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Review

Auctioning approaches for ecosystem services – Evidence and applications

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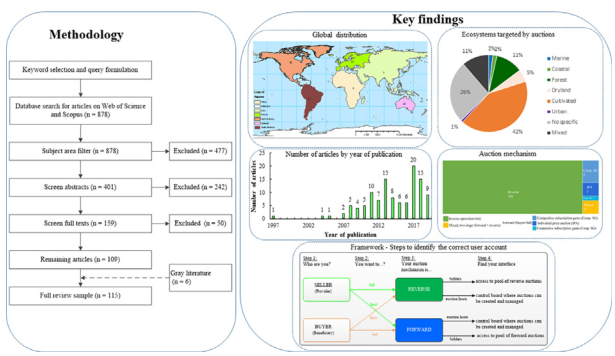
HIGHLIGHTS

- Ecosystem Service (ES) auctions call for scientific research.
- We provide a review of the current state of the art of ES auctions.
- Majority of reviewed articles focus on reverse auctions.
- Development of online ES marketplaces remains at an early stage.

GRAPHICAL ABSTRACT



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ABSTRACT

Auctions have attracted growing attention as bidding mechanisms for soliciting or allocating payments for a wide range of ecosystem services (ES). This paper reviews the latest scientific knowledge on ES auctioning approaches. Using systematically selected academic articles, we trace and discuss the development of ES auction literature across space, time, target ecosystem, and mechanism type. We integrate previous attempts to organize this body of work to produce a composite factor map of entry points to more specialized sub-literatures engaging with current issues in auction design and implementation. The results show that most academic work focuses on reverse auctions, where landowners bid their willingness to accept contracts to protect or promote ES provisioning, but we also locate several forward (i.e. beneficiaries bid their willingness to pay for ES) and mixed mechanisms. We critically analyze major advantages and challenges for each approach, emphasizing issues related to transaction costs and accessibility for participants and agencies. Overall, our findings suggest that ES auctions have a robust track record but remain administratively and logistically challenging. Further investment in open-source tools, shared infrastructure, and other efforts to make auctions more accessible to researchers, agencies, and participants alike is strongly indicated.

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1. Introduction

Ecosystem services (ES) are the direct and indirect contributions of ecosystems, e.g. land use/land cover (LULC) types, to human wellbeing and survival (MEA, 2005; Engel et al., 2008; Schägner et al., 2013; Costanza et al., 2014). These include not only provisioning (e.g. food, fiber and water supply), but also regulating (e.g. climate regulation, water purification and disturbance regulation), supporting (e.g. nutrient cycling, pollination and soil formation) and cultural services (e.g. aesthetic and recreation values) (Costanza et al., 1997; De Groot et al., 2002; MEA, 2005; Costanza et al., 2017). However, many ecosystems are seriously vulnerable to human-driven modifications (Martínez et al., 2009; Kindu et al., 2016). Because these impacts affect ES provisioning, they have become a focus of increasing interest (Troy and Wilson, 2006; Butler et al., 2013) and number among the most popular issues in ecological economics (Troy and Wilson, 2006; Bateman et al., 2013).

While the exchange value of some ES like timber, food, or bioproducts can be easily quantified via market transactions, many others—such as carbon sequestration, pollinator support, habitat conservation, or water regulation—are underprovided because they are public goods or common pool resources that lack functioning markets (Krieger, 2001; Whitten et al., 2017; Wainwright et al., 2019). Market failures can drive land-use changes that cause serious ecological and social harm (Alig et al., 2003). For example, treating essential forest ES like carbon storage, water purification, and erosion control as uncompensated externalities can contribute to forest loss and degradation (Chen et al., 2019; Knoke et al., 2020), particularly in the tropics (Foley et al., 2007; Knoke et al., 2021). Securing the health and continued vital existence of ecosystems requires new and better tools to capture the value of the services they provide, and integrate those values into decision-making (Franklin Jr and Pindyck, 2018). To this end, a number of regulatory and voluntary instruments have been created to increase the provision of public goods and common-pool resources (Emiris and Marentakis, 2010; Lennox and Armsworth, 2013; Narloch et al., 2013; Adhikari et al., 2017; Cooke and Corbo-Perkins, 2018; Bond et al., 2019).

Market-based instruments can be useful tools for efficiently allocating limited capital to promote the provisioning of environmental public goods (Latacz-Lohmann and van der Hamsvoort, 1997; Ulber et al., 2011; Rolfe et al., 2017). Examples include forest certification (Elbakidze et al., 2022), subsidies to encourage the adoption of agricultural best management practices (Palm-Forster and Messer, 2021), community-based management (Perfect-Mrema, 2022), legal requirements for deforestation offsets (de Freitas et al., 2017), and even direct bargaining between polluters and beneficiaries (Bingham, 2021).

Auctions are a class of designed markets that can be used to increase the efficiency of allocating ES contracts (Buckley et al., 2006; Ferraro, 2008; Comerford, 2013; Andeltová, 2018; Banerjee and Conte, 2018). They are described by a set of rules that specify how the winner is selected and how the monetary value of the resulting contract is determined (Wolfstetter, 1996; Hailu et al., 2010; James et al., 2021; Glebe, 2022). As possible approaches, auctions can be grouped as *reverse* or *forward*. In a *reverse auction*, providers bid the minimum compensation they would be willing to accept (WTA) to sign a contract obligating them to provide a product or service (Arnold et al., 2013; DePiper, 2014; Valcu-Lisman et al., 2017; Chakrabarti et al., 2018). Generally, buyers are government agencies or NGOs seeking to procure ES on behalf of the public (Greenhalgh et al., 2007). Following Bingham et al. (2021), we use the term *forward auction* to refer not only to the standard seller's auction, but also to other demand-side mechanisms where beneficiaries bid amounts they would be willing to pay (WTP) to secure the provision of some ES (e.g., Smith and Swallow, 2010). Usually, this is done collectively by pooling conditional financial contributions or commitments to donate. Note that the word “bidder” thus refers to different actors depending on the direction of the auction: in a forward auction, bidders are *beneficiaries* or indirect stakeholders offering to pay for guarantees about the future supply of some (set of) ES, but in a reverse auction, bidders are *providers* offering to make these guarantees in exchange for payment. A forward auction bid is an offer to buy; a reverse auction bid is an offer to sell.

Over the last two decades, a growing number of ES auctions have been implemented in contexts ranging from forests (Rousseau and Moons, 2008; Primmer, 2017; Thorsen et al., 2018) and agricultural lands (Latacz-Lohmann and Hamsvoort, 1998; Hellerstein and Higgins, 2010; Schilizzi and Latacz-Lohmann, 2012a,b; Banerjee et al., 2015; Pant, 2015; Palm-Forster et al., 2016a,b; Narloch et al., 2017; Reynolds et al., 2017; Bell and Streletskaya, 2019; Liu et al., 2019), to wetlands (Hill et al., 2011) and coastal areas (Smith and Swallow, 2010). Auctions have been tested in the field (e.g. Stoneham et al., 2003; Groth, 2011; Blackmore and Doole, 2013; Pant, 2015), in laboratory experiments (e.g. Cason et al., 2003; Smith and Swallow, 2010; Boxall et al., 2013), and through various computational models (e.g. Hailu et al., 2011; Iftekhar and Tisdell, 2016; Drechsler, 2017a,b; Choi et al., 2018). Much of this body of research is dedicated to exploring different configurations of design variables for ES auctions, typically comparing economic performance metrics like efficiency or cost-effectiveness between different designs and under different conditions (Comerford, 2014; Liu et al., 2019). In addition, ES auction related reviews are available: for instance, laboratory research (Schilizzi, 2017), conservation tenders in Australia (Rolfe et al., 2017), metric development (Whitten, 2017), spatial coordination incentive design (Nguyen et al., 2022), and the role of disciplinary perspective in shaping the main themes of auction discourse (Bingham et al., 2021). Thus, although several topical literature analyses are available, a comprehensive systematic review of where, when, and how auctions have been used to promote ES provisioning is missing.

In order to disseminate work in this dynamic field and encourage continued interdisciplinary collaboration, in this article we set out to systematically map the "where, when, and how" of ES auction research. Using an applied classification system based on criteria like target ecosystem, location, and participant type, we trace the development of the auction literature across time and space, situate ES auctions conceptually in the broader context of direct incentive mechanisms, synthesize major issues for forward and reverse mechanisms, and present a novel concept for an online platform to make auctions more accessible and support further research. Specifically, we address the following questions:

(1) What are the main approaches, applications (in terms of ecosystems and services), and programs described in the scholarly and gray literatures on ES auctions?
(2) What are the main advantages and limitations of auction approaches in the ES context?
(3) What attributes are required to develop a comprehensive framework for a web-based ES auctioning platform?

2. Materials and methods

Using previous review articles as a guideline (Rolfe et al., 2017; Schilizzi, 2017; Bingham et al., 2021; Knoke et al., 2021), our systematic review from query formulation to full text analysis follows the PRISMA diagram (Moher et al., 2009) (Fig. 1). We performed a systematic search carried out up to 2020 and filter of scholarly and gray literature about ES auctions. First, we performed a systematic search of Scopus and Web of Science (WoS) for ES auction research up to 2020 using the keywords (auction AND ecosystem AND service, bid AND ecosystem AND service, conservation auction, conservation tender, procurement auction). After applying a subject area filter, we screened titles and abstracts for relevance, eliminating e.g. studies exploring auctions in the cloud computing environment, those with the auctioned goods not listed in the MEA (2005) (e.g. solar energy), and those without an explicit focus on ES (e.g. auctioning conservation construction projects to contractors). Finally, we screened the remaining full texts using the same criteria as for abstracts: that is, to verify that the text in question substantively engaged with the issue of applying auction mechanisms in the context of supporting the provisioning of ecosystem services as described in the MEA (2005), producing a final systematic sample of 109 articles. To round out the treatment of online tools in the ES auction space, we supplemented this sample with several examples of online auction innovations we selected from the gray literature, producing a final database of 115 items (listed in Supplementary Table S1).

We classified these items according to several criteria to provide a basic outline for comparison and synthesis. From the systematically selected articles, we extracted publication year, research type, geographical location, auctioning mechanism (e.g. forward, reverse, mixed), and target ecosystem and ES considered, then calculated descriptive statistics for each category (RQ1).

