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Review

Ecosystem Services Auctions: The Last Decade of Research

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Abstract: Auctions offer potential cost-effectiveness improvements over other mechanisms for payments for ecosystem services (PES) contract allocation. However, evidence-based guidance for matching design to application is scarce and research priorities are unclear. To take stock of the current state of the art, we conducted a systematic review and thematic content analysis of 56 peer-reviewed journal articles discussing ES auctions published in the last decade. Auctions were approached from three overlapping perspectives: mechanism design, PES, and policy analysis. Five major themes emerged: (1) *performance*, including measures like cost-effectiveness and PES criteria like additionality; (2) *information dynamics* like price discovery and communication effects; (3) *design innovations* like risk-integrating and spatially coordinated mechanisms; (4) *contextual variables* like policy context and cultural values; and (5) *participation* factors. Additional attention from policymakers and continued efforts to coordinate research in this diverse and interdisciplinary subfield may be beneficial.

Keywords: payments for ecosystem services; reverse auctions; subscription games; market-based instruments

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1. Introduction

Markets are prone to failure in situations involving public goods, but command-and-control instruments often struggle to incorporate preference and provision cost heterogeneities [1–3]. Payments for ecosystem services (PES) have attracted growing attention for their potential to support the provision of non-market ES [4,5] (a list of abbreviations can be found at the end of this article). Budget-constrained programs may wish to maximize their impact by targeting high-value, high-threat, low-cost parcels [6,7], but information asymmetries pose an obstacle to optimally allocating contracts. (For a game-theoretic analysis of bidding in budget-constrained auctions, see [8]; for the impact of constraint type on bidding, see [9].) Auction methods seek to induce competition to overcome these asymmetries and increase allocational efficiency. Apart from a handful of large-scale examples like the US Conservation Reserve Program (CRP) [10] or Australia's EcoTender [11], however, adoption into practice has been slow. In lower-income countries, the proliferation of PES programs is well-documented, but the use of auctions remains mostly confined to small field experiments [12,13]. Although several useful primers exist (notably, those by Schilizzi [14], Whitten et al. [15], and Thorsen et al. [16]), anecdotally, obtaining a global view of the current state of the art can be challenging. We conducted a systematic review and thematic content analysis of the last decade (2010–2020) of ES auction literature.

Our sample reflects three broad conceptual approaches to auctioning ecosystem services. The first is rooted in mechanism design, analyzing how incentives and information can be structured to create efficient markets. Methodologically, this perspective generally engages with auctions through theoretical work, numerical simulations and models, and laboratory experiments (e.g., [17,18]). The second approach stems from the PES paradigm; it favors case studies and field experiments, exploring issues like additionality and conditionality (e.g., [13,19,20]). The third is aligned with policy analysis and considers the

auction niche (e.g., [21,22]). Within the scholarly conversation between these perspectives, we identified five major themes: (1) *performance*, (2) *information dynamics*, (3) *design innovations*, (4) *contextual variables*, and (5) *participation*.

This paper is organized as follows. First, basic PES and auction terminology is reviewed. Next, we present our methodology for data collection and analysis. The content analysis method used in this paper implies some repetition: themes and subthemes are not mutually exclusive (and in fact are closely intertwined), so some papers and concepts are referenced repeatedly in multiple sections. For readers interested in a specific perspective or issue relating to auctions, the results section is structured as a reference: in most cases, it should be possible to skip directly to the theme of interest rather than reading the entire article sequentially. Extensive internal references are included to avoid excessive redundancy for readers interested in obtaining a more global view of recent research. A table of useful sources (including some not included in our systematic review sample) organized by subtheme is available in the Supplementary Materials (SM2). For an alternative, practice-oriented treatment of reverse auctions organized by functional area rather than discursive themes, see [16]. For a useful conceptual introduction to auctions oriented toward laboratory research, see [14].

The discussion section below considers linkages between themes, including how disciplinary orientation can produce divergent conceptualizations of the same underlying issue (e.g., what mechanism design views as a strategic issue of *incomplete information* may be constructed as a problem of *trust* or *social capital* when approached from a social science perspective). Potential knowledge gaps are also suggested here. The conclusion offers a brief synthetic summary.

