 4 (05–12); 6 (05–12)
	Emergency Forest Restoration Program (EFRP)	C-S/R	FSA	FPAC-BC (2020c)	1
	Conservation Stewardship Program (CStP)	C-S/R	NRCS	FPAC-BC (2020b)	1; 7 (10–16)
	Environmental Quality Incentive Program (EQIP)	C-S/R	NRCS	FPAC-BC (2020b)	1
	Forest Land Enhancement Program	C-S/R	FS	Mercer et al. (2011)	1
	Forest Legacy Program (FLP)	E	FS	USDA Forest Service (2020)	1
	State programs	Varies [d]	State	[e]	7
B. Compliance					
B1. Carbon	California cap-and-trade	CT	CA ARB	ARB (2020)	2
B2. Water	Wetland mitigation banks	CT	State & USACE	USACE (2020)	2; 5
	Stream mitigation banks	CT	State & USACE	USACE (2020)	2; 5
	Water quality trading	CT	State & USACE	USACE (2020)	3; 5 (18–19); 7 (05–13)
B3. Wildlife habitat	Conservation banks	CT	State & USACE	USACE (2020)	2, 5
B4. Bundled	Mitigation and conservation banks	CT	State & USACE	USACE (2020)	2, 5
C. Voluntary					
C1. Carbon	Voluntary carbon offsets	CT	N/A	ACR (2020); CAR (2020); Verra (2020)	2 (11–19); 3 (05–07); 4 (08–10); 5 (08–19)
C2. Water	None recorded	N/A	N/A	N/A	7
C3. Wildlife habitat	Hunting	AF/L	N/A	FWS (2006, 2011, 2016)	3; 4; 5 (05, 07–10, 12–15, 17–19)
	Wildlife viewing	AF/L	N/A	FWS (2006, 2011, 2016)	3; 4; 5 (05, 07–10, 12–15, 17–19)
C4. Bundled	Conservation easements	E	N/A	DU and TPL (2020); TPL (2020)	2; 3; 5 (16–19)

N/A = not applicable

[a] – Method by which payments were made to the landowner. Abbreviations as follows: C-S/R = cost-sharing, reimbursement, and rental payment programs; E = permanent conservation easements; AF/L = access fees and leases; and CT = credit or offset trading

[b] – Implementing agency or governing body. Abbreviations as follows: NRCS = U.S. Department of Agriculture (USDA) Natural Resources Conservation Service; State = state agency; FWS = U.S. Fish and Wildlife Service; FSA = USDA Farm Service Agency; FS = USDA Forest Service; CA ARB = California Air Resources Board; USACE = United States Army Corps of Engineers

[c] – Uncertainty sources as follows (see table 2 for greater detail) (years for which each uncertainty source applies in parentheses): 1 - Complete or nearly complete; 2 - Complete or nearly complete quantity; survey for prices; 3 – Survey; 4 - Proportional allocation within state; 5 - State-wise interpolation; 6 - Proportional allocation by state in certain years based on years with complete data; 7 - Known or suspected data gaps; 8 - Other approaches; 9 - Alternate information sources.

[d] – 48 out of 50 state programs utilize a cost-sharing approach, sometimes in combination with grants and rentals. 2 of 50 used grants.

[e] - Data on state programs from a data request to state agencies.

consumers for sustainable harvested timber and wood products, leases and access fees for forest-based recreation other than hunting and wildlife viewing (e.g., camping or hiking), payments from water utilities or other sources for watershed protection outside wetland and conservation mitigation markets tracked by RIBITS, and incentive payments by forest industry or forest professional associations could not be included in the analysis since no consistent data source that tracks those data over time was identified.

RIBITS was expanded from a pilot to the national level in 2007, and should include comprehensive coverage of any bank or in-lieu fee mitigation projects approved by the U.S. Army Corps of Engineers since then. Furthermore, most projects from before 2007 have also been incorporated (Martin & Brumbaugh 2011), but it is impossible to completely discount the possibility that some pre-2007 projects might have been missed.

Water quality and wildlife habitat compliance can take three forms: mitigation banking, in-lieu fee mitigation, and permitee-responsible mitigation (EPA 2008). In the former two forms, a permitee (who is making an impact that needs to be offset) pays a third-party for mitigation that occurs off-site. With banking the mitigation generally occurs before the impact, while with in-lieu fees the mitigation occurs after the impact. These two forms of mitigation are documented in RIBITS (Martin & Brumbaugh 2011); however, permitee-responsible mitigation is not. In this last form, the permitee undertakes mitigation itself, so in theory no payment is made to a third-party landowner. Since this form of mitigation is conducted by the same entity creating the impact, there may not be any direct payment to a private forest landowner that would qualify as PFES. However, conceptually, a permittee could independently contract with a third-party landowner outside the conventional mitigation system. It is unknown if such independent contracts exist. Such a contract would be considered PFES by our criteria but would not be included in RIBITS data.

Some sources were able to report both payments (dollars) and land area (hectares or acres) for various programs. However, frequently, land area was not available, since programs use different units of measure, such as linear feet of forest buffers planted, tons of carbon dioxide sequestered, or pounds of nitrogen removed from waterways. We were unable to devise a way to reliably estimate land area from these various units of measure. Therefore, we only report land area for those programs which reported it – typically bundled service payments.

Even though we utilized the most comprehensive datasets available, some are based on estimates from surveys or are not frequently updated. Also, some sources grouped payments to forest and non-forest, or private and public lands together. We used estimation procedures described below in these cases. Furthermore, acquisition of certain survey data sources was limited by confidentiality concerns, particularly in cases where the number of transactions was small. For credit/offset trading, although we were generally able to obtain information on quantities traded, data on price per unit of ecosystem service transacted were a frequent limitation.

2.2. Estimation procedures

Our goal was to obtain full accounting of payments only for forest-based ecosystem services, from private forest lands, in each state, for each year (2005–2019). We included payments in all 50 U.S. states, but not U.S. territories. We sought information on dollars per state per year, and land area enrolled per state per year. Some of the data sources, in particular administrative data for certain public program payments, provided this information. However, other data sources had limitations, for which we used the following procedures to limit the values only to our desired types, or to find reasonable estimates. A detailed description of procedures used for each data source is available in Frey et al. (2021). The following paragraphs summarize the approaches.