Next, we conducted a focused critical analyses of each mechanism type to identify major advantages, challenges, and design considerations (RQ2). For forward and mixed mechanisms, we exhaustively evaluated each design in our database. Because reverse auctions are the focus of a much larger literature, we conducted a meta-synthesis of past reviews and conceptual frameworks for these mechanisms. We identified seven frameworks structuring key sub-problems in the auction space, analyzed overlaps

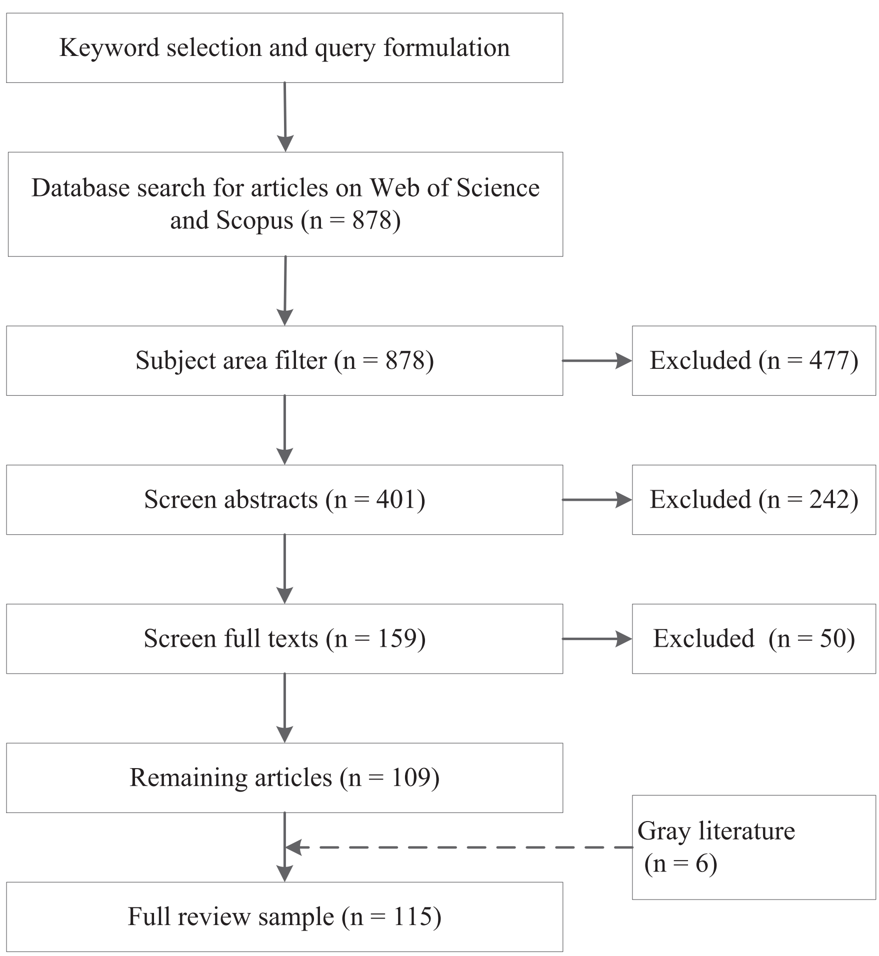

Fig. 1. Searching and screening process in defining articles for review.

between their component factors, and merged them to produce composite factor map. This map guides readers to sub-literatures focused on specialized auction design problems, and also offers a broad overview of the kinds of problems that reverse auction researchers have prioritized to date. From this critical analysis and literature synthesis, we derive lessons learned and use them to develop a concept for an online hosting platform aimed at expanding the accessibility of auction tools and supporting the mainstreaming of auction research (RQ3).

3. Results and discussion

3.1. Ecosystem services and auctioning approaches

3.1.1. General overview

The literature on ES auctions has grown substantially over the last decade (Fig. 2): 88 % of the articles in our sample were published since 2010, at a rate of 5–18 items per year. This shows that the topic has gained increasing scientific attention in recent years. This trend is in line with Schilizzi's (2017) review of laboratory research on conservation auctions showing the number of experimental studies from 2003 to 2014.

Of the 115 items, "case study" was the most prominent classification (34 = 30 %), followed by "mixed" (27 = 23 %), "experiment" (25 = 22 %), and "modelling/simulation or theoretical" (19 = 16 %) (Table 1). Additionally, we identified 6 (5 %) "literature review".

The studies in our sample spanned eight regions (Table 2, Fig. 3). The greatest number of articles were from North America (28 %) and Oceania (18 %)—an expected result considering that the US and Australia pioneered the use of conservation auctions as land management tools at scale with the Conservation Reserve Program (CRP) and BushTender (Hellerstein and Higgins, 2010; Blackmore et al., 2014; Everard, 2018). Europe was the region with the third-highest number of items in our sample (15 %). There were a few items each from Asia (6 %), Africa (5 %), and South America (3 %); we did not locate any studies from Central America or the Caribbean.

About 16 % of the sample could not be allocated to a specific region. Except for one article (a laboratory experiment without geographic information about study participants), all non-region-specific items were literature reviews, model/simulation studies, conceptual frameworks, or a combination thereof.

Of the 32 items from North America, 28 (88 %) were from the USA and four from Canada (12 %). All three South American papers were from the same project.

Fifty-one (45 %) of the items we reviewed were connected to an auction program or project. Of these, more than one-third were related to either a PES (Payments for ES) or PACS (Payments for Agrobiodiversity Conservation Services) program. The other two-thirds were distributed among 20 other programs or projects (Fig. 4). Here, we mean to refer to publications that clearly indicate a relationship to larger research initiatives or PES programs (as opposed to theory papers or isolated one-off experiments, for instance). Such a relationship could take several different forms: for example, a literature review that was conducted in support of a series of international auction experiments funded by a large project grant; using data drawn from a real-world auction program like the CRP to analyze auction design variables or conduct simulations; or reporting results from an auction-based case study or pilot within a larger PES program. The distinction between project and non-project publications can be a fuzzy due to the complex nature of research funding; we draw it here mainly as a way of highlighting especially prominent initiatives as a resource for readers. Table 3 lists the projects/programs together with their number of associated articles. If an article was related to a project, but the project itself was related to another bigger program, that article was classified under the bigger program. For example, the Bobolink Project designed its auction based on the PES scheme. Therefore, the two Bobolink items in the database (Chakrabarti et al., 2014, 2019) were sorted into the PES-related group. The project Spurring INnovations for forest eCosystem sERvices in Europe (SINCERE), on the other hand, is an independent project on its own and not part of any other umbrella of auction program (https://sincereforests.eu/about-sincere/). Hence it was listed separately in Table 3.

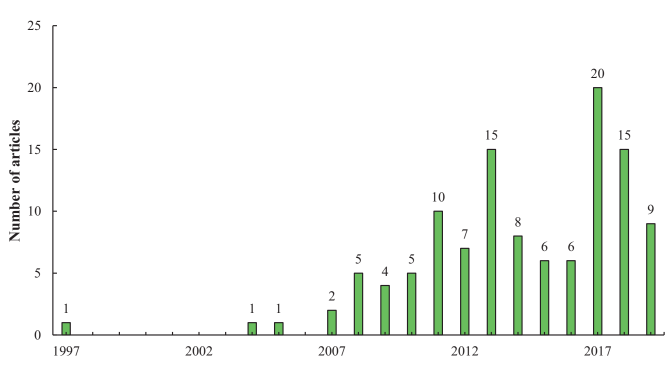

Fig. 2. Distribution of the number of reviewed articles by publication year (n = 115).

Table 1
Summary of articles selected for systematic analysis of the review by type.

Research type	Number of articles
Review	6
Modelling/simulation/theoretical	19
Experiment (laboratory/field)	25
Case study (with real contracts and payments)	34
Conceptual framework	1
Report	1
Brochure/website	2
Mixed[a]	27

[a] Refers to articles that could not be exclusively allocated to one of the other study types.

3.1.2. Auctioned ecosystems and ecosystem services

We adopted the list of ecosystem categories from the MEA (2005). We also added two more categories "No specific" (when a specific ecosystem was not mentioned) and "Mixed" (when at least two ecosystems, including 'No specific', were identified in one item). About 42 % (48) of the articles we reviewed considered cultivated land (Fig. 5). Studies not specifying an ecosystem type accounted for the second-largest share of the sample (26 %, or 30 papers). Forest ecosystems accounted for 11 % (13) of the reviewed items. Forest-related studies were distributed among Europe (6), North America (5, all from the USA), Asia (1), and Africa (1). Although Oceania represented the second-largest number of articles in the study, we did not locate any forest-related studies there.

Our systematic selection process did not capture any papers that substantively engage with the Australian Emissions Reduction Fund (ERF), partly because it is not specifically focused on ecosystems or their services and funds projects ranging from transportation efficiency to the capture of fugitive coal mine emissions (Kragt et al., 2017; ERF, 2022). However, the ERF is Australia's foremost climate policy instrument (Schenuit et al., 2021) and a rare example of a government-led voluntary offset program

Table 2
Distribution of reviewed articles based on region.

Region	Countries involved
North America	USA, Canada
Oceania	Australia
No specific region	N/A
Europe	Belgium, Denmark, Finland, Germany, Poland, Portugal, UK
Mixed	Australia, Canada, Germany, USA, Zambia, no specific country
Asia	China, Indonesia, Japan, Nepal
Africa	Kenya, Malawi, Tanzania, Zambia
South America	Bolivia, Peru
Central America	None
The Caribbean	None

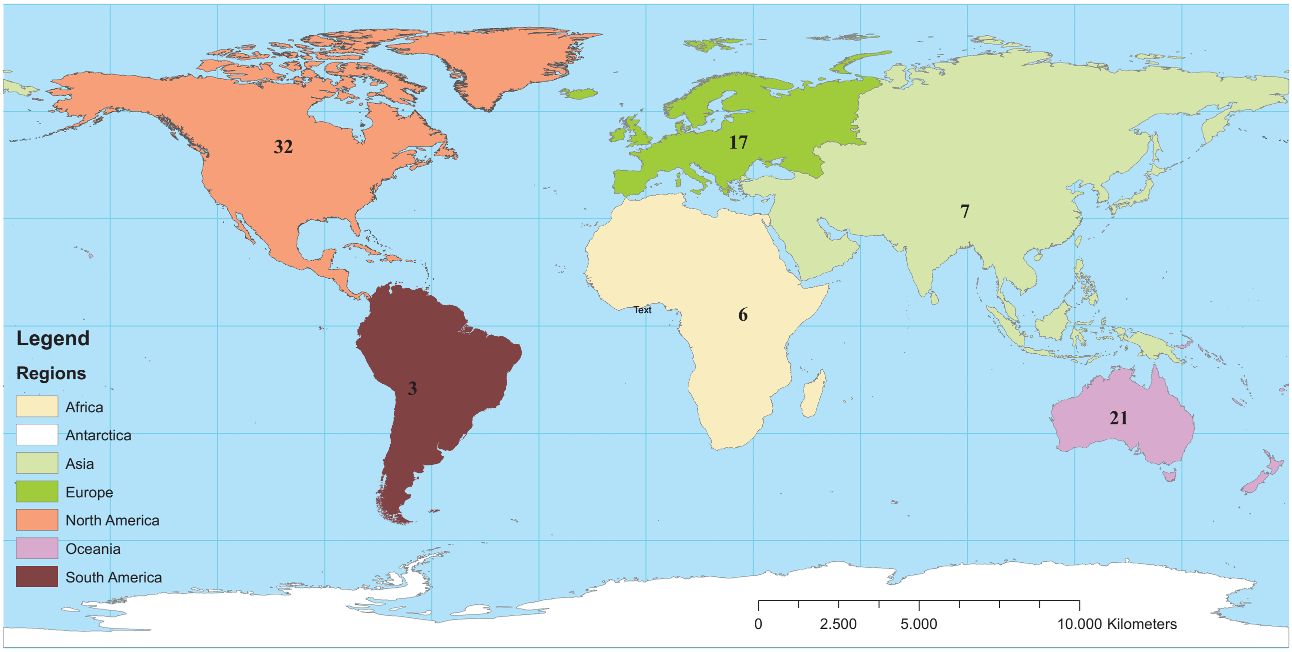

Fig. 3. Global distribution of articles on ES auctions across countries (Source: base map from Esri).