1.1. Terminology

This glossary briefly introduces key terms of art in PES and auction research, respectively, that are used throughout this article.

In the PES literature, the distinction between *efficiency* and *cost-effectiveness* is made inconsistently [23]. Here, *efficiency* refers to total welfare maximization: it is the ratio between the value associated with the outcome and the social cost of achieving it, expressed as a percent [24] (p. 217). *Effectiveness* refers to the realization of performance objectives above the business-as-usual (BAU) baseline. *Cost-effectiveness*, in turn, refers to bang for your buck: either "maximization of output for a given budget, or minimization of cost for a given output" [23]; it is expressed as a ratio between outcome and budgetary layout (e.g., trees planted per dollar) (p. 67). Thus, an efficient program is always cost-effective, but the inverse is not necessarily true: cost-effectiveness is evaluated against a management objective like increased provision, whereas efficiency is measured against total welfare (arguably making the latter an unrealistic criterion for PES evaluation) (p. 67).

Additionality refers to ES provision above some baseline. A program yields zero additionality if a landowner or operator is paid for an action they would have performed anyway, or negative additionality if it enables damaging activities to be undertaken elsewhere (*leakage*) [6,25,26]. (Note: the distinction between land owners and land operators like tenant farmers is often overlooked, but may have significant consequences in some settings [27,28]. We mostly follow existing research in eliding this difference, but look forward to further work on the topic.) *Conditionality* means the provider is only paid if they comply with the contract. Conditionality can be evaluated using an *outcome-* or *performance-based* approach, where environmental outputs are measured empirically to determine compliance, or an *action-* or *process-based* approach, where the landowner instead demonstrates conformity with a management prescription [13,29]. *Motivational crowding* represents an unresolved issue in PES whose effect likely varies from context to context. In some cases, the introduction of financial incentives could risk "crowding out" intrinsic motivations to engage in responsible stewardship, conceivably causing the scheme to backfire: once the monetary incentive is withdrawn, providers may shift to more extractive management, leading to an overall reduction in ES provision [14,20,30,31]. In others, it is

possible that motivation could be "crowded in" if payments encourage land managers to view their stewardship contribution as more important than they had previously estimated, or if partially subsidizing costs enables managers to engage in stewardship they were already motivated to perform but unable to fully fund [22,32].

Next, it may be useful to briefly review auction terms used throughout this paper. The following discussion of the primary design variables used to characterize auctions is largely simplified from Klemperer [33], Thorsen et al. [16], and particularly Whitten et al. [15] (p. 555), and tracks closely with Schilizzi's [14] summary.

Reverse auctions. Reverse auctions (*procurement auctions*, *tenders*) classically involve one buyer (*principal*) and many sellers (*agents, bidders*), whose interaction may be mediated by a third entity responsible for actually administering the auction (*auctioneer* or *administrator*). Depending on the context, the term *principal* can refer either to the buyer or to the auctioneer. We use *principal* where this distinction is not important, or we follow the usage of the article being referenced if we are unable to confidently determine the meaning intended by that source. Reverse auctions usually fall in the category of Pigouvian, government-financed PES (sometimes called PES-like schemes) [34–37], but in some cases they may be funded by private foundations or NGOs and more closely resemble Coasean, user-financed PES as conceptualized by, e.g., Wunder et al. [6,7]. In either case, the principal is generally interested in securing the provision of some ES at least cost. The sellers are ES providers, who compete to sign contracts at the lowest price, bidding their *willingness to accept* (WTA). Bids are arranged by *ascending price*: those below some threshold win, and those above it lose. If a winner underbids their true opportunity costs (*bid shading* if intentional) and is paid less than their provision cost, they suffer from *winner's curse.* In the ecosystem services context, reverse auctions are the standard; mechanisms of this type dominate our sample.