First, some data included payments for non-forest conservation programs or practices, such as cropland or grassland practices. When possible, we extracted payment data for only those practices which were related to trees or forests (Frey et al. 2021). This was possible for programs from NRCS and FSA, and FWS's Partners for Fish and Wildlife. For carbon credits, only forest-related carbon credits were included. In the case of conservation banking, where possible, we limited credits only to include banking for forest species. In the case of wetland credit trading, credits were included only for classifications that denoted forest ecosystems. In cases where there was no way to limit to practices related to forests or trees, we allocated payments based on the proportion of forest to total rural land cover in the state. This was the approach used for data on hunting and wildlife-viewing leases and access fees, which could be for forest or non-forest land. This approach is narrowed by more specific land cover type where appropriate, for example, when a program focuses on wetlands but specific payments do not specify forested versus non-forested wetlands, we multiplied the total payments by the area of forested wetland area in the state and then divided by total wetland area in the state. This was the approach used for the NAWCA and NCWCG programs. Forestland and non-forest rural land cover data for these purposes were obtained from the National Land Cover Database (NLCD) (MRLC 2020) (Frey et al. 2021). By thus allocating payments proportionally by land cover class, we provide a conservative estimate of payments for forest-based ecosystem services, since forests generally provide a disproportionately larger share of most ecosystem services in the United States compared to other land classes (Warnell et al. 2020).

Second, we sought to ensure all payments were for private lands, not public. For most of the mechanisms included, public lands were not eligible, with some exceptions.

Third, in cases where data were incomplete for certain programs or payment types in certain years, we used interpolation or averaging of values by state or states to estimate revenues in those years. For example, with for hunting and wildlife viewing leases and access fees, we used survey data for expenditures by state for the years 2006, 2011, and 2016 (FWS, 2006, 2011, 2016) and estimated the amount attributable to private forest land using the procedure described above. Then, we used linear interpolation by state to estimate the years between 2006 and 2011, and between 2011 and 2016. After 2016, we held those expenditures constant in real terms. In cases where aggregate information on payments was available for a particular year, but not state-level, we estimated states individually in a proportional way such that the sum of the estimated state values was equal to the actual aggregated total.

Fourth, several market-based credit or offset trading programs had relatively complete registries of the amount of credits traded, but no information on the price at which they were bought or sold. The price data obtained from Forest Trends' Ecosystem Marketplace was relatively sparse in terms of not covering all years and all states. We used a combination of averaging by year and interpolation to generate price estimates for each state. Finally, all dollar values were converted to real 2015 dollars using the GDP Implicit Price Deflator for the United States (OECD 2020).

2.3. Sources of uncertainty and degree of accuracy

Because of the data limitations and various estimation procedures used, as described above, there is uncertainty inherent in the results. Table 1 identifies the sources of uncertainty in each program or market, and Table 2 indicates the related degree of accuracy. There were nine data/estimation types, which each created a different source of uncertainty and had a different degree of accuracy, based on the authors' judgments (Table 2). Public payments, which largely correspond to bundled services, had a much higher degree of accuracy than compliance and voluntary payments. This is largely because the former category has clear administrative data and in most cases allowed filtering to forest-only payments, whereas the latter two categories frequently had registries of quantities sold but lacked comprehensive and consistent price data, or were based on surveys from a single point in time.

Table 2
Uncertainty sources, descriptions, and degree of accuracy in the resulting estimates, based on authors' judgment.

Number	Source type	Description	Degree of accuracy
1	Complete or nearly complete	Complete or nearly complete administrative data, sorted and filtered to include only those payments prescribed in the research definition/criteria.	Very high
2	Complete or nearly complete quantity; survey for prices	Complete or nearly complete data on quantity transacted, but estimation of price based on averaging of prices by state and year from a survey of market participants. In many such cases, prices are not available for each year/state combination, so interpolation and averaging are also used. In such case Note 5 fill are also used.	Moderate
3	Survey	Estimates derived from random-sample surveys of market participants.	Moderate
4	Proportional allocation within state	Estimates based on proportional allocation of payments/land area by state according to research definition/criteria (e.g., if data include payments for forest and non-forest, the total payments are allocated proportionally according to the forest cover to all rural land in the state). Also represents equal allocation to individual states for projects involving multiple states (e.g., in two-state projects, each state receives one half; in three-state projects, each state receives one third).	Low
5	State-wise interpolation	State-wise interpolation of yearly values between years where data are available. If no data available for a specific state in any year, that state is assigned the yearly average of states with data.	Very low
6	Proportional allocation by state in certain years based on years with complete data	State-wise proportional allocation of payments/land area when allocation according to specific criteria can be observed in some years through data filtering, but other years only have total payments/area and do not permit filtering.	Moderate
7	Known or suspected data gaps	Known or suspected data gaps where estimation was not possible. These should be considered lower bound values.	Very low
8	Other approaches	Other estimation approaches.	Varies
9	Alternate information sources	Values extracted from alternate information sources.	Varies

3. Results and discussion

3.1. Payments by mechanism type

Table 3 summarizes total U.S. PFES by year, payment mechanism, and ecosystem services category. PFES to U.S. landowners from all payment mechanism types were estimated to be $3.63 billion in 2019 (all values are real 2015 dollars), the most recent year with data available. This is the equivalent of an average $19.19 per hectare ($7.77 per acre) for the estimated 189 million hectares (467 million acres) of private forestland across the U.S. (USDA Forest Service 2021). Of these total 2019 payments, public payments accounted for $503 million (14%); compliance transactions provided $1231 million (34%); and voluntary transactions provided $1899 million (52%).

Looking more specifically at the method by which payments were made to the landowner, we identified four categories: (1) cost-sharing, reimbursement, and rental payment programs; (2) permanent conservation easements; (3) access fees and leases; and (4) credit or offset trading. In 2019, cost-sharing, reimbursement, and rental payment programs accounted for $475 million (13%); permanent conservation easements $214 million (6%); access fees and leases $1700 million (47%); and credit or offset trading $1244 million (34%). In general, most public mechanisms were related to cost-sharing, reimbursement, and rental payments; most compliance mechanisms were related to credit or offset trading; and most voluntary mechanisms were related to access fees and leases, and some credit or offset trading. Permanent easements included both public and voluntary approaches.

Table 4 summarizes the average annual payments for the ten-year period 2010–19. For this period, average annual payments to forest landowners averaged $3.35 billion per year (2015 dollars), or $17.69 per hectare ($7.16 per acre) per year. Payments included public payments of $605 million (18%), compliance transactions of $1077 million (32%), and voluntary transactions of $1667 million (50%).