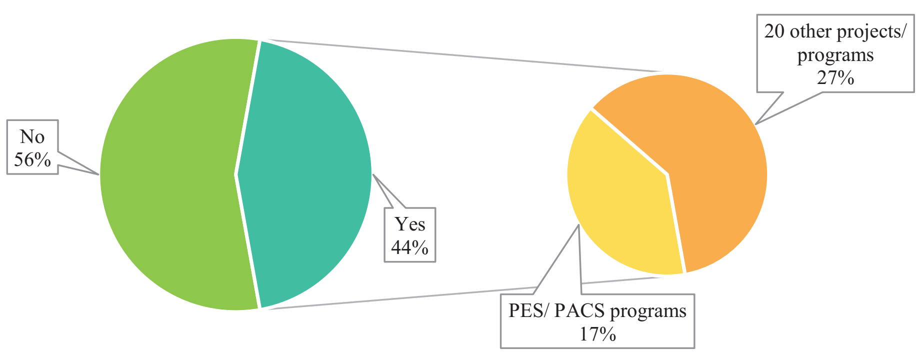

Fig. 4. Percentage of reviewed articles having a relation with an auction project/program. Yes = reviewed connected to an auction program or project. No = reviewed not connected to an auction program or project.

Table 3
List of projects/programs related in the review and their number of associated articles (the sum adds to >51 because some articles were related to more than one project/program).

Name of project/program	Web links	Location	Nr. of articles
PES/PACS Program	https://alliancebioversityciat.org/	Worldwide	20
ECOSEL	https://ecosel.cfr.washington.edu/	USA	5
BushTender/ecoTender/Green Gaze	https://www.environment.vic.gov.au/	Australia	5
Burdekin water quality tender	https://acquire.cqu.edu.au/	Australia	4
Conservation Reserve Program (CRP)	https://www.fsa.usda.gov/index	USA	3
SINCERE Project	https://sincereforests.eu	Europe	3
Queensland's Vegetation Incentives Program (VIP)		Australia	2
Catchment Care Australian	https://environment.des.qld.gov.au/	Australia	1
Eastern Mt. Lofty Ranges BushBids project	https://www.cbd.int/	Australia	1
Environmental Stewardship Scheme		Australia	1
Maryland and Virginia auction of Chesapeake Bay	https://www.chesapeakemarketplace.com/	USA	1
Natural Values Trading (Southern Finland Forest Biodiversity Program METSO)	https://www.metsonpolku.fi/en-US	Finland	1
NatureAssist	https://www.qld.gov.au/	Australia	1
NaturEtrade	https://nfmea.sylva.org.uk/	UK	1
North America Waterfowl Management Plan (NAWMP)	https://nawmp.org/	USA	1
SEERAD Scottish fishing vessel decommissioning auctions	https://muse.jhu.edu/article/484304/figure/apptabA2	UK	1
Stormwater Tender		Australia	1
Sustainable Landscape Program in Mackay region		Australia	1
Trading in natural values (TNV) pilot program		Finland	1

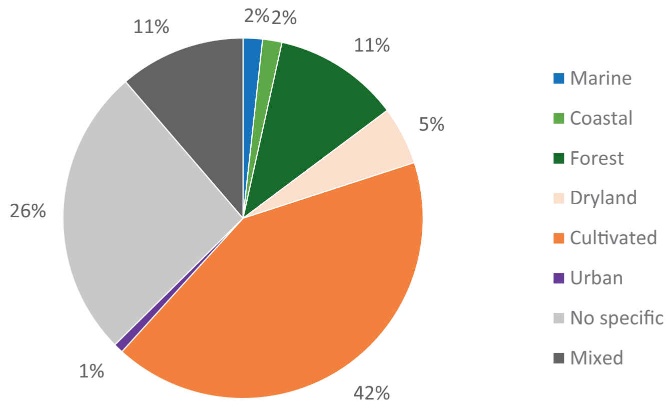

Fig. 5. Ecosystems targeted by auctions in our sample.

based on discriminatory reverse auctions (Grafton et al., 2021). Despite some potentially serious limitations (Burke, 2016; Crowley, 2017; Baumber et al., 2019), the ERF accounts for a large share of Australia's PES expenditures (Keenan et al., 2019) and arguably constitutes one of the largest forest carbon markets in the world (Evans, 2018; Regan et al., 2020).

Thirty-seven studies (32 %) did not specify an ES category (Table 4). Six of these referred to nonspecific forest ES; they encompassed modelling (e.g. Hailu and Schilizzi, 2005; Glebe, 2013; Iftekhar et al., 2014; Polasky et al., 2014; Lundhede et al., 2019), laboratory experiments (e.g. Latacz-Lohmann et al., 2011; Vogt et al., 2013; Vogt, 2015; Messer et al., 2017; Conte and Griffin, 2019), or a combination thereof (Kawasaki et al., 2012). These studies are mostly focused on issues related to mechanism design and bidder behavior, so they are typically decontextualized to some degree and tend not to target specific ES.

In other cases, even contextualized field experiments may decide not to target specific ES because they are action- or outcome-based rather than benefit-based. For example, Andeltová et al. (2019) conducted an auction-based field experiment to increase the forested area on agricultural lands. Rather than focusing on the benefits associated with reforestation, performance indicators included the number of trees planted and survival ratio. Therefore, although planting trees implies increasing the production of multiple ES, the study was classified as 'Ecosystem services in general (not forest-specific)' since it did not focus specifically on any services and the planting took place on farmlands.

Of the studies identifying specific ES, biodiversity/habitat-related services were the most commonly targeted (41 = 36 %) (e.g. Hajkowicz et al., 2007; Windle and Rolfe, 2008; Klimek et al., 2008; Windle et al., 2009; Crossman et al., 2011; Narloch et al., 2011; Reeson et al., 2011; Schilizzi and Latacz-Lohmann, 2011; Iftekhar et al., 2018), followed by water-related services (16 = 14 %) (e.g. Latacz-Lohmann and Schilizzi, 2007; Rolfe and Windle, 2010; Rolfe and Windle, 2011; Schilizzi and Latacz-Lohmann, 2011; Nemes et al., 2015; Takeda et al., 2015), and then by 'mixed' services (e.g. Rolfe et al., 2009; Hill et al., 2011; Jindal et al., 2013; Whitten et al., 2013; Boxall et al., 2017). The sample addressed soil-related (4 = 3 %) (e.g. Jack et al., 2009; Leimona and Carrasco, 2017; McGrath et al., 2017) and climate-related (3 = 3 %) (Latacz-Lohmann and van der Hamsvoort, 1997; Pant, 2015; Sharma et al., 2019) services much less frequently than the previously mentioned ES. Studies oriented toward biodiversity and soil-related ES are comparatively recent: 2007 was the year of the first study on diversity/habitat-related services as well as for water-related studies, and 2009 for soil-related studies. Climate-focused work is even more recent: since the seminal conservation auction paper by Latacz-Lohmann and van der Hamsvoort (1997), which focused on reducing nitrogen emissions from fertilizers, the next explicitly climate-oriented auction in our database was published almost 20 years later.

Table 4
Distribution of reviewed articles based on auctioned ecosystem services.

	Ecosystem services	Number of articles
1	Biodiversity/restoration/habitat	41
2	Ecosystem services in general (not forest-specific)	31
3	Water quality/regulation	16
4	Mixed[a]	14
5	Forest ecosystem services in general	6
6	Soil quality/erosion protection	4
7	Reduction of greenhouse gas emissions/carbon sequestration	3

[a] Refers to articles that could not be exclusively allocated to specific ecosystem services.

3.1.3. ES auctioning approaches

Nearly 90 % of the reviewed papers used reverse (providers-bid) auctions, where landowners bid the price they would like to receive in order to provide the services (Fig. 6) (e.g. Hailu and Schilizzi, 2004; Connor et al., 2008; Mayer et al., 2012; Conte and Griffin, 2017; Holmes, 2017). The preponderance of reverse auctions could be attributable to the fact that many non-market ES are public goods and common-pool resources, the provision of which are typically incentivized by public bodies (Iftekhar et al., 2012a; Kits et al., 2014; Juutinen et al., 2013; Khalumba et al., 2014; Kits et al., 2014; Krawczyk et al., 2016; Flanders, 2018).

All three articles combining reverse and forward auctions (which we call "mixed" mechanisms) were case studies from North America (Chakrabarti et al., 2014; Uchida et al., 2018; Chakrabarti et al., 2019). They tried to establish a market by conducting 2-sided auctions: reverse auction on the supply side, and on the demand side, a kind of forward auction called an individual price auction (IPA) that involves conditionally pledging donations to purchase different levels of ES (Smith and Swallow, 2010).

Of the nine articles exclusively focused on forward (buyers-bid) auctions, five involved the ECOSEL mechanism (USA) (Tóth et al., 2009, 2010, 2013; Rabotyagov et al., 2013; Roesch-McNally et al., 2016). Note that "ECOSEL" is a project name, not an acronym. One article was from the project NaturETrade (UK), which originally planned to use a subscription mechanism similar to ECOSEL but selling individual ES rather than multi-service bundles (Dericks, 2014), though the project ended before auctions could be implemented. The remaining three articles exclusively using forward auctions were also experiments conducted in the USA using IPAs to ascertain public willingness to pay for public goods (Smith and Swallow, 2010, 2013; Liu et al., 2019). In these studies, the public goods were not produced by private landowners: two studies targeted restoration of a local coastal area (Smith and Swallow, 2010, 2013), while the third involved a laboratory experiment with student participants, asking their WTP for different amounts of unspecified public goods (Liu et al., 2019). In this group of articles, only ECOSEL features a competitive element: by this we mean that bidders make decisions to support, mutually-exclusive management alternatives (and thus different combinations of ES). Only ECOSEL and the Bobolink Project involve the use of forward mechanisms to procure ES produced on private land, although Uchida et al. (2018) purchase management changes on private lands that affect water quality in a public reservoir. This is important, as procuring ES from private landowners requires a different set of tools and incentives than environmental management on public lands—especially when private landowners derive income from their properties.