Forward auctions. We refer to demand-side mechanisms involving many buyers (*bidders, donors;* beneficiaries) and a small number of sellers (providers) as *forward auctions*. The most familiar version is the standard *seller's auction* found in places like eBay, fine art shows, and charity events: many buyers compete with one another for a discrete good, driving up its price. In the land management context, this can take the form of landowners/operators bidding their *willingness to pay* (WTP) a Pigouvian tax for the right to develop a parcel, e.g., [18,38]. However, we also examine other many-buyers-few-sellers auctions that do not quite fit this model: rather than competing with one another, buyers pool contributions (*bids*) to procure ES. These bids may reflect buyers' WTP, although such designs are not incentive compatible (i.e., bids are unlikely to match the bidder's true Hicksian WTP exactly) [39]. While these mechanisms employ the auction lexicon, they derive from provision point mechanisms and subscription games. This article focuses on two such mechanisms: ECOSEL [40] and individual price auctions (IPA) [41].

Pricing rules. In a *discriminatory price auction* (DPA), winners are paid the price they bid [42]. In a *uniform price auction* (UPA), every winner is paid the same amount—typically, the price of the first rejected bid. Because all winners are guaranteed to receive more than they bid, there is a strategic incentive to bid honestly (*incentive compatibility*). This is called a *first-rejected price* or *second-price* auction; when bids are sealed, a *Vickrey* auction (see [43] and Appendix A). The *Vickrey–Clarke–Groves* (VCG) mechanism is a multi-item extension [44–46] used in some mechanisms discussed below, notably [18,46].

Bid selection. ES auctions vary significantly in how they select winners. The principal may simply sign contracts from lowest price/area to highest. This could produce a suboptimal allocation if provision is heterogenous, so the principal might consider additional criteria, like participation, multiple ES, or spatial arrangement, complicating the *winner determination problem* (WDP): selecting the optimal combination of bids. Criteria are not always communicated to bidders and are sometimes applied post hoc.

Rounds and repetition. In *single round* auctions, bidders bid once. In *multi-round* or *iterative* auctions, some may revise their bids based on the results of the previous round (iteration) before deciding on a final bid. *Repetition* refers to multiple identical auctions

being repeated. Because bidder behaviors can be very sensitive to design, even slight changes from previous versions may be regarded as a new auction rather than a repetition. Using an auction with multiple rounds or repeating auctions can offer bidders opportunities to learn and refine rent-seeking strategies.

Bid sealing. If bidding is *open*, bid values are disclosed; if *sealed* (sometimes *closed*), this information is only available to the principal. Bidders may attempt to coordinate bids to obtain higher rents (*collusion*). In multi-round auctions, open bidding may be followed by a sealed final round (e.g., Anglo–Dutch design; for examples and related variants, see [33,47–49].). In forward auctions, bid sealing is usually intended to prevent *cheap* or *free riding* if a bidder expects to benefit regardless of their contribution (e.g., due to non-excludability).

Reserve price. In reverse (forward) auctions, the principal may place an upper (lower) bound on what it will pay (accept) for a contract. In reverse auctions, this reduces the probability of awarding the entire budget to a single winner and increases the probability of allocating contracts to more bidders. In forward auctions, the reserve price usually represents a *provision point*. Its stated function is to ensure that the seller's opportunity costs are met, but if disclosed it may also serve a signaling function: if the seller expects bidders to treat the reserve price as a goal to be achieved (typical of crowdfunding campaigns), there may be an incentive to inflate opportunity cost claims.

Constraint type. In a *budget-constrained* auction, the buyer signs contracts until the budget is exhausted. In a *target-constrained* auction, the buyer stops when a target provision level has been reached. This terminology is not easily transferable to forward auctions, but the issue of constraint type is discussed in more detail with reference to specific mechanisms below.

Design disclosure. Auctions vary in the extent to which they communicate these variables—as well as more general issues like conditionality or compliance monitoring—to bidders [15] (p. 555).

The remainder of the article presents the design and results of the systematic review itself. Our aim was not to systematically assess the evidence base for specific designs or offer methodological critiques, but rather to provide a map for this diverse and growing subfield by identifying the major topical threads in the current scholarship, situating those threads in relation to one another, and highlighting commonly-cited gaps.