3.2. State-administered public programs

In addition to obtaining data on public programs from federal agencies, we polled state forestry agencies about state-administered programs.[5] Although these programs only accounted for 2% ($12 million per year for 2010–19) of total public programs in our data, since they are less well-known than federal programs, some detail is merited here. Agencies in 29 of 50 states responded; three of 29 responding agencies reported that no such programs were implemented by state agencies in their state. Thirteen of the remaining 26 responding states reported multiple programs (between two to five programs per state); we recorded information related to 50 different state-implemented programs. Forty-eight of these programs use a method consistent with cost-sharing or reimbursement of expenditures (some of these 48 also include rental payments and smaller grants), and the remaining two programs exclusively use grants to landowners. Twenty-three programs are funded by federal agencies, and three were funded by a combination of federal and state appropriations. Sixteen were funded by state funds, either general budget appropriations (eight), special funds or a special tax (such as a tax on timber harvests that is used to finance replanting) (five), or a combination of the two (three). Of the remaining eight programs, two were financed by nonprofits and six had no response. Bundled services dominated state-administered PFES programs, averaging $12 million and 61700 hectares (152000 acres) per year (2010–19). By comparison, state-administered wildlife habitat PFES

[5] At time of writing this manuscript, these data on state-administered programs are summarized here and within the broader research data archive in Frey et al. (2021), but the detailed underlying data are unpublished. They are planned to be published at a future date in the USDA Forest Service Research Data Archive (https://www.fs.usda.gov/rds/archive/).

Table 3
Estimated annual (2005–2019) payments for forest-based ecosystem services by transaction type (public payments, compliance transactions, and voluntary transactions) and ecosystem services category (carbon sequestration and storage, water quality and watershed protection, wildlife habitat, bundled services). All values are millions of 2015 dollars.

Type/ category	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
	millions of 2015 dollars														
A. Public															
A1. Carbon	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
A2. Water	0	0	-	0	2	1	2	1	1	0	0	0	0	0	0
A3. Wildlife	38	40	41	52	57	73	80	56	58	41	44	40	37	42	42
A4. Bundled	558	598	541	614	595	589	592	562	542	526	564	602	557	539	460
SUBTOTAL	596	639	583	666	654	664	673	619	600	567	607	642	594	581	503
B. Compliance															
B1. Carbon	-	-	-	-	-	-	-	-	-	57	112	92	411	719	314
B2. Water	417	441	651	591	599	352	609	1,105	974	915	1,294	1,461	809	496	872
B3. Wildlife	2	1	3	12	9	3	1	9	4	3	12	38	16	29	42
B4. Bundled	-	-	-	-	1	1	1	5	1	1	3	1	2	2	3
SUBTOTAL	418	443	654	603	608	356	611	1,119	979	975	1,421	1,591	1,238	1,245	1,231
C. Voluntary															
C1. Carbon	1	2	2	2	3	3	3	3	5	4	4	7	7	5	12
C2. Water	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
C3. Wildlife	902	902	939	981	1,032	1,079	1,114	1,234	1,351	1,463	1,584	1,700	1,700	1,700	1,700
C4. Bundled	298	175	326	337	269	167	340	184	67	130	346	219	173	177	186
SUBTOTAL	1,201	1,079	1,267	1,321	1,304	1,249	1,457	1,421	1,423	1,597	1,934	1,926	1,881	1,882	1,899
TOTAL	2,215	2,160	2,504	2,590	2,567	2,268	2,741	3,159	3,003	3,139	3,962	4,159	3,712	3,708	3,633

Values may not sum to the subtotals or total due to rounding.
- = recorded as zero; no known payments of that type in the year indicated
0 = value recorded less than $ 0.5 million.
n.d. = no data; payments of that type are known/believed to have occurred in the year indicated, but no data source was identified

Table 4
Estimated average annual payments for environmental services, by service category and payment mechanism for 2010–19. All values are millions of 2015 dollars.

	Environmental service class				
Mechanism	**Carbon**	**Water**	**Wildlife habitat**	**Bundled**	**TOTAL**
Public	–	1	51	553	605
Compliance	170	889	16	2	1,077
Voluntary	5	n.d.	1,463	199	1,667
TOTAL	176	889	1,529	754	3,349

Values may not sum to the subtotals or total due to rounding.
- = recorded as zero; no known payments of that type in the year indicated
n.d. = no data; payments of that type are known/believed to have occurred in the year indicated, but no data source was identified

programs averaged only $112000 and 4900 hectares (12000 acres) per year, whereas state-administered water PFES programs averaged only $61000 and less than 20 hectares (50 acres) per year.

3.3. Payments by ecosystem service category

The largest amount of payments by ecosystem service category was for wildlife habitat (Table 3). In 2019, of the total $3.63 billion in payments, $327 million (9%) were for carbon, $872 million (24%) for water, $1,785 million (49%) for wildlife habitat, and $650 million (18%) for bundled services. Averaged over the ten-year period (2010–19) (Table 3), of the total annual $3.35 billion in payments, 5% were for carbon, 27% for water, 46% for wildlife habitat, and 23% for bundled services.

Most public PFES payments in 2010–19 were for bundled services, $553 million per year (91% of public payments); followed by wildlife habitat, which was $51 million per year (8%) (Table 4). Bundled PFES payments include cost-sharing and rental payments from well-known conservation programs such as the CRP/CREP (average $376 million per year 2010–19 for forest-related payments), EQIP ($110 million per year), and several smaller programs; as well as the FLP, which funds permanent conservation easements for private forestlands ($53 million per year). Public wildlife habitat payments were from programs including NAWCA ($29 million per year), PFW ($12 million per year), and the now-defunct WHIP ($9 million per year during this period). WHIP was substantially larger than $9 million per year during 2010–13, but was later subsumed into the EQIP program. Carbon- and water-specific payments were only a minor portion of public payments, although those services, as well as wildlife habitat, can be included in the suite of services promoted within the "bundled" services category. Many of the government programs noted here are actually substantially larger in dollar terms; however, the programs also included payments for non-forest land uses (e.g., cropland or grassland). Our estimates are only for forest- and tree-oriented practices within each program.

Most compliance transactions in 2010–19 were for the sales of watershed protection credits of $889 million per year (83% of

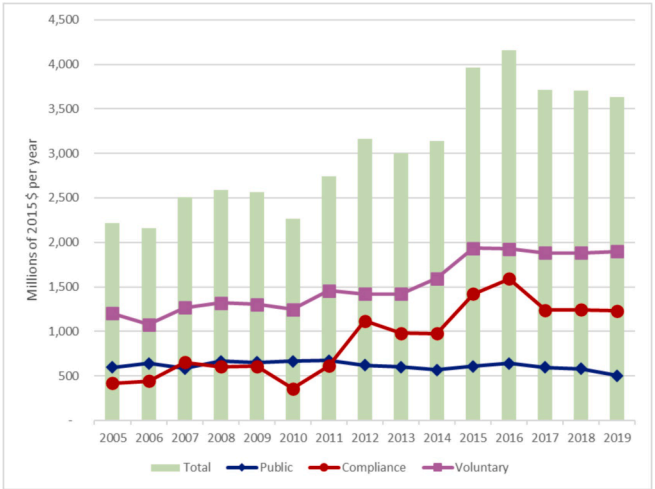

Fig. 1. Estimated total payments for forest-based ecosystem services by mechanism by year (2010–19) for the United States (millions of real 2015 dollars).

compliance transactions), followed by carbon offsets credits of $171 million per year (16%). Water compliance payments include trading wetland and stream mitigation banking credits to meet requirements under the Clean Water Act, as well as other state-level programs. Carbon compliance payments are related to California's carbon cap-and-trade program.