Although experiences and innovations from low-income countries have strongly shaped the literature surrounding reverse ES auctions (Whitten, 2017; Whitten et al., 2017; Wünscher and Wunder, 2017), we were unable to locate any examples of forward auctions outside North America. This discrepancy might be partly explained by different use cases and requirements (e.g. forward auctions may not be attractive in places where beneficiaries have limited disposable income). In a review limited to recent ES auction publications, however, Bingham et al. (2021) suggest that forward auctions are rare in general. Indeed, despite assembling a sample that is twice as

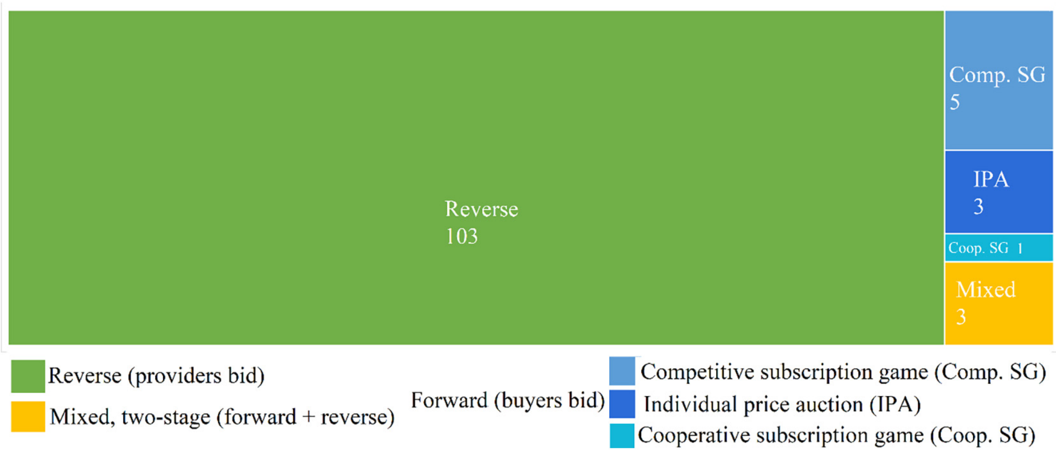

Fig. 6. Distribution of reviewed articles based on auction mechanism.

extensive and which spans a much longer time horizon, we only add two additional studies to this category, both published in the last decade (Dericks, 2014; Chakrabarti et al., 2014). This implies that forward auctions may be concentrated in North America not because they are non-viable elsewhere, but rather because they represent a relatively recent innovation that has yet to diffuse to other regions. If true, extensions to other geographic contexts could offer opportunities for future study.

3.1.4. Online bidding

At its most basic, an online auction platform might do little more than serve as a digital informational brochure, postbox, and bookkeeper. The forward auction component of the Bobolink Project, for example, featured a project website where bidders could learn about the project, complete a bid form, and back up their bid pledge with a credit card payment (Chakrabarti et al., 2019). Similarly, a reverse auction to improve water quality in the River Fowey (UK) built an online portal where farmers could register an account, provide information about their farm's type and size, and submit multiple-round bids (Day and Couldrick, 2013). The online platform was not essential to the auction in either of these cases; both accepted bids by post. However, Chakrabarti et al. (2019) note that people who used the online method tended to pledge larger donations. Meanwhile, a report about the River Fowey project expressed reservations, noting the software and technical expenses associated with developing even a relatively simple platform entails operational and administrative transaction costs that could potentially reduce auction efficiency.

Examples of more ambitious platforms include ECOSEL and NaturEtrade (Table 5). The ECOSEL platform allows buyers to bid for alternative forest management plans, each of which is designed to produce a different "bundle" of multiple ES, by donating to their preferred plan(s) in the context of a competitive subscription game (see Section 4 for a detailed analysis). Bundles are generated by combining forest growth models with multi-objective optimization. The platform has not yet hosted real transactions, although it has been explored through laboratory experiments

Table 5
Comparison of two pilot auction platforms.

	ECOSEL[a]	NaturEtrade[b]
Location	USA	UK
Target	Forest ES (timber, carbon storage, old growth habitat)	Agri-environmental ES (water regulation, flood management)
Project period	2009–2014, 2020–2022	2013–2018
Auction type	Forward	Reverse. Forward planned[c] but not yet implemented; trading platform only

[a] https://ecosel.cfr.washington.edu.
[b] Reverse: https://nfmea.sylva.org.uk Forward: https://zoo-naturetrade.zoo.ox.ac.uk/.
[c] Dericks (2014). All links accessed 26 March 2021.

(Rabotyagov et al., 2013) and mock auctions (Tóth et al., 2010, 2013). An online demonstration offers an overview of the concept (https://ecosel.cfr.washington.edu).

Whereas ECOSEL offers multi-objective optimization, NaturETrade's platform features an online mapping tool where farmers can demarcate their parcels to obtain estimates of its potential to provide multiple ES. This information can be integrated into an online trading platform hosting a marketplace for providers and beneficiaries. The platform is designed so that user accounts can act as both buyers and landowners (https://zoo-naturetrade.zoo.ox.ac.uk/). In the flood management case study, farmers compete for government financing to implement flood protection measures through a reverse auction (https://nfmea.sylva.org.uk/login).

3.2. Advantages and challenges of ES auctioning

3.2.1. Auctions in context: direct incentives for ES

An expansive body of research has accumulated around efforts to develop and vet a diverse array of regulatory and incentive-based approaches to support sustainable resource use, from externality-correcting taxes (Cherry et al., 2017) and supranational initiatives to combat illegal logging (Rutt et al., 2018) to voluntary carbon markets (Regan et al., 2020; Streck, 2021), direct bargaining (Bingham, 2021), and consumer-oriented ecolabelling initiatives (Delmas and Gergaud, 2021). Deep engagement with that much larger body of literature lies beyond the scope of this article, but interested readers will find no shortage of attempts to map its contours (e.g. Requate, 2005; Pacheco-Vega, 2020; Ejelöv et al., 2022), delineate its intellectual roots and sublineages (Gómez-Baggethun et al., 2010; Meckling and Allan, 2020), and—crucially—assist policymakers in selecting instruments that are well-matched to objectives, constraints, and context (e.g. Pannell, 2008; Bryan et al., 2016; Villamayor-Tomas et al., 2019).

Where might auctions fit in this crowded and increasingly differentiated ecosystem? Although they belong—broadly speaking—to the PES and MBI paradigm (Gómez-Baggethun et al., 2010; Pirard and Lapeyre, 2014; Wunder et al., 2020), ES auctions are a relatively young area of inquiry, and systematic efforts to integrate them into the environmental management toolbox are not yet well-developed (Fitzsimons and Cooke, 2021). This is especially true for forward auctions, which are theoretically entangled with subscription games, crowdfunding, and charitable giving (Liu et al., 2019; Bingham et al., 2021). Insofar as they aim mainly to efficiently generate, rather than allocate, funds for PES procurement, forward auctions are arguably more of a piece with the literature on public goods valuation than direct incentives in the strict sense. Since we only located a handful of studies on this topic and just two field experiments (Uchida et al., 2018; Chakrabarti et al., 2019), this section focuses specifically on reverse auctions: what they are, and what they are not.

As non-cooperative games, reverse auctions are constellations of incentives and information asymmetries whose configuration determines equilibrium strategies and thus, ideally, in-game behaviors (Milgrom, 1979; Banerjee et al., 2015). But although the game contains incentives, it is not itself an incentive: it has no intrinsic value to the bidder except as a path to a potential reward. Similarly, while it is not uncommon to encounter references to "auction programs", this is just a convenient shorthand: auctions are not "programs" in the standard PES usage (i.e. voluntary contractual arrangements between providers and beneficiaries featuring conditional payments) (Wunder, 2015). Instead, auctions are components of programs with a specific function, which is to determine how incentives should be allocated.

This delimitation renders the prospect of conducting a comparative analysis somewhat more approachable. If an agency wants to prevent nutrient runoff and leaching from agricultural fields, it must first choose between pursuing a strategy based on command-and-control instruments, taxation, efforts to support industry self-regulation, and so on (Pannell, 2008; Pacheco-Vega, 2020). Only after it decides to pursue its goal by offering direct incentives to stimulate farmers to adopt groundwater-friendly management does the question of allocation arise. Who gets paid, and how much?

The agency might consider an open enrollment mechanism. Interested farmers could sign up to receive a flat-rate subsidy, or perhaps request reimbursement for approved expenses through a cost-share program (Campbell et al., 2021; Eberhard et al., 2021). Alternatively, a competitive grant program might be offered: farmers submit funding proposals, which are then scored by an expert jury. Options like these are familiar and comparatively easy to administer, despite red tape surrounding eligibility and expense documentation. But they also carry significant limitations.

The cost-effectiveness of flat subsidies often declines with increasing opportunity cost heterogeneity: farmers with low costs might extract large rents, while those with high costs might be excluded even if their activities have a disproportionate environmental impact (Parkhurst et al., 2016; Thorsen et al., 2018). Cost sharing requires farmers to front their own capital, and easy-to-reimburse expenditures on supplies and equipment only capture part of their opportunity costs, ignoring e.g. yield risk due to fertilizer reduction (Bergtold et al., 2019; van Oosterzee et al., 2020). Grants are vulnerable to abuse because it can be difficult and time-consuming identify inflated cost claims, and selection processes must be carefully designed to avoid issues relating to transparency, legitimacy, and corruption (Doocy et al., 2008; Maljković, 2016).

Reverse auctions were designed with challenges like these in mind. Farmers name their own opportunity costs while facing competitive disincentives against inflating their cost claims; budgetary allocations can account for opportunity cost heterogeneity; farmers do not have to exhaustively document expenditures and are free to price a risk premium into their bids; and selection processes generally follows clear, understandable rules, improving perceptions of transparency even if some need for professional judgment remains (Hellerstein, 2017; Cramton et al., 2021).

Reverse auctions are often classified based on how payments to winning bids are calculated (Bingham et al., 2021; Schilizzi, 2017). The two most common pricing rules are *discriminatory* and *uniform*. Recall that in reverse auctions, a bid consists of an offer to sell something at a price specified by the bidder. The auctioneer collects all the bids, arranges them in ascending order, and accepts all bids below a certain threshold, which is usually defined either by a procurement target or a budgetary constraint. Discriminatory or "pay-as-bid" pricing means that each bidder within the threshold will be paid the price that they asked for. Uniform pricing means all bidders within the threshold will be compensated at a flat rate equivalent to the price specified by the first bid outside the threshold (i.e. winners will generally receive a higher payment than the requested, but never a lower one). Overpayment is built into the design of uniform price auctions because it is believed to disincentivize bid shading, or overstating one's opportunity costs. Which of these pricing rules delivers more efficient results in different contexts is subject to debate and a focus of ongoing research (Iftekhar and Latacz-Lohmann, 2017; Boxall et al., 2017; Schilizzi, 2017; Lundberg et al., 2018).