2. Materials and Methods

2.1. Data Collection

The Scopus database was queried for peer-reviewed articles published between 2010–2020 (inclusive) containing the terms "auction" and "ecosystem services" in the title, abstract, or keywords. Google Scholar was also searched for the same keywords but limited to title (it is only possible to search title or fulltext), returning only duplicates of the articles located through Scopus and papers not published in scholarly journals that were not eligible for inclusion (e.g., gray literature and several working papers representing previous versions of articles that were included). The initial Scopus search returned an initial sample of 64 sources. One duplicate, one Russian-language article for which an English fulltext could not be located, and four clearly irrelevant sources (e.g., an article on education pedagogy that used an auction example) were excluded to yield a final sample of 58 sources, 42 of which focused exclusively on auction methods (Figure 1). The remaining articles had a broader policy orientation encompassing other instruments but were retained in the sample if they also included substantive comments about auctions (see, e.g., *Auction niche* in Section 3.5.2 and column *Niche* in SM2).

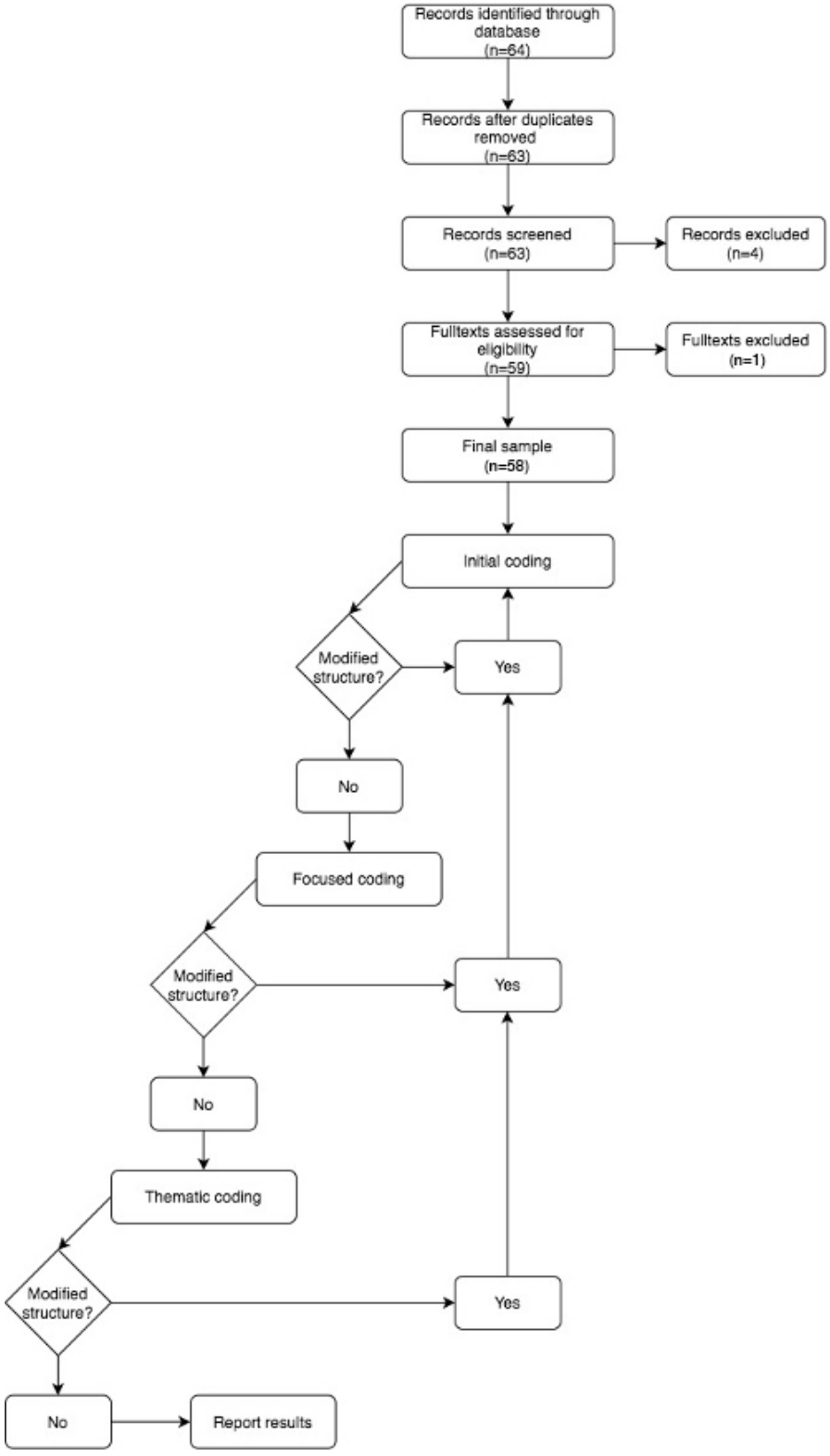


Figure 1. Overview of sampling procedure and analytic protocol.

2.2. Analytic Protocol

We conducted a thematic content analysis using NVivo 12 and NVivo-Mac 20.1.0 (QSR International), adopting an inductive approach drawn from grounded theory [50,51] and adapted from, e.g., [52–54]. This process can be divided into initial, focused, and thematic coding [50,51,54]. Initial coding is a bottom-up, descriptive process of summarization

involving classifying each line by topic. In focused coding, a higher level of abstraction is achieved by collecting initial codes into clusters and categories; loose themes begin to take shape. Finally, thematic coding adopts a more synthetic focus on associations and hierarchies, producing an integrated structure [51,54,55]. When theory generation is a primary objective, considerable effort may be invested in this final stage. Because we were interested in taking stock of an unfolding conversation, we focused mainly on identifying themes and their relationships.