Most voluntary transactions in 2010–19 were for wildlife habitat, which was an estimated $1463 million per year (88% of voluntary transactions). The primary form of voluntary wildlife habitat payments is in the form of hunting leases and private entrance fees ($1332 million per year, or 80% of voluntary transactions). Indeed, payments for the right to hunt account for the single largest type of forest-based environmental service payments on private land in the United States. Privately-funded conservation easements were considered part of the "bundled services" category and accounted for 199 million per year (12% of voluntary transactions) (Table 3).

3.4. Temporal trends in payments

Fig. 1 shows temporal trends of PFES over the period 2005–2019 (2015 dollars), by payment mechanism category from 2010-2019. Overall, PFES grew substantially over this period, from $2.21 billion in 2005 to $3.63 billion in 2019, a 10-year real increase of 62%. However, our estimates show something of a decrease over the last few years, from a peak of $4.16 billion in 2016. From 2006, the year with the lowest estimated total payments, to 2016, total PFES increased 93%.

Much of the growth in overall PFES is attributable to two trends, first the creation and expansion of compliance markets for carbon and water quality, and second a continuous growth in voluntary markets for hunting leases and access fees on private forest lands. Compliance transactions increased from a low of $356 million in 2010 to $1231 million in 2019, peaking in 2016 at a value of $1591 million. The major contribution to the rise during 2010–2016 was from growing markets for wetland mitigation banking and carbon offset trading, however, there was substantial year-to-year variability. Voluntary transactions increased from $1079 million in 2006 to $1899 million in 2019, mostly reflecting a growing market for hunting leases. On the other hand,

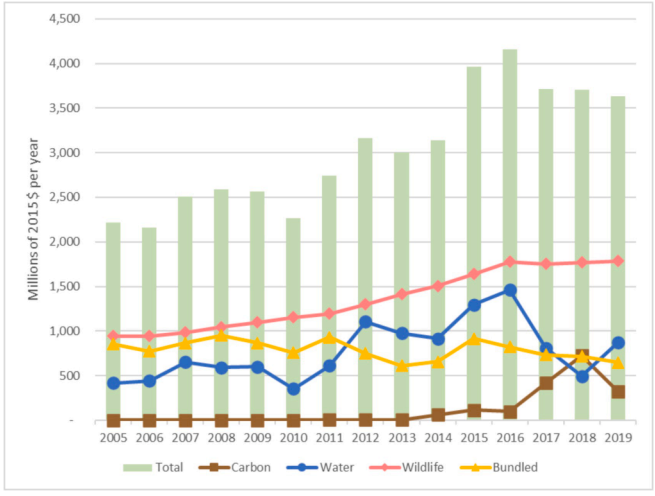

Fig. 2. Estimated total payments for forest-based ecosystem services by category by year (2010-19) for the United States (millions of real 2015 dollars).

public payments declined 25% in real terms from a high of $673 million in 2011 to $503 million in 2019. This is despite the fact that we believe there is some recency bias in the data; that is, reports on federal and state programs further back in time are less likely to have data available (thus recorded erroneously as zero), and older programs that have been discontinued may have been neglected. Thus, we believe the real decline of government payments over time to actually be somewhat steeper than that shown here.

Fig. 2 shows trends by environmental service class. Payments for carbon and wildlife habitat services both increased substantially over the period. Carbon payments grew from less than $1 million in 2005 to a peak of $723 million in 2018. Wildlife habitat payments increased from $942 million in 2005 to $1784 million in 2019. The increase in carbon payments has been driven primarily by the implementation of forest carbon offsets in California's carbon cap-and-trade compliance program, the first of which were issued in 2013. The increase in wildlife habitat payments is mostly due to a steadily growing voluntary market for leases and entrance fees to hunt and view wildlife on private land from 2006-2016.[6] Payments for water services, which include wetland mitigation, stream mitigation, and water quality trading, peaked in 2016 at about $1461 million. Payments for bundled services were highly variable but overall decreased during the period, from a high of $951 million in 2008 to a low of $611 million in 2013, rebounding in 2015 before declining again to $650 million in 2019. The declines in bundled service payments largely reflect lower funding (in inflation-adjusted terms) for public payment programs, as well as variability in purchases of new conservation easements.

Several changes and emerging trends may impact PFES magnitudes and patterns over the coming years. First, California's carbon cap-and-trade compliance program will reduce the percentage of compliance obligations allowed from offset from 8% through 2020 down to 4% from 2021-25 (ARB 2021). However, Donofrio et al. (2021) has documented a large increase in voluntary carbon offset in the time since the data reported in this research, with market size in the first eight months of 2021 already doubling that seen in all of 2019. This was attributed to corporations taking new initiatives to meet climate goals. Further, Donofrio et al. (2021) notes that voluntary market participants tend to prefer forestry and land use voluntary offsets over other types of voluntary carbon projects. Even though the voluntary forest carbon offsets as of 2019 was only 4% of the total forest carbon offset market in the U.S., such dramatic growth in the voluntary sector could blunt the impact of the changes in California's climate program.

Although participation in PFES mechanisms is open to private landowners for provision of a broad suite of services, to date, there has been substantial limitations and barriers to accessing the markets. If PFES programs seek to encourage provision of services from smaller parcels, such as those 0.4–40 hectares (1–99 acres) in size, which account for 94.8% of family forest ownerships and 42.0% of family forest area (Butler et al. 2020), they may choose to address these eligibility and investment barriers. For example, public programs may have eligibility requirements that exclude large portions of the landowner population (such as minimum area requirements), or which incur a cost (such as a mandatory forest management plan). Similarly, many of the credit and offset trading programs involve substantial investment in planning, monitoring, and evaluation, and may require commitment periods of decades or even centuries. In recent years, newer programs have been developed that aim to lower these transaction costs. These include Silvia Terra's Natural Capital Exchange (NCX), which features no participation fee for landowners and one-year commitment periods (Parisa et al. 2020), and the American Forest Foundation/The Nature Conservancy's Family Forest Carbon Program, which features no upfront costs, 10 to 20-year commitments, and access to information and professional assistance (AFF 2020). Both programs are in their infancy, and it remains to be seen what impacts they can generate.