Of course, auctions—like all mechanisms—entail efficiency-effectiveness-equity trade-offs, which can vary substantially based on context and mechanism design. Because they select for low-opportunity cost bidders, reverse auctions can backfire, reducing additionality by targeting low-cost but low-threat parcels (Arnold et al., 2013; Jackson et al., 2017; Burke, 2016; Evans, 2018), although flat subsidies can face similar problems. In small communities, bidders might collude to extort higher prices (Jindal et al., 2013; Fooks et al., 2016). Reverse auctions can employ different protocols for calculating payments: if winners are paid the price they bid, there may be large discrepancies in how neighbors are compensated despite producing similar services—but if the auction instead determines a uniform price, then low-cost bidders reap higher profits than their high-cost neighbors. Because auctions are competitive mechanisms, they may produce results that are seen as distasteful or even unfair (e.g. awarding the largest contracts to the richest landowners) (Narloch et al., 2011; Leimona and Carrasco, 2017). Although auctions are generally considered transparent, they are not immune from controversy (McGrath et al., 2017).

Finally, auction dynamics may be sensitive to technological change. Our review identifies a range of efforts to support auctions with various technological and computational adjuncts like advanced optimization tools (Tóth et al., 2010; Iftekhar and Tisdell, 2016; Lewis and Polasky, 2018; Hajkowicz et al., 2007) and simulations of ES response to management changes (Uchida et al., 2018), with the integration of artificial intelligence (e.g. Rammer and Seidl, 2019) likely soon to follow. Simultaneously, the cost of obtaining detailed site assessment data to feed models and improve cost-benefit targeting continues to decline with the development of increasingly sophisticated remote and "near sensing" techniques, from satellite sensors and multispectral imaging to handheld LIDAR and terrestrial laser scanning (e.g. Pascual et al., 2022; Jacobs et al., 2021; Martos et al., 2021; Sebald et al., 2021). Using these tools could greatly improve the precision and cost-effectiveness of bid targeting and post-contract compliance checks, but it could also erode the transparency of auctions and leave bidders feeling informationally disadvantaged. While the increasing power and availability of these tools will have far-reaching implications for the environmental management and policy toolbox as a whole, auctions are competitive instruments that hinge on dynamics related to asymmetric information and participation patterns (Bond et al., 2018; Rolfe et al., 2018, 2021; Nguyen et al., 2022), which could make them especially sensitive to technological change.

Having situated auctions within the broader context of policy tools and incentive mechanisms, the following subsections take a more granular look at some key design variables in forward and reverse auctions.

3.2.2. Navigating reverse auctions: a map of key design factors

Much of our sample is devoted to investigating design problems, such as examining the effects of modifying specific factors related to mechanism, program implementation, or context. As the ES auction literature has grown, so has the number of relevant variables. We identified a set of articles aiming to better structure the problem space through conceptual frameworks. These frameworks highlight relationships between auction design considerations and performance factors identified by more narrowly-framed primary research (Table 6). Because auctions are ultimately allocation mechanisms for PES contracts, some analyses incorporate PES considerations that are not specific to auctions, such as leakage and conditionality (Jack and Cardona Santos, 2017; Wünscher and Wunder, 2017).

We merged these frameworks to provide a general overview of key functional interfaces between compartments and factors (Fig. 7). Schilizzi (2017) proposes a three-stage framework to organize auction attributes into (1) *causal factors* related to mechanism, program, context, and pre-existing bidder characteristics, (2) *intermediate effects* that refer to behaviors within the auction game, and (3) *final effects* that determine mechanism performance. We adopted this three-stage structure as a backbone and appended factor clusters drawn from the remaining six frameworks while avoiding duplication. In some cases, the overlap was significant: building on Ferraro (2008), for instance, Whitten et al. (2017) outline eight core tender design considerations, six of which are also shared by Schilizzi (2017).

Table 6
Key sources for structuring auction design problems.

	Focus of framework	
1	Context-matching allocation, price, and targeting	Lundberg et al. (2018)
2	Core auction design variables and country context	Whitten et al. (2017); adapted with minor changes from Ferraro (2008)
3	Analysis of conservation tenders	Schilizzi (2017)
4	Participation and market entry decisions	Rolfe et al. (2018); Rolfe et al. (2022)
5	Design factors to support participation	Whitten et al. (2013)
6	Contextual factors for auctions in low-income countries	Wünscher and Wunder (2017)
7	Designing metrics for bid targeting and scoring	Whitten et al. (2017)

Even so, generating this meta-framework required significant simplification. For instance, we list factors but refer readers to the source frameworks for explanatory examples and further explanation using the key in Table 6.

The duplication of factors across frameworks dealing with different aspects of the auction process highlights the multifunctional nature of the design problem. Notably, participation has emerged as one of the most important determinants of auction performance (Rolfe et al., 2022), revealing an alternate pathway by which auction design variables impact outcomes: design variables intended to influence in-game behaviors can also shape self-selection from the pool of eligible bidders. We represent this participation effect as a colored tier horizontally linking causal factor compartments, and vertically connecting causal factors to intermediate effects. This participation band highlights key factors identified mainly by Whitten et al. (2013) and Rolfe et al. (2018), but this does not mean that other factors are irrelevant. Whitten et al.'s (2013, 2017) frameworks for contract design and tender metrics also create horizontal linkages. While contract elements are generally disclosed in advance and thus affect participation and bidding behavior, metric design details may not be. If they are, prospective bidders may use them to make inferences about the stringency of the process and associated risks and transaction costs. Because the bid pool defines the possibility space, the effects of each factor cluster on auction outcomes are all ultimately mediated by who participates.

Spatial criteria offer a good example of this. Imagine a purchaser with a strong preference for procuring contiguous parcels, because they expect high habitat connectivity to promote biodiversity in a planned conservation area (Drechsler, 2017a; Fooks et al., 2016). The auction designer might introduce a minimum area threshold or require group bids, but this comes at the cost of restricting the pool of eligible bidders. Instead, they could offer applicants an incentive for submitting group bids, or a bonus if their submission is adjacent to another accepted parcel (agglomeration) (Drechsler, 2017b; Drechsler et al., 2010). But this, too, could have a cascading effect that changes the performance of other factors in Fig. 7. Some community members, like those who are well-connected, might be more likely to participate; those who are sensitive to complexity and transaction costs might be deterred (Banerjee, 2018; Nguyen et al., 2022). The process of assembling a group bid could present opportunities for collusion (Thorsen et al., 2018), and some may underbid their costs in anticipation of obtaining a bonus, risking winner's curse (Liu et al., 2019). In short, the addition of a single small bonus could require changes to the auction format, eligibility criteria, metric selection, bid formulation process, and contract design.

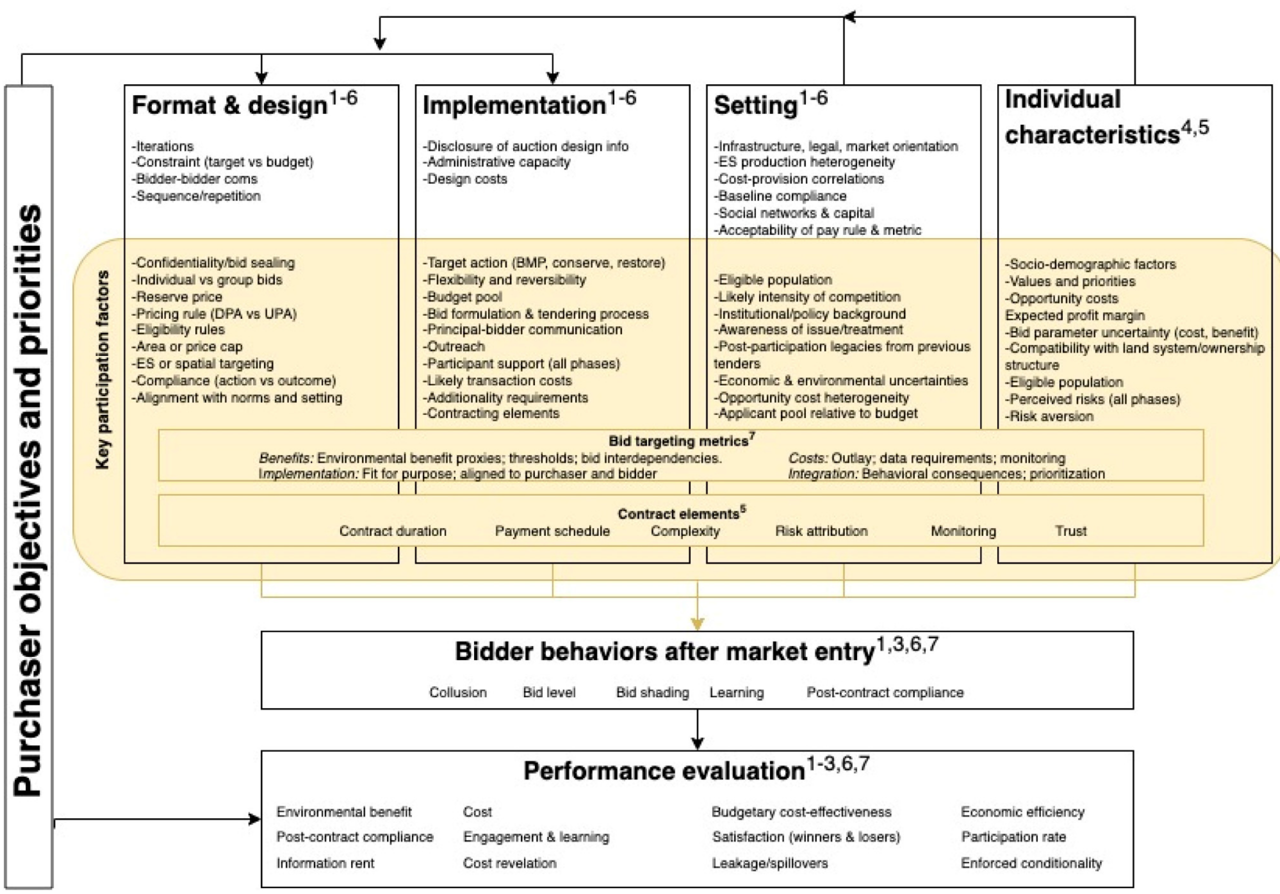

Fig. 7. Composite factor map for overview of key functional interfaces between compartments and factors.
DPA = Discriminatory price auction, UPA = Uniform price auction, BMP = best management practice. Superscript sources refer to Table 6. [1] Lundberg et al. (2018). [2] Whitten et al. (2017). [3] Schilizzi (2017). [4] Rolfe et al. (2018). [5] Whitten et al. (2013). [6] Wünscher and Wunder (2017). [7] Whitten et al. (2017).

Table 7
Studies using forward auction mechanisms.