Each phase is performed multiple times: once the end of the corpus is reached in one phase, the protocol repeats until subsequent iterations fail to produce substantive changes, which initiates the next phase [50,51,55]. Backtracking is expected, either to improve coherence or to reflect evolving understanding of the material; modifications trigger a new iteration. These iterative and recursive elements make this method time-consuming for large volumes of data [53]. Although it aims to improve the reliability of qualitative analysis, it is also subjective. Some suggest using multiple coders [56,57], but others prefer a single coder using temporally separated recodings to avoid inter-coder reliability issues [52,58]. We consider our use of a single-coder approach a limitation, but recognize that its significance is debated (see, e.g., [50,51,55,59–62]).

Complete coding coverage was limited to the abstracts of auction-focused articles. Other sections (particularly introductions) cover similar background, so coding entire fulltexts would have produced seemingly dominant themes on generic, uncontroversial topics. Instead, relevant passages in the body of each article were selected to expand on the abstract, foregrounding novel elements.

3. Results

The content analysis identified three basic conceptual approaches (mechanism design, PES, and policy analysis) that interactively produce the scholarly conversation on ES auctions. Within that conversation, we identified five major themes (*Performance, Information dynamics, Design, Context,* and *Participation*). These themes provide the structure for the results section; linkages to the underlying conceptual approaches are highlighted in the text.

First, Section 3.1 provides a summary of some key studies that appear frequently across themes. These include some innovative mechanism designs (Table 1) and recent field trials (Table 2) chosen because they offer useful touchpoints for linking different dimensions of the thematic discussion. Next, the remaining subsections summarize the major themes and subthemes that emerged from the thematic analysis itself. For each, relevant passages and perspectives are discussed. With the exception of *Participation*, which we did not structure into subthemes, each theme concludes with a short summary and a list of key takeaways. (*Relevant scholarship from outside our sample is highlighted with italics in parentheses, like this. See SM2 for a classification of all auction references by theme.*)

The five major themes contained substantial paragraph-level overlaps with one another, with intersections between *Context*, *Information*, and *Design* being particularly prominent (Figure 2). These connections are commonly driven by closely-linked pairs of codes within each theme: for instance, *Design* codes relating to multiple objectives and spatial coordination frequently overlapped with *Performance* codes relating to economic criteria (Figure 3).