The reasons for the increase in lease and land use/access fees for hunting on private lands over time are not clear, and comes despite an

[6] The bulk of wildlife habitat payments are from hunting and wildlife-viewing leases and entrance fees. The most recent survey data available on these expenditures are from FWS (2016). Estimates for subsequent years (2017–19) hold the 2016 values constant in real terms.

Table 5
Estimated annual average payments for forest-based ecosystem services (PFES) by state and service category for the decade 2010–2019.

State	State abbr.	Private forest land[a]	Carbon	Water	Wildlife habitat	Bundled	Total
		1000 has	millions of 2015 dollars				
Alabama	AL	8,710	0	25	76	15	117
Alaska	AK	14,608	42	0	9	2	53
Arizona	AZ	2,877	15	-	1	3	18
Arkansas	AR	6,139	1	5	71	16	92
California	CA	5,052	23	1	25	28	76
Colorado	CO	2,167	-	0	5	39	45
Connecticut	CT	509	1	1	8	10	19
Delaware	DE	113	-	0	2	5	7
Florida	FL	4,351	1	456	38	24	519
Georgia	GA	8,784	3	18	85	24	131
Hawaii	HI	235	-	0	2	5	8
Idaho	ID	1,192	-	-	4	14	19
Illinois	IL	1,625	0	3	15	57	75
Indiana	IN	1,608	0	0	25	10	35
Iowa	IA	990	-	0	6	58	64
Kansas	KS	919	-	0	3	16	20
Kentucky	KY	4,429	1	2	70	7	79
Louisiana	LA	5,235	0	130	35	22	187
Maine	ME	6,523	8	85	32	8	133
Maryland	MD	723	-	0	12	4	16
Massachusetts	MA	774	1	-	8	25	34
Michigan	MI	5,017	6	0	76	8	90
Minnesota	MN	3,203	0	3	27	32	62
Mississippi	MS	6,888	0	45	59	38	141
Missouri	MO	5,067	-	1	48	9	57
Montana	MT	2,688	0	0	4	19	23
Nebraska	NE	498	-	0	1	8	10
Nevada	NV	149	-	0	0	1	2
New Hampshire	NH	1,379	2	47	11	12	72
New Jersey	NJ	373	0	0	13	14	27
New Mexico	NM	4,358	6	0	1	7	15
New York	NY	5,538	5	-	146	5	156
North Carolina	NC	6,272	1	10	48	14	72
North Dakota	ND	235	-	0	1	19	20
Ohio	OH	2,673	-	1	44	7	52
Oklahoma	OK	4,209	-	1	22	4	26
Oregon	OR	4,314	4	0	8	15	27
Pennsylvania	PA	4,655	0	0	129	12	142
Rhode Island	RI	102	-	-	2	8	10
South Carolina	SC	4,529	2	2	42	15	61
South Dakota	SD	302	-	-	1	14	16
Tennessee	TN	4,675	5	2	63	11	81
Texas	TX	23,468	-	46	51	26	123
Utah	UT	1,066	-	0	2	7	9
Vermont	VT	1,444	0	0	11	3	15
Virginia	VA	5,326	6	4	72	10	92
Washington	WA	3,745	21	-	12	17	50
West Virginia	WV	4,208	17	1	37	4	59
Wisconsin	WI	4,781	3	1	66	20	90
Wyoming	WY	597	-	0	1	4	6
TOTAL		**189,321**	**1756**	**889**	**1,529**	**754**	**3,349**

Values may not sum to the subtotals or total due to rounding.
[a] from (USDA Forest Service, 2021).
- = recorded as zero; no known payments of that type in the year indicated.
0 = value recorded less than $ 0.5 million.

overall decrease in hunting participation from 2011-16 (FWS 2016). It is unclear if the increasing trend in payments to private forest landowners for hunting will continue to increase. Further, since the period of our data, the COVID-19 pandemic has affected outdoor recreation trends. The emerging research on the effect of COVID-19 on outdoor recreation show mixed results relative to hunting - in the initial months hunting participation was reported to have either declined (Rice et al. 2020) or stayed constant (Morse et al. 2020) relative to pre-pandemic levels. Rice et al. (2020) reported that use of private lands for recreation had increased relative to public lands.

3.5. Geographic trends in payments

Revenues from forest-based environmental services vary significantly by state (Table 5, Fig. 3a). The mean annual revenue per state over the period 2010–2019 was $67 million per state per year, with a median of $53 million per state per year. The states receiving the lowest total payments were Nevada (NV) ($2 million per year), Wyoming (WY) ($6 million per year), and Delaware (DE) ($7 million per year). The highest total payments occurred in Florida (FL) ($519 million per year), Louisiana (LA) ($187 million per year), and New York (NY) ($156 million per year).

Much of the variation in total payments per state can be explained by the total land area, proportion of forest cover, and land ownership patterns (public vs. private) in each state. To account for these state-level differences, we divided total payments by the private forest land area in each state (from USDA Forest Service 2021). Fig. 3b shows the total PFES per area of private forest land for each state. As stated

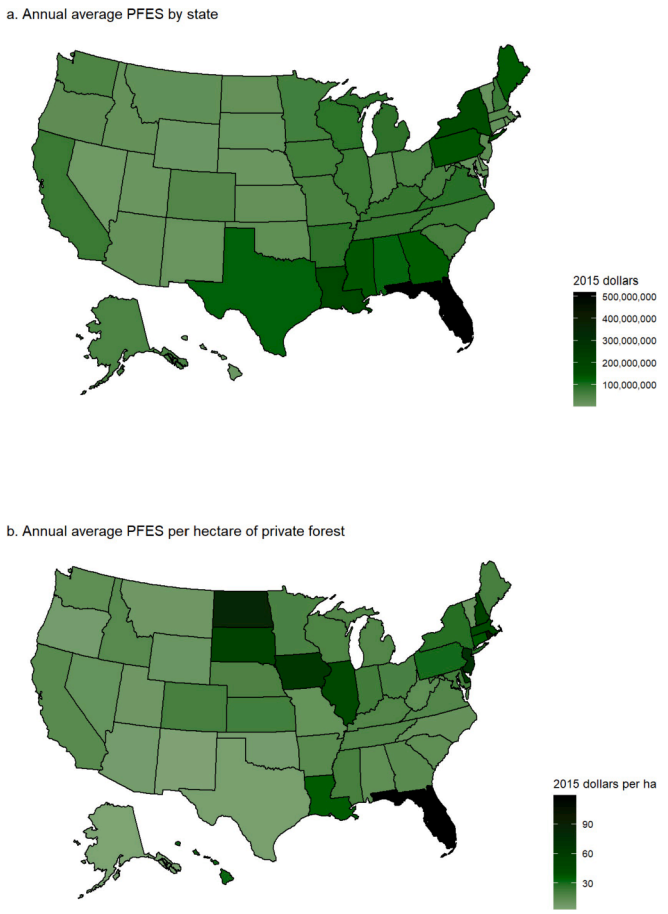

Fig. 3. Estimated total annual average (2010–19) payments for forest-based ecosystem services (PFES) (constant 2015 dollars). a. Payments by state. b. Payments per hectare of private forestland in each state.

previously, average payments from all sources across the U.S. was $17.69 per hectare per year of private forest land per year. When comparing across states, private forests in the median state received an average of $18.32 per hectare ($7.41 per acre) per year. These payments were lowest in New Mexico (NM) ($3.34 per hectare per year), followed by Alaska (AK) ($3.62 per hectare per year), and Texas (TX) ($5.22 per hectare per year). The states with the highest revenues per acre of private forest land were Florida (FL) ($119.32 per hectare per year), followed by Rhode Island (RI) ($98.42 per hectare per year), and North Dakota (ND) ($84.57 per hectare per year).