Mechanism	Target ecosystem	Study focus	Reference
ECOSEL	Forest ES (timber, carbon, mature forest habitat)	Theoretical formulation and mock auction pilots	Tóth et al. (2009, 2010, 2013)
		Testing design variables (induced value laboratory experiment)	Rabotyagov et al. (2013)
		Qualitative exploration of experience of mock auction participants	Roesch-McNally et al. (2016)
IPA	Coastal (bird habitat, sea grass shellfish)	Field experiment to test incentive compatibility and free riding	Smith and Swallow, 2010
	Non-specific	Theoretical introduction and research overview	Smith and Swallow, 2013
	Agro-ecosystems, watershed service	Field experiment establishing markets through a double auction (IPA + reverse auction)	Uchida et al. (2018)
	Non-specific	Testing design variables (induced value laboratory experiment)	Liu and Swallow (2019)
	Agroecosystem (bird nesting habitat)	Field experiment establishing markets through a double auction (IPA + reverse auction)	Chakrabarti et al. (2014, 2019)

3.2.3. Forward auctions: applications and design considerations

Unlike reverse auctions, forward auction research consists primarily of a handful of studies built around two mechanisms, ECOSEL and the IPA (Table 7). Both involve asking ES beneficiaries to make trade-offs between cost and ES provision, and both pool bids to crowdfund a budget that can be expended only if bidders' procurement objectives are met. However, they differ in how trade-offs are evaluated and the information that can be extracted from bid data (Bingham et al., 2021, pp. 28–29). While IPAs typically target a single management change (e.g. conservation) and ask bidders to name their WTP for placing increasing areas under contract, ECOSEL asks bidders to make trade-offs between multiple ES in a fixed area. Below, we offer a brief critical analysis of each approach.

3.2.3.1. Individual price auctions. The IPA approach is rooted in the economics of non-market resource valuation, and particularly Lindahl pricing (Smith and Swallow, 2013). Although the underlying theory is not trivial, the IPA process itself is fairly straightforward: each bidder privately specifies a series of philanthropic donations they would be willing to make in exchange for increasing levels of ES provision, with the caveat that each donation will accepted if and only if the auctioneer can successfully procure the corresponding provision. After collecting all bids, the auctioneer pools them together to set the budget available for each provision level, then attempts to procure the highest level of provision possible (Chakrabarti et al., 2019; Uchida et al., 2018). It is an "individual price" auction because each bidder specifies their own WTP for each provision level: none pay more than they pledged or receive less than they paid for. Thus, deliberate underbidding is weakly discouraged: it risks forgoing provision for which one would have been willing to pay. Free and cheap riding have been observed experimentally, but at relatively low levels (Liu and Swallow, 2019; Swallow, 2013).

From start to finish, the process resembles a stated preference survey—except, of course, that the costs are not hypothetical. Indeed, comparative studies suggest that bid data from IPAs can approximate marginal WTP curves obtained through traditional stated preference methods (Smith and Swallow, 2013). This is arguably the IPA's distinguishing feature: by combining a private marginal WTP elicitation with real but conditional monetary pledges, it can generate not only an actual conservation budget, but also analytically tractable valuation data. The downside is that the bidding process can be substantially more time- and labor-intensive than the friction-minimizing donation funnels that typically accompany philanthropic solicitations, so there is an opportunity cost to data collection (Chakrabarti et al., 2019; Munz et al., 2020). Future research might seek to mitigate this cost by implementing technical and marketing solutions to reach a wider audience and streamline the bidding process.

The relatively time-consuming bidding process for IPAs is one reason they typically focus on procuring a single management action or even a single ES: the solicitation procedure would likely be too cumbersome if multiple services are included (Chakrabarti et al., 2019). Anecdotally, however, PES programs sometimes seek to "bundle" social and environmental co-benefits, so that by purchasing one ES (e.g. biodiversity) they know they will also receive another (e.g. pollination services) (see e.g. Summers et al., 2021; Baumber et al., 2019). It should be possible to strategically design IPAs to leverage co-benefits in a similar way, although it may be challenging to communicate this in the bid solicitation. The next subsection examines a mechanism designed to make these trade-offs explicit.

3.2.3.2. ECOSEL. ECOSEL is less concerned with producing clean valuation data than with generating financially attainable compromises in multifunctional management problems (Tóth et al., 2010; Bingham et al., 2021). Rather than seeking to construct balanced, unbiased bid solicitation questionnaires, it is geared toward creating a dynamic, interactive market. The base use-case envisions a privately-owned landscape of public interest (e.g. a productive forest with local recreation value), where the owner's opportunity costs for implementing a range of ES-friendly management alternatives can be reliably estimated through modelling and optimization.

The process works like this. First, bidders are presented with a set of mutually-exclusive ES provisioning scenarios, represented as Pareto-efficient "bundles" of multiple ES that can be produced by different management plans (Tóth et al., 2013; Roesch-McNally et al., 2016). Here, *Pareto efficiency* means that in order to increase the provision of one ES, the provision of another must be reduced (see Debreu, 1954 explaining the principle from a consumer perspective). Over the course of several rounds, bidders provisionally commit money to their preferred bundles. After each round, the total sum contributed to each bundle is revealed, and bidders have the option to change their allocation. A final binding round determines if any bundles are profitable (i.e. *Bid sum – Reserve price* > 0). If so, the profit-maximizing bundle is selected for implementation (though other market-clearing rules are possible). A PES contract is signed, donations to the winning bundle are transferred to the landowner, and all other bids are released back to bidders. The interactive nature of this process means that bidding behavior may strategically respond to, and seek to manipulate, the balance of bid totals across bundles and rounds. If communication is allowed and bids are not sealed, social signaling might influence behavior as well. Thus, the extent to which actual preferences can be inferred from bidding behavior is unclear.

Configuring an ECOSEL auction, therefore, is not a trivial problem. Important factors include choice variables (e.g. the number of ES per bundle, the number of bundles per auction); community variables (e.g. eligibility rules, sealed or open bids, communication structure), and design variables (e.g. reserve price disclosure, market-clearing rules).

The choice variables are closely linked. The optimal number of ES per bundle has not yet been investigated empirically, but the number of alternatives needed represent the decision space can be expected to increase exponentially with the number of attributes (Garcia-Gonzalo et al., 2014; Mariel et al., 2021; Obeng et al., 2021). Because ES bundles correspond to points on a Pareto frontier defined by continuous decision variables, the auctioneer is free to offer as many bundles as they like. Although a wider selection might help bidders accommodate their preferences to a certain extent, the number of bundles that the mechanism can feasibly handle is likely to be restricted by cognitive and procedural factors. Cognitively, people struggle to compare large numbers of alternatives and alternatives composed from large numbers of attributes, relying on heuristics like attribute nonattendance that weaken the connection between choice behavior and their true preferences (Thiene et al., 2019). Procedurally, spreading donations thinly across too many bundles might mean reserve price, not community preference, determines the auction outcome. While laboratory evidence suggests that reducing the number of bundles can increase seller profit without reducing the relative efficiency of the auction (Rabotyagov et al., 2013), this may not be true for real-world settings. Finding the balance between offering a selection that is wide enough to attract a large bidder pool, but not so wide that it triggers decision fatigue or impedes coordination, will likely require practical experience.

Community variables are also likely to entail trade-offs. While most crowdfunding projects seek to maximize the pool of potential donors, ECOSEL's decision-making function means that outcomes may be viewed as more legitimate if they are determined by local stakeholders rather than wealthy external interests (Roesch-McNally et al., 2016). Similarly, sealed bids may enable bidders to be more honest about their preferences, but open bids and efforts to facilitate communication between bidders could stimulate pro-social behaviors and increase donations. Although earlier work was equivocal (Tóth et al., 2009), Rabotyagov et al. (2013) find that facilitating limited communication between bidders can increase the relative efficiency of ECOSEL auctions.

Finally, the effect of disclosing design information like reserve price requires further study (Rabotyagov et al., 2013). On the one hand, sellers can use reserve price disclosure strategically, much like anchoring with an exorbitant initial ask when bargaining, bluffing in poker, or setting a fundraising goal on a crowdfunding site (Yang, 2014; Pope et al., 2015; Kuo et al., 2018; Backus et al., 2019). On the other hand, bidders who know the reserve price—even if it is inflated—can use it to calibrate their bids and avoid overpayment (Rabotyagov et al., 2013). If reserve prices are sealed, however, sellers should set them equal to cost to maximize the chances that the provision point will be met (Dericks, 2014). The administrator of an ECOSEL auction, therefore, may have to decide whether it is more important to reveal landowner opportunity costs, or to maximize the likelihood that the auction will succeed by giving bidders a clear goal to work toward.

3.2.4. Synthesis: key opportunities and challenges

The decades-long effort to bring auction mechanisms to bear on environmental management is aimed squarely at a deceptively simple problem: how to allocate scarce budgetary resources in a way that maximizes environmental benefit. In practice, solving this problem has often meant fusing mechanism design innovations with environmental modelling and even decision support tools. The ES auction literature has attended closely to issues related to asymmetric information and risk (Bingham et al., 2021), but uncertainties in estimated ES production functions, particularly under growing natural disturbance risk, are likely to pose challenges moving forward.

First of all, the perceived reliability of model predictions about how ES flows will respond to management changes could have a strong influence on bidding patterns. Providers who see model predictions for market ES like timber as overly pessimistic (Knoke et al., 2008), or model predictions for non-market ES as overly optimistic, may demand a risk premium to accept an outcome-based contract (Derissen and Quaas, 2013); similarly, beneficiaries could steeply discount future provision that is perceived as uncertain (Davies, 2020). Thus, model uncertainty and natural disturbance risk could have the combined effect of reducing forward auction bidders' maximum WTP, and increasing reverse auction bidders' minimum WTA. This could be a troubling dynamic for mixed mechanisms, since it exacerbates the risk of a budgetary mismatch between beneficiaries making smaller donations and providers demanding higher payment; further experiments are needed. Finally, of course, rigorously evaluating the performance of auctions designed to induce land-use changes—likely to be vital for continuing to mainstream these tools—also requires navigating significant environmental and economic uncertainties regarding baseline conditions and counterfactual reference conditions. In short, auction scholarship should probably invest in developing methods for communicating uncertainty in a way that is intuitive for beneficiaries, providers, and policymakers alike. This project will require interdisciplinary collaborations between ecologists, land managers, economists, and science communicators. Previous research has explored the role of extension services (Rolfe et al., 2017; Whitten et al., 2013) and managing environmental and economic risk through contract design (Ferraro, 2008; Wichmann et al., 2017), certification (Tóth et al., 2013), and insurance elements (Palm-Forster et al., 2016a,b, 2017), but transferable methods to quantitatively communicate model uncertainty and disturbance risk to auctioneers and bidders are largely missing.