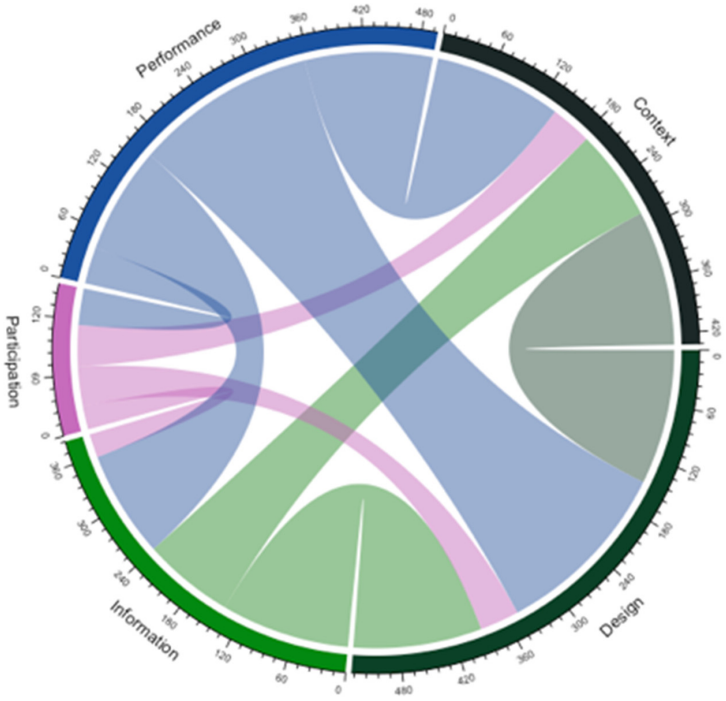


Figure 2. Intersections between the five major themes. An intersection occurs when a code belonging to Theme A and a code belonging to Theme B are applied to the same unit of text (here, typically paragraphs).