Strong spatial trends are difficult to discern from the consolidated map of total PFES (Fig. 3a-b). From this portrayal, there does appear to be an indication of higher payments per hectare in some states with small private forest area, such as in the "corn belt" and "northern great plains" states of Illinois (IL), Iowa (IA), North Dakota (ND), and South Dakota (SD), as well as the relatively small, urbanized northeastern states of Delaware (DE), Connecticut (CT), Massachusetts (MA), New Jersey (NJ), and Rhode Island (RI). On the other hand, some southeastern states with large areas of private forestland, including Florida (FL) and Louisiana (LA), also have high payments per hectare. Lower revenues appear in several states in the south-central, Rocky Mountain, and Pacific northwest regions, as well as the more rural northeastern states.

A full investigation of the factors correlated to or driving larger payments per hectare on average is beyond the scope of this manuscript. Still, there are a few trends that become more obvious when viewing the geographic distribution of PFES by ecosystem service category (Fig. 4a-h). In particular, it becomes clear that the high total PFES in the corn belt and northern great plains states are largely attributable to public payments, mostly the CRP and CREP programs. These are largely encapsulated in bundled services (Fig. 4g-h). Although we restricted payments to only those practices that are forest- or tree-related, these programs largely target installation of conservation practices on farmlands. Therefore, it is not surprising that highly agricultural states with small total forest area such as Iowa and Illinois (outside of the Chicago metro area) would have high levels of payments to farmlands. North and South Dakota are less agricultural, but also have very small areas of private forestland, so the ratio of private forest to farm is quite small. It is also worth noting that some of the forest- or tree-related conservation practices may result in tree plantings on farms that are too small or narrow to qualify as "forest" under the FIA definition (Oswalt et al., 2014), such as windbreaks/shelterbelts or narrow riparian buffers. This might further skew the ratio of payments to private forest area.

On the other hand, the northeastern states have relatively low levels of public payments, but high average PFES payments are from two quite different sources. First, high payments in states including Connecticut, Delaware, Massachusetts, New Jersey, and Rhode Island are largely or partly due to conservation easements in those states. In contrast to the corn belt and northern great plains states, the private forests that still exist in these northeastern states are threatened by urban development, and conservation easements are viewed as a way to permanently protect green space. Second, high payments in states including Pennsylvania, New Jersey, and New York are due to high levels of payments for hunting access on private lands, potentially also related to urban dwellers looking for a recreational opportunity outside of the city. New York and Pennsylvania are different from the smaller states listed above in that, while they do have large urban centers (New York City, Philadelphia, etc.), they also have large areas of rural land where hunting is common. New Jersey is somewhat intermediate in size and the other characteristics of the two distinct groups, and has high levels of payments both for conservation easements and for hunting access.

States in the southeast have high levels of private forestland and high levels of overall PFES, but Florida and Louisiana stand out. These two states have high levels of payments for water ecosystem services, related to large markets primarily for wetland mitigation. The rural northeastern states of Maine and New Hampshire also have active water quality markets. Finally, we note that Alaska (AK) stands out in the carbon market. Two of the three largest forest carbon projects in the Californian compliance program are located in Alaska.

3.6. *Participating land area*

Table 6 reports land area participating in PFES by year, payment mechanism, and ecosystem services category. Data on participating land area for many compliance and voluntary transactions are non-existent or incomplete, as most of those programs operate on the basis of credits or other measures, not land area. However, we obtained relatively complete information on land area participating in public payment programs.

The largest area of forestland participating in public payment programs were in the bundled service category, averaging 2.7 million hectares (6.6 million acres) per year over the decade 2010–2019. The majority of this bundled service area was enrolled through the FSA CRP and CREP programs, which jointly enrolled 2.0 million hectares (5.0 million acres) per year. This is followed by the NRCS EQIP program, which enrolled 0.5 million hectares (1.3 million acres) per year. Public wildlife habitat programs enrolled a total of 0.2 million hectares (0.5 million acres) per year, primarily through PFW (87,100 hectares or 215,000 acres), WHIP (60,400 hectares or 149,000 acres), and NAWCA (52,400 hectares or 129,000 acres). It is worth noting that WHIP was discontinued after 2014 and rolled into NRCS bundled services programs including EQIP; from 2010-2013 enrollment in WHIP averaged 148,000 hectares (365,000 acres) per year. Public water PFES programs only total 1600 hectares (4000 acres) per year, and much less since