A preliminary foundation for that work might be established by expanding the use of qualitative research methods to improve our understanding of how participants interpret and experience these competitive processes. While the incorporation of interviews into reverse auction field studies is not uncommon (Cooke and Corbo-Perkins, 2018; Leimona and Carrasco, 2017), buyer perspectives are lacking for forward mechanisms. ECOSEL has only been tested in laboratory settings, so the perspectives of actual bidders are not known—though Roesch-McNally et al. (2016) interviewed real stakeholders who participated in a mock ECOSEL auction. For IPAs, Chakrabarti et al. (2019) describe exchanges (but not formal interviews) with real-life donors, while Uchida et al. (2018) recount interactions from a forward auction workshop. Further effort to build up a holistic, multidimensional understanding of the experience of real auction participants (and less reliance on reading the process through the eyes of *Homo economicus*) could shed light on participation issues and strategies for representing uncertainty alike (Cooke and Lane, 2018; Leroy and Barrasa Garcia, 2021; Mariola, 2012).

Of course, communication is only part of the problem: mechanisms and targeting metrics should be developed to account for uncertainty as well. While most treatments focus on private information in non-cooperative games (e.g. Wichmann et al., 2017), some work has begun to engage more directly with uncertainties about the ecological future. Notably, Lewis and Polasky (2018) describe a reverse auction mechanism that accounts for climate risk by soliciting bids for conservation in a current and future period, then using dynamic programming to select winning bids in a spatially explicit way. Thus, ES auctions may offer new applications for risk-sensitive environmental planning tools like stochastic programming (e.g. Eyvindson and Kangas, 2016) and robust optimization (Knoke et al., 2020). For instance, constructing Pareto frontiers based on robust solutions (Zhou et al., 2018) could guarantee bidders minimum provision levels. We expect risk integration to represent an important step in the mainstreaming of ES auctions.

The prospect of multi-objective mechanisms or multicriteria bid selection metrics could also expand the scope of application for ES auction tools. Intuitively, single-objective environmental auctions are likely best suited to programs based on land-sparing: i.e., procuring area to set aside either through a forward (e.g. IPA) or reverse (e.g. a simple conservation tender) approach. Given increasing land-use competition and the ascendency of paradigms like multifunctional forestry (Schulz et al., 2022; Takahashi et al., 2022) and sustainable/ecological intensification (Kleijn et al., 2019; Knoke et al., 2022), however, this neglects a broad spectrum of possible land-sharing-based PES designs that require trade-offs between multiple criteria in addition to biophysical modelling uncertainty (Paul et al., 2017; Borges et al., 2017; Keith et al., 2017; Manning et al., 2018). For reverse auctions, these challenges are rendered navigable, in part, by the presence of a central decision-maker with the scientific capacity to interpret models, impose criteria weights, and make trade-offs on behalf of the public (Bingham et al., 2021; Lowell et al., 2007). Forward auctions do not have this luxury. ECOSEL is the only forward auction tool currently targeting the multicriteria land-sharing niche, but it comes at a cost: unlike IPAs, ECOSEL is unlikely to generate generalizable ES valuation data to inform environmental policy beyond specific contexts.

Finally, the importance of accessibility for forward and reverse mechanisms alike is difficult to overstate. With reference to bidders, accessibility is about driving participation: who hears about the auction, the ease with which information about the program design and desired treatment can be located, and overall friction inherent in the process of communicating with administrators, formulating and submitting bids, setting expectations for post-contract monitoring, and so on. With reference to agencies, accessibility has to do with the demands on technical capacity imposed by such a complex mechanism. This includes things like basic familiarity with common design configurations, the ability to effectively field stakeholder inquiries about the bidding process and desired management changes, the infrastructure to handle and process potentially large amounts of data (especially if using metrics that rely on spatial or other site-specific data), and processes for receiving and/or disbursing potentially large payments. An agency considering implementing an auction-based program must consider not only how to access and coordinate economic and environmental expertise, but also keep in mind a plethora of logistical subproblems related to outreach, scheduling, information management, document review, and so on. Mainstreaming auctions means making them more accessible to agencies and bidders alike. That is partly a scientific project, but it is also partly a practical one that can be advanced by developing technical resources to reduce barriers to adoption and market entry.

3.3. Framework for a web-based auction platform: rationale and design concept

On a very broad level, this review identifies a fairly large number of reverse auction tools applied to the ES context, two forward mechanisms (ECOSEL and IPAs), and two examples of field experiments that combines a forward auction for funding with a reverse auction for procurement to create markets for ES (Chakrabarti et al., 2019; Uchida et al., 2018). We also located a number of environmental programs featuring auction-based contract allocation mechanisms, ranging from small-scale case studies and pilot programs to large-scale programs like the US CRP and Australia's BushTender and EcoTender (Table 3). Most or all of these programs appear to have built the requisite administrative infrastructure from scratch, and typically in ways that are not transferable to other organizations. This is a major transaction cost for academic case studies and real-world programs featuring auction mechanisms.

Indeed, transaction costs have been repeatedly identified as a major impediment to the uptake and efficiency of auctions for ES (Messer et al., 2017; Schilizzi, 2017; Whitten et al., 2017; Bingham et al., 2021). Even if an auctioneer already has the institutional competence to design an auction that is well-matched to context and objectives (i.e. neglecting learning costs), it would still likely face important transaction costs like bidder outreach and communication, establishing a bid submission protocol, and implementing processes to receive bids, organize the information they contain, check them for completeness, and evaluate them, and—in the case of multi-round auctions—communicate provisional and final results to bidders. These processes and associated infrastructure, such as websites with online bid submission functions, are typically built anew each time a new actor decides to hold an auction (e.g. the Bobolink Project, NaturEtrade). Reducing these transaction costs might help facilitate more field research, make auctions more accessible to interested organizations who are deterred by logistical complexity, and streamline market entry for bidders to improve participation rates.

This section, then, sketches a conceptual framework for a centralized online platform for hosting ES auctions. Key features include: (1) guiding users (buyers or sellers of ES) to an appropriate auction type; (2) allowing them to locate ongoing auctions they may be eligible to participate in, or to create their own auction; and (3) facilitating administration of the auction process itself.

One important advantage of an online platform is the possibility of using eligibility criteria to easily scale auctions from local to regional, national, or international scales without the need to reconstruct the basic bidding architecture. For example, an environmentally-conscious consumer in Germany might bid in an ECOSEL-like auction to improve local water regulation provided by a forest in Vietnam; forest owners around the world might bid in carbon tenders funded by international or cross-regional organizations. There is no question that such arrangements would have to navigate complex issues surrounding governance, monitoring, contract enforceability, and legal compliance, which have been discussed at length in the PES literature, particularly with respect to initiatives like REDD+ (McAfee, 2012; Rodriguez-Ward et al., 2018; Oberhauser, 2019; Gifford, 2020; Fleischman et al., 2021). These are not challenges that an online platform can resolve, and they may ultimately preclude efforts to apply the platform we sketch below in cross-border contexts. In some cases, it may be desirable to restrict eligibility to the local or regional scale to target a specific ecosystem or "to maintain process legitimacy (Roesch-McNally et al., 2016); see also Lundhede et al. (2022a,b) for reverse auction pilots in Denmark and Belgium." Nonetheless, even auctions run at highly local scales may face fixed administrative costs that could be alleviated to some extent by the availability of a versatile, user-friendly platform where auction parameters can be configured, auctioneer-bidder communications hosted, and payments transacted.

Our framework therefore serves as a generic outline to be adjusted to specific contexts, which may be defined by legal frameworks, technology, data availability, personnel, socio-cultural factors, and so forth. The outline is also general enough that it could be adopted and implemented by a range of potential responsible entities, from university-administered platforms supported by government grants like ECOSEL or the EU's Copernicus database (Lacava et al., 2020; Tóth et al., 2013), which might later be handed off a non-profit as in the case of the Bobolink Project (Chakrabarti et al., 2019); to platforms run by charitable foundations like Restor.eco (Crowther et al., 2022) or private entities like environmental consultants or technology companies supporting implementing open data projects like the Google Earth Engine (Gorelick et al., 2017).

3.3.1. A platform with both reverse and forward mechanisms

The auctioning platforms we identified only consider either reverse (e.g. Day and Couldrick, 2013) or forward mechanisms (e.g. Roesch-McNally et al., 2016). The question is whether it would be possible to create a marketplace where buyers and sellers can meet, and bid conveniently in ongoing auctions for which they are eligible, or to start a new auction.

Prospective ES providers and beneficiaries represent different use cases for the platform. Thus, Fig. 8 illustrates how these user categories might be oriented to the appropriate interface. Although the roles of being a bidder or hosting an auction could change, one feature that normally would not change is whether such person is an owner (hence a service seller or provider) or a service buyer (beneficiary). In the first step (1), the platform will require users to create their profile as either a seller or a buyer. In the (presumably rare) case where an owner wants to subsidize services provided by another owner, a seller can create a new account as buyer, and vice versa. In the second step (2), once logged in to their account, users decide whether they want to buy or sell. Depending on their answer and their identity as seller or buyer, they should be taken into either a reverse or a forward sub-site in the third step (3). In the last step (4), the platform automatically displays the correct interface: a person wanting to bid should get access to a pool of available auction campaigns hosted on the platform, while a person wanting to organize an auction should be directed to a control management board where they can create a new auction, make changes, and see statistics for previous or ongoing campaigns. In creating an auction, the interface should walk users between simple design decisions with short explanations (e.g. forward vs. reverse, discriminatory vs. second-price, rounds and time limits, reserve price disclosure, etc.).

A platform that hosts both forward and reverse auctions would provide opportunities to further experiment with two-stage mechanisms—one of the most intriguing and under-explored possibilities identified in our review. The Bobolink Project offers an intuitive model: first use a forward auction to crowdfund donations, then hold a conservation tender to procure as much area as possible (Chakrabarti et al., 2019). The presence of the reverse auction might even reassure bidders that their donations will be used transparently and cost-effectively, which could increase their willingness to donate.