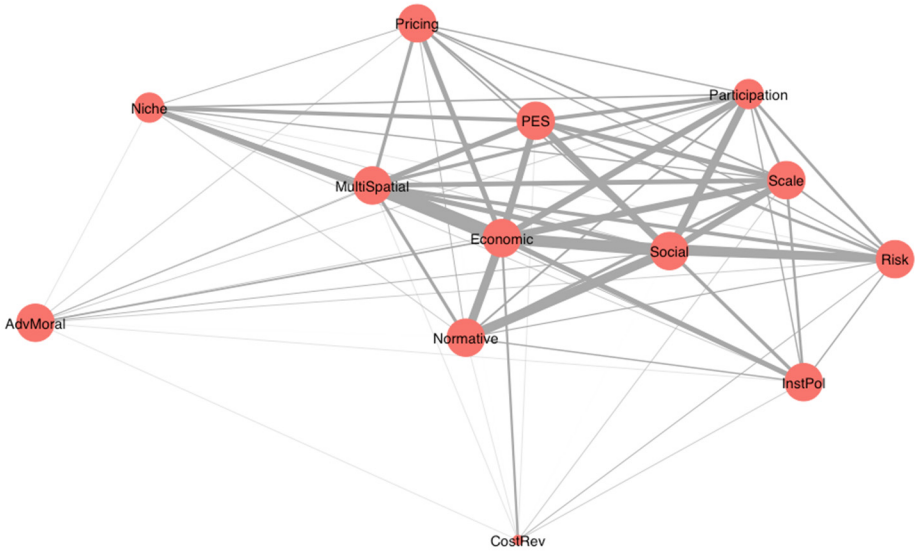


Figure 3. Intersections between the most prominent codes belonging to each theme. Nodes are scaled by degree, edges weighted by the number of intersections between each pair. Since only the most frequently-occurring codes from each theme were selected to avoid crowding the figure, connectivity is high, but prominent pairs are apparent in the central cluster. *AdvMoral:* adverse selection and moral hazard (see Section 3.3.3). *Niche:* Auction niche (Section 3.5.2). *Pricing:* see Sections 1.1, 3.2.1 and 3.3.2. *PES:* aggregate code, see Section 3.2.2. *Participation*: see Section 3.6. *Scale*: see Section 3.4.2. *Risk:* see Sections 3.3.1 and 3.4.3. *InstPol:* Institutional and policy factors, see Section 3.5.2. *Social:* social and relational factors, see Section 3.5.3. *CostRev:* cost revelation or price discovery, see Section 3.3.2. *Normative:* normative performance criteria, see Section 3.2.3. *Economic:* economic performance criteria, see Section 3.2.1. *PES:* see Section 3.2.2. *MultiSpatial:* combines codes for multiple objectives and spatial coordination, see Section 3.4.3.

Analyzed as a valued network, the four central nodes are those corresponding to (1) economic performance criteria, (2) social and relational factors, (3) multiple objectives and spatial coordination, and (4) PES performance criteria, with degrees of 298, 232, 178, and 158, respectively. Dichotomized, this ranking is maintained across multiple measures of centrality: *Economic* (degree = 10, closeness = 16, eigenvector = 0.417, betweenness 13.533) is followed by *Social* and *MultiSpatial* (degree = 8, closeness = 18, eigenvector = 0.384, betweenness = 4.033; measures identical for both nodes due to the dichotomization threshold), which are followed by *PES* (degree = 7, closeness = 19, eigenvector = 0.352, betweenness = 2.700). Even dichotomized, the network remains quite cohesive (average degree = 4.615, connectedness = 0.7051, average distance = 1.4545).

The reader should note that these figures are highly sensitive to subjective decisions about things like code definitions and aggregation from child to parent codes. We include this analysis mainly to provide a generalized, conceptual summary of the content analysis, to highlight that themes are interconnected, and to illustrate that these interconnections reflect overlaps between more narrowly-defined codes and subcodes.

3.1. Index of Key Sources

3.1.1. Mechanism Innovations

We identified three loose categories of innovation: (1) designing novel mechanisms (e.g., D-PLPN, ECOSEL, and Bobolink); (2) testing combinations of design variables to achieve more "advanced" functionalities like [17,63,64]; and (3) adapting existing mechanisms to the ES context like [65] (Table 1).

Table 1. Comparison of selected mechanism designs.

Mechanism	Demand-Side	Supply-Side	Risk Integration	Multiple Objectives	Spatial Coordination	Reference, Publication Year
Combinatorial auction	No	Yes	No	Yes	Yes	[65] (2012)
ECOSEL	Yes	No	No	Yes	Yes	[40,66] (2010, 2016)
Targeting + network bonuses	No	Yes	No	No	Yes	[63] (2016)
D-PLPN	No	Yes	Yes	No	Yes	[18] (2018)
Bobolink (IPA + UPA)	Yes	Yes	No	No	No	[67] (2019)

Combinatorial auctions. *Problem addressed:* Typically, ES auctions focus on a single management action, like conservation set-asides or tree planting. When multiple benefits are considered, they are often condensed into a site quality scalar, so it is difficult to make trade-offs between component services (see Sections 3.3.1 and 3.4.3). *Premise:* Combinatorial auctions allow bidders to submit combinations (*baskets*, *bundles*, or *packages*) of multiple projects; the auctioneer then makes trade-offs between multiple benefits in selecting winning bundles. *Summary:* Iftekhar et al. [65] review the literature to explore potential issues with applying combinatorial mechanisms to the ES context. Giving bidders the flexibility to propose a bundle of management actions could allow them exploit synergies between them and potentially realize economies of scale; the principal examines between-bundle "complementarities" to choose winners (p. 82). *Issues:* Landowners' ability to design efficient baskets may vary, and WDPs could be challenging to solve. (Combinatorial WDPs are often NP-hard, see, e.g., [68–70]). While the literature review by Iftekhar et al. offers a useful starting point for exploring applying combinatorial auctions to ES, original research involving the collection of primary data is lacking.