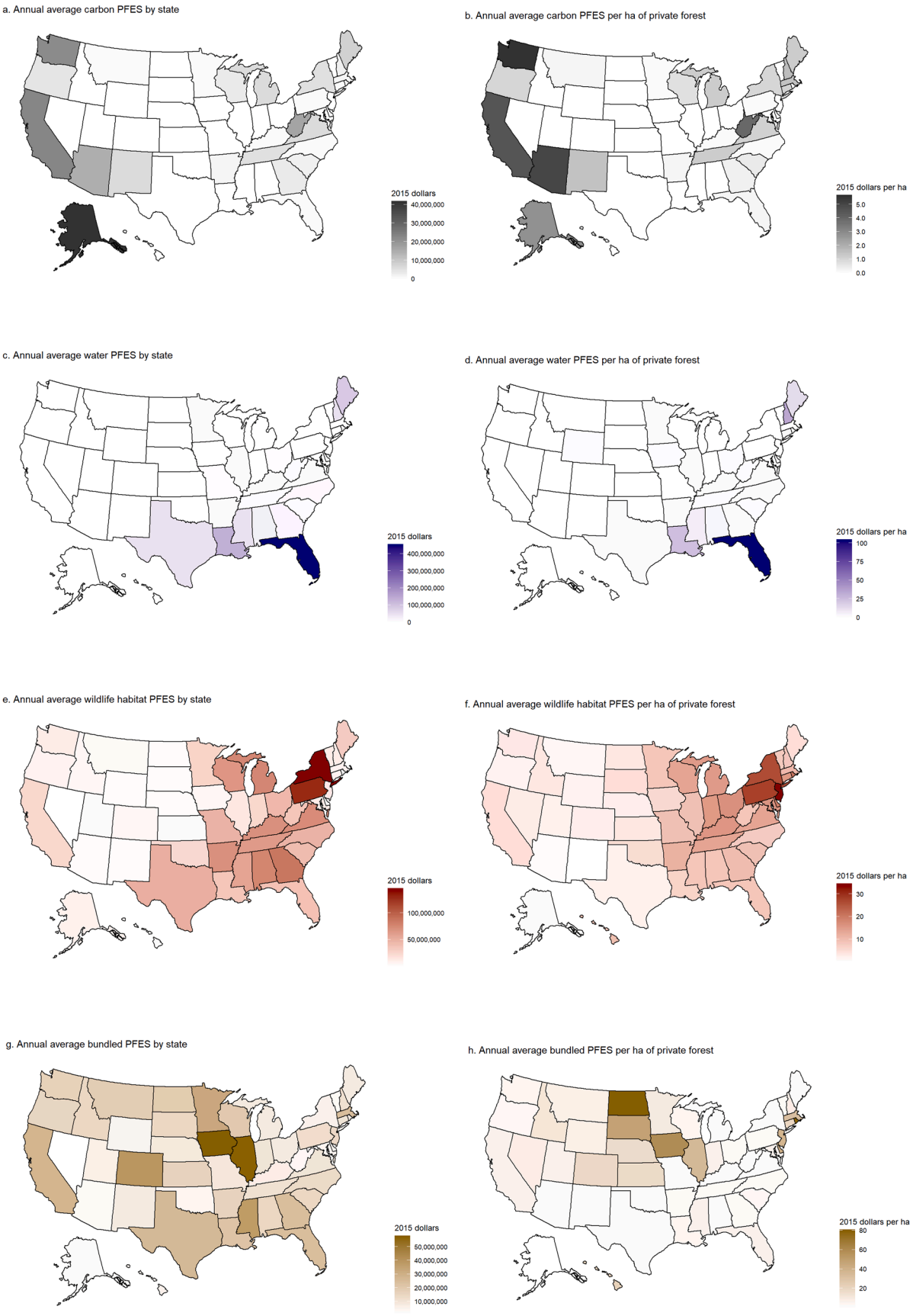

Fig. 4. Estimated annual average (2010–2019) payments for forest-based ecosystem services (PFES) by category. a. Carbon PFES by state. b. Carbon PFES per acre of private forest in each state. c. Water PFES by state. d. Water PFES per acre of private forest in each state. e. Wildlife habitat PFES by state. f. Wildlife habitat PFES per acre of private forest in each state. g. Bundled PFES by state. h. Bundled PFES per acre of private forest in each state.

Table 6
Estimated annual (2005–2019) land area participating in programs/markets for forest-based ecosystem services by transaction type (public payments, compliance transactions, and voluntary transactions) and ecosystem services category (carbon sequestration and storage, water quality and watershed protection, wildlife habitat, bundled services). Data on compliance and voluntary transactions are known to be incomplete (underestimate); public payments relatively complete.All values are thousands of hectares.

Type/ category	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
	thousands of hectares														
A. Public															
1. Carbon	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2. Water	0.0	0.0	-	0.1	6.3	1.6	4.6	3.0	5.9	0.0	0.2	0.0	0.1	0.1	0.0
3. Wildlife	125.9	152.6	127.2	237.4	165.4	287.6	282.8	264.9	272.0	109.2	111.4	192.1	127.8	168.8	234.4
4. Bundled	3,320.7	3,256.2	3,271.8	3,201.7	3,078.0	3,083.0	3,204.0	2,922.1	2,709.4	2,857.5	2,621.0	2,436.5	2,390.0	2,374.4	2,032.6
SUBTOTAL	3,446.6	3,408.8	3,399.0	3,439.2	3,249.7	3,372.2	3,491.5	3,190.0	2,987.4	2,966.7	2,732.6	2,628.6	2,517.9	2,543.3	2,267.0
B. Compliance															
1. Carbon	-	-	-	-	-	-	-	-	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
2. Water	1.4	1.2	1.3	1.4	1.4	1.2	1.4	3.0	1.7	2.2	2.3	1.9	2.1	1.0	1.8
3. Wildlife	0.1	0.1	0.2	0.5	0.4	0.2	0.0	0.6	0.1	0.1	0.3	1.3	0.7	1.3	0.6
4. Bundled	-	-	-	-	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SUBTOTAL	1.4	1.2	1.5	1.9	1.8	1.4	1.4	3.7	1.8	2.3	2.6	3.2	2.9	2.3	2.4
C. Voluntary															
1. Carbon	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
2. Water	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
3. Wildlife	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
4. Bundled	89.1	128.4	99.0	62.8	95.7	130.1	42.5	73.8	51.3	62.0	53.8	59.9	78.2	77.2	87.6
SUBTOTAL	89.1	128.4	99.0	62.8	95.7	130.1	42.5	73.8	51.3	62.0	53.8	59.9	78.2	77.2	87.6

- = recorded as zero; no known area enrolled in programs of that type in the year indicated.
0.0 = value recorded less than 0.1 thousand hectares.
n.d. = no data; area known/believed to have enrolled in programs of that type in the year indicated, but no data source was identified to estimate land area.

2014.

3.7. Comparison to past estimates

Table 7 compares the estimates of PFES in this research study to past estimates in the literature. As noted previously, Mercer et al. (2011) is the only known past research to report estimates for payments specifically to forest land uses from most of these same sources in the United States. Converting Mercer et al.'s (2011) estimates to 2015 dollars for comparison to this study, payments ranged from $2.08 billion in 2005 up to $2.26 billion in 2007. These are generally in line with our estimates, in total, which ranged from $2.22 billion to 2.50 billion for the same period. However, there are some differences in the estimated values for some specific mechanisms and categories. Some of Mercer et al.'s (2011) average estimates for the period 2005–2007 were substantially lower than ours, including for public payments ($449 million versus $606 million, respectively, in 2015 dollars) and hunting leases ($486 million versus $683 million). Conversely, some of Mercer et al. (2011)'s average estimates for the period 2005–2007 were substantially higher than ours, including wetland mitigation banks ($870 million versus $490 million, respectively, in 2015 dollars). These differences are the result of different data availability and estimation approaches, as noted in Table 7. Specifically, to the extent possible, in this research we used information in the program and market databases to filter the data and only include payments that were demonstrably tied to forest ecosystems and forest management practices, whereas Mercer et al. (2011) based estimates on the proportion of forest to total land in each state. Our approach is more accurate in some cases and more conservative in others. For example, in the case of wetlands, many of the payments specified forest or non-forest, but many also provided a classification that was indeterminate (such as "palustrine wetland" or simply "wetland"); in these cases we classified as non-forest for conservativeness.