Linking ECOSEL to a reverse auction would require more reconfiguration. The original ECOSEL papers (Tóth et al., 2010; Rabotyagov et al., 2013; Roesch-McNally et al., 2016) envision a setting in which one large forest owner uses ECOSEL as a channel through which stakeholders can

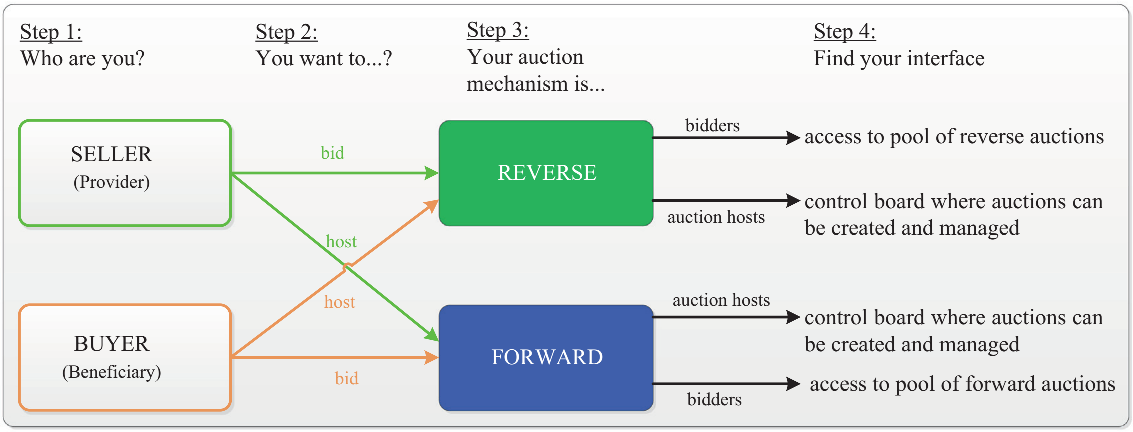

Fig. 8. Framework - Steps to identify the correct user account.

shape how that forest is managed. A procurement auction, by contrast, requires multiple landowners to compete for contracts. We can envision two possible avenues for adjusting ECOSEL to match such a use-case.

The first possibility is to follow the simple forward-for-budget, reverse-for-procurement sequence used in the Bobolink Project. This requires a small reconfiguration to ECOSEL's current design because information about landowner opportunity costs is only generated in the second phase, precluding the possibility of communicating reserve prices in the forward auction (i.e. the Pareto frontier would be generated using only ecological, but not financial, criteria). Doing so would make strategic bidding more difficult: in the absence of reserve price information, bids might better reflect stakeholders' preferences for different ES. The forward auction selects the winning bundle and sets the budget. Next, the reverse auction seeks to procure combination of ES represented by the winning bundle.

In such a model, the winner determination problem could take several forms. A logistically challenging but computationally simple approach would be to hold a reverse auction where each landowner bids their willingness to accept a contract to implement the winning bundle, which would be replicated across all selected parcels. A logistically simple but computationally intensive alternative would be to hold a combinatorial reverse auction (Iftekhar et al., 2012a,b,c) so that the selected proposals cumulatively produce the winning bundle, even if individual parcels do not. If smallholders are organized into joint management areas that submit collective bids, solutions from the Pareto frontier might be decomposed and distributed across smaller management units (Marques et al., 2021). Much as forward auction bidders pool funds, allowing landowners to pool existing ES production in a reverse auction might mitigate the “lumpiness” problem in bid selection (Iftekhar et al., 2018). This could also enable environmental (Baumber et al., 2019; Standish and Prober, 2020) and social co-benefits associated with cooperation, communication, and community management—dynamics that reverse auctions have been criticized for impeding (Cooke and Corbo-Perkins, 2018; Fitzsimons and Cooke, 2021).

The most obvious problem with using ECOSEL as the first component of a two-stage mixed mechanism is the risk of auction failure. Without reserve price information, the first phase could result in a budgetary constraint that precludes any meaningful procurement at all. Data collection, optimization, donor outreach, and auction administration become sunk costs.

A second possibility might be to invert the Bobolink Project's model and lead with a reverse auction. As before, an initial Pareto frontier would be generated featuring only ES trade-offs. Using this frontier, a set of bundles expected to be attractive to the larger community might be selected based on market research (e.g. a stakeholder consultation or choice experiment). A reverse auction would then used to solicit the opportunity costs of implementing the selected bundles for each landowner. The absence of a budgetary constraint would not be problematic in itself, since conservation tenders regularly conceal this information to deter collusion (Messer et al., 2017). In the final step, a standard ECOSEL auction (complete with reserve prices) would be used to identify the community's preferred bundle and generate the funds to purchase it. Again, however, the risk of the reverse auction concluding with prohibitively high reserve prices is a serious one: a potentially expensive and time-intensive process might fail to lead to a transaction, and management defaults to the status quo.

In light of these considerations, we stress that an online platform would not automate away the need for ecological, economic, or legal expertise. Forward auctions are young tools requiring further research, and the possibility of combining them with reverse auctions to create markets for ES is an even more recent innovation. Nonetheless, the transaction costs associated with web development, public outreach, bid submission and processing, and data management are not negligible. The current need to build these processes from scratch is not only an impediment to research, but also contributes to the sunk cost risk in the case of auction failure. A user-friendly online platform like the one sketched in this section could serve as a lubricant, making these challenges more manageable and facilitating experimentation.

3.3.2. Considerations for platform users and developers

Table 8 summarizes four types of potential users (based on the framework presented above) together with examples of the legal proof they might to provide in order to be officially registered.

Platform developers should strive to communicate scientific information in practical language. Measurements of ES values should be scientifically valid, but the presentation of this information to bidders needs to be understandable (Rode et al., 2016). This issue is analogous to the relationship between back-end and front-end software development: the former ensures the technical functionality while the latter translates it into a user-centered experience. Illustrative and simple communication tools, such as infographics, animations, and drawings should be utilized to improve accessibility. It may be beneficial to allow users to customize the level of detail (e.g. choosing between a two-page summary of highlights, and a comprehensive performance report).

Because spatial information can be critical for both forward and reverse auctions, a general-purpose platform for ES auctions will likely require an intuitive, user-friendly mapping tool where landowners can upload coordinates or highlight vectors indicating the location and boundaries of relevant parcels (see NaturEtrade for an interactive mapping example). This feature could also allow bidders to browse available auctions based on geographic location or landscape characteristics. The Restor project, originally founded by the Crowther Lab at ETH Zurich, offers another compelling example of integrating user-friendly mapping features for ES (https://www.restor.eco). An ongoing reverse auction pilot in Denmark also incorporates an online bidding tool with a user-friendly mapping function; more details on the project are forthcoming (Lundhede et al., 2022a,b).

Table 8
Framework - analysis of platform users and their initial checklist.

User type	Auction mechanism	User description	Legal proof required	Initial checklist
Sellers bidding	Reverse (procurement)	• Forest owners who want to be paid to change their management practices. • General landholders who want to plant trees or re/afforest their land.	Forest/land ownership or holder rights.	• Enough knowledge/experience to implement the management changes. • Good information on own implementation and opportunity costs and how the outcomes will be monitored
Sellers organizing auctions	Forward (subscription, donation)	• Landholders who want to be paid to change their management practices and who have good understanding and capacity to host an auction. • General landholders who want to raise funds for the forest (donation).	Forest/land ownership or holder rights.	• Data (from inventories, simulation, etc.) on the services provided by each management plan. • Decision on auction formats, implementation, contract details. • Transparent information on how the expected outcomes will be monitored and evaluated. • For donations: PayPal or similar tools to enable quick payment.
Buyers bidding	Forward (subscription, donation)	• Private/public entities or individuals who want to voluntarily contribute to continued ES provision • Private/public entities or individuals who want to purchase offsets (e.g. carbon, biodiversity).	Proof of identity might not be required for anonymous donation.	• Fundamental knowledge or willingness to learn about different FES and the specific forest being auctioned. • Online payment (credit/visa card, PayPal) in case of quick donation.
Buyers organizing auctions	Reverse (procurement)	• Usually public entities with conservation funds.	Legal identity and legal approval to conduct the auction.	• Data (from inventories, simulation, etc.) on values of ecosystem services to evaluate bids. • Decisions on auction formats, implementation, selection criteria, contract details. • Establishment of a monitoring and evaluation system.

3.4. Limitations of the review

In this article, we have attempted to present a relatively broad overview of current state of the ES auction space, as well as a roadmap to further resources and previous reviews about better-studied facets of this literature. However, several important limitations should be highlighted.

Readers should take note that this review has sometimes prioritized breadth over resolution and granularity. For instance, we mention issues relating to contextual variables like geographical, political, and governance effects on auction design strategies in passing. Similarly, we have merged, grouped, and summarized design factors and considerations without deeply engaging with variations, interlinkages and design considerations that mediate how these elements interact in practice. Representing topics like "risk and uncertainty", "additionality", or "compliance" as discrete, unitary factors is necessarily reductive. While significant open questions remain regarding these topics, it is also true that substantial scholarly effort has been invested in both constructing and dissecting them, as well as exploring their mutual interactions. We have tried to provide readers with some useful entry points into these topics (see e.g. the composite map in Fig. 7), but we stressed that this is an imperfect effort to capture a rich and dynamic body of literature; it should be viewed as an introductory adjunct, not an exhaustive elaboration of the anatomy of auction research.

The framework proposed in this study outlines how forward and reverse auctions might be integrated into an online platform. However, it does not address how those auctions should be designed given a specific context and set of objectives. Making decisions about auction format, implementation rules, and contract conditions is an extremely complex task that should take into account local cultural, legal and institutional conditions.

4. Conclusions

This review takes stock of a growing collection of academic and gray literature exploring the adaptation of auction tools to promote the provision of ES. Overall, we assess that auction tools have a strong potential to improve the cost-effectiveness of programs aimed at supporting ES provisioning through direct incentives. Nearly 90 % of the articles in our sample use reverse auction mechanisms, which have a well-developed theoretical foundation and a non-negligible track record of field trials and applications. Even so, there is ample room to expand the application of these tools to additional real-world settings. We argue that this robust track record, combined with the administratively challenging process associated with real-world implementations, should justify further investment in open-source tools and shared infrastructures improve the accessibility of ES auctions for researchers, agencies, and participants. To facilitate future experimentation, we sketch a framework for an online platform for hosting customizable forward and reverse auctions, which could improve the accessibility of auctions and potentially connect buyers with sellers.

Finally, issues relating to ES modelling uncertainty and natural disturbance risk are likely to play a growing role in the development of ES auctions. To some extent, auction tools require bidders to make their own judgments about relevant financial and environmental risk factors. However, efforts to base compensation on environmental outcomes (rather than compliance with prescribed management changes) might benefit from improved science communication regarding uncertainty and risk, as well as decision tools that account for input variability and stochastic disturbance. Addressing these issues will require further interdisciplinary collaboration between economics, social sciences, statistics, environmental modelling, and decision science. This kind of interdisciplinary exchange lies at the foundation of the ES auction field, and we expect it to remain a major catalyst for insight and innovation as ES auction research scales up its contribution to reconfiguring environmental-economic incentive structures in the face of a mounting global sustainability crisis.

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CRediT authorship contribution statement

Mengistie Kindu: Conceptualization; Investigation; Methodology; Resources; Supervision; Validation; Visualization; Writing – original draft, review & editing. Trang Le Ngoc Mai: Conceptualization; Data collection; Formal analysis; Investigation; Methodology; Visualization; Writing – review & editing. Logan Robert Bingham: Visualization; Writing – review & editing. José G. Borges: Writing – review & editing. Jens Abildtrup: Writing – review

& editing. Thomas Knoke: Conceptualization; Funding acquisition; Project administration; Resources; Supervision; Writing – review & editing.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Mengistie Kindu reports financial support was provided by European Union's Horizon 2020.

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