ECOSEL. *Problem addressed:* Standard reverse auctions typically rely on a central purchaser, and stakeholders may have little (if any) direct input into making trade-offs between multiple ES. *Premise:* ECOSEL [40] is a forward mechanism that allows stakeholders to make voluntary contributions to fund different ES baskets, which are differentiated from

each other by the relative provision levels of each component service. The best-funded basket is implemented. *Summary:* Technically a type of public good subscription game, this mechanism is designed with a large landowner whose decisions affect many stakeholders in mind. First, multi-objective mathematical programming is applied to generate a possibility frontier representing all Pareto-efficient baskets of ES (e.g., carbon sequestration, biodiversity, timber, etc.). A representative subset of these baskets is then selected and put up for auction. Each bundle has a different reserve price defined relative to the basket that maximizes the landowners' NPV (assumed to correspond to the BAU and thus the landowner's opportunity cost of implementing alternative management). In the auction, bidders pool contributions to their preferred basket(s) over multiple rounds; the basket B that (1) meets the landowner's reserve price and (2) generates the largest bid sum, wins. This sum is paid to the landowner, who is contractually obligated to implement management to produce B, and contributions to losing baskets are refunded. If no basket meets the reserve price, all bids are refunded and BAU management is implemented. Thus, ECOSEL establishes a price floor for each alternative, but not a ceiling: unlike reverse auctions, it aims to maximize ES price and thus seller revenue. *Issues:* There may be ethical objections to linking decision-making to the relative purchasing power of stakeholder groups. More laboratory experiments and field testing are needed. (*For an example of how ECOSEL might be extended to scenarios involving coordinated groups of landowners through a Pareto decomposition approach, see* [71]*; further experimental work is forthcoming.*)

Targeting and network bonuses. *Problem addressed:* The biophysical processes determining ES supply are often blind to property boundaries, so including spatial criteria might improve cost-effectiveness (see Section 3.4.3). Many important environmental objectives emerge from landscape mosaics (e.g., fire resistance, wildlife corridors), but ES auctions typically focus on management changes at the parcel level. *Premise:* To access landscape-scale benefits, auction mechanisms can be modified to produce spatially coordinated outcomes. *Summary:* Generally, spatial information can either be included on the front end by incentivizing prospective bidders to submit bids that are spatially coordinated (e.g., by offering network/agglomeration bonuses), or on the back end by prioritizing bids in desirable locations when the principal selects winners (bid targeting) (e.g., [17,72]). Fooks et al. [63] experimentally evaluate the best way to combine these strategies in four experimental treatments: bidders either (1) receive network bonuses or (2) do not; and the buyer's spatial preferences either (3) influence bid selection, or (4) do not (p. 2). The results indicate that bonuses without targeting produce suboptimal welfare outcomes—but when both are used together, they can improve environmental and social benefits by expanding the bid pool. *Issues:* Bonuses themselves represent additional expenditures, creating a coordination/cost-effectiveness trade-off (p. 19). It may be possible to manage this trade-off by identifying the optimal bonus size to maximize participation at least cost [63]. Research on spatially coordinated mechanisms is largely confined to laboratory settings, and there is a need for field data.

D-PLPN. *Problem addressed:* Revealing the auctioneer's spatial preferences through agglomeration bonuses can create opportunities for collusion, reducing the cost-effectiveness of payments. Additionally, given the unpredictable impacts of climate change on ES production functions, today's optimal allocation may not be as cost-effective a decade from now. *Premise:* D-PLPN uses a two-part bidding process to make a spatially explicit selection of winning bids given current conditions, with the option to release or retain parcels in the future. *Summary:* Polasky et al. [46] originally proposed a mechanism (PLPN) that uses a VCG variant for price discovery, enabling the principal to transform the WDP into a spatially explicit optimization problem (p. 6249; see Section 1.1, Appendix A). The payout is based on each enrolled parcel's ES contribution given the final contract allocation. Lewis and Polasky [18] subsequently developed a temporally dynamic version we refer to as D-PLPN, which adds a double-bidding feature to accommodate adaptive management under climate risk. Owners bid their WTA to forego (