Other similar estimates of PES market sizes have come from sources such as Bennett et al. (2017); Donofrio et al. (2019, 2021); Salzman et al. (2018) (Table 7). However, those sources differ primarily in the fact that (1) they provide information on global markets, rather than the United States; and (2) they provide information on payments related to forest and non-forest. These differences explain why our estimates are substantially smaller than theirs. We also believe that, while these and other sources document voluntary and compliance payments, other than Mercer et al. (2011), we are the only source to comprehensively document public PFES payments in the U.S., a significant portion of total payments.

In addition to these direct payment mechanisms, private forest landowners are often indirectly compensated via tax provisions that lower the amount of property, income, or other tax they would otherwise owe. Kilgore et al. (2018) estimated annual property tax reductions justified by the ecosystem services provided by enrolled private forestlands totaled $1.63 billion in 2014, the equivalent of $8.48 per hectare ($3.43 per acre) of private forestland per year, based on the estimated 192 million hectares of private forestland in 201 (USDA Forest Service 2021), or $18.98 per enrolled hectare ($7.68 per enrolled acre). For that same year, we estimated $3.14 billion in direct PFES payments to landowners. This indicates that property tax incentives for forest-based ecosystem services may be the primary financial incentive mechanism for many private forest landowners.

4. Conclusions

This research provides the most robust and complete accounting of payments for forest-based ecosystem services (PFES) in the United States possible. Although many of the values are based on estimates, the results provide a comprehensive and fundamental understanding of the nature, magnitude, and trends of these programs and markets. Such information can assist in landowner education, technical training, organizational

Table 7
Comparison of estimates from this research with similar estimates from alternate sources.

Type/ category	Year	Estimate from this research (million 2015 $)	Similar estimate from alternate source (million 2015 $)	Source of similar estimate	Differences between this research and alternate source
Public payments	2005–07 (average annual)	606	448	Mercer et al (2011)	This research calculates payments to forest land uses based primarily on designated practices that specify use of trees; alternate source estimates based on proportion of forested land in a state.
Compliance water quality and watershed protection	2005–07 (average annual)	503	870	Mercer et al (2011)	This research calculates payments to forest land uses based primarily on designated credit classifications that specify forest ecosystems; alternate source estimates based on proportion of forested land in a state.
Voluntary wildlife access fees (hunting/viewing)	2005–07 (average annual)	915	525	Mercer et al (2011)	This research calculates payments to private forest land based on survey results specifying private land use and proportion of forested land; alternate source estimates based on proportion of forested land in a state.
Voluntary conservation easements	2005–07 (average annual)	266	268	Mercer et al (2011)	Different data source.
Compliance wetland and stream mitigation banks	2016	1,437	3,524	Bennett et al. (2017); Salzman et al. (2018)	This research estimates payments to forested land uses only; alternate source includes credits from all sources and land uses.
Compliance conservation and mitigation banks	2016	39	354	Bennett et al. (2017); Salzman et al. (2018)	This research estimates payments to forested land uses only; alternate source includes credits from all sources and land uses.
Voluntary forest carbon	2017–18 (average annual)	6	112	Donofrio et al. (2019)	This research only calculates payments for forestry in the United States, alternate source includes forestry and land use globally.

communication, research, and policy formulation. Furthermore, the publicly-available underlying data (Frey et al. 2021) can provide an input to future research on policy, landowner behavior, and more.

This article presents actual payments, rather than underlying ecosystem service values. Many ecosystem services have missing or underdeveloped markets or payment mechanisms. Furthermore, payments that do occur are often disconnected from any meaningful measure of supply or societal demand for ecosystem services. As a result, the revenues reported here should not be confused with the economic value forests provide to society.

This research highlights programs and markets supporting provision of a broad suite of ecosystem services attributable to forests, including carbon sequestration and storage, water quality and watershed protection, wildlife habitat, and bundled services. These payments are provided via various mechanisms, including public payments, compliance transactions, and voluntary markets. Total PFES averaged $3.3 billion per year (2015 dollars), or about $17.69 per hectare of private forest per year over the decade 2010–19. This includes an average of $176 million per year for carbon, $889 million per year for water, $1529 million per year for wildlife habitat, and $754 million per year for bundled services.

Hunting leases, the largest single source, have grown substantially up to $1.6 billion in 2016. At the same time, compliance and voluntary markets for carbon and water have also grown. In particular, the establishment of a market for carbon offsets within California's cap-and-trade program has increased the size of forest carbon offset markets by two orders of magnitude from $3 million in 2010 to $326 million in 2019. However, public programs connected to PFES have steadily decreased in real dollar terms over time, as has participating land area.

Various states and regions in the U.S. have higher or lower level of PFES connected to different service categories, for various apparent reasons. Results suggest that some small, highly-urban states received high levels of payments for conservation easements. Other states with a large agricultural land base relative to forestry received relatively high levels of public conservation program payments. Some states with both large private forest area and large urban centers had high values of payments for recreational access, such as hunting and wildlife viewing.

Compiling data on quantity of services bought and sold has become somewhat more feasible since Mercer et al. (2011), with the creation of registries such as RIBITS (USACE 2020) and the three leading voluntary carbon registries (ACR 2020; CAR 2020; Verra 2020). Furthermore, in many situations we were able to access some details about specific payments that allowed us to determine precisely whether or not payments were related to forest ecosystems. Newer and emerging programs and markets frequently lack these registries, but as they mature, such data may be expected. However, we are still extremely limited in data on prices for things like carbon and wetland credits, which continues to be a large source of uncertainty. Further maturation of these markets may see organizations establish databases on prices paid, which would make tracking the markets much more feasible. Unfortunately, also, many registries do not include geospatial information that allows a more granular tracking, for confidentiality or other reasons.

At a higher level, more research comparing the effectiveness, efficiency, and equity of the various programs and markets may be valuable. Although analyses of some specific characteristics of the longer-running programs have been analyzed, such as the CRP auction mechanism (Claassen et al. 2008), comparisons of current options for PFES are lacking. Broad comparison and evaluation of program characteristics such as eligibility requirements, restrictions on land use, commitment periods, contract flexibility, bidding/auction levels, and payment level could provide valuable information about program design and implementation. For example, analyses of state-level preferential forest property tax programs illuminated the fact that eligibility requirements and restrictions on land uses deterred participation, whereas the magnitude of the financial incentive had no discernible impact (Frey et al. 2019). Such research on PFES may illuminate opportunities and barriers for continued growth of these programs and markets.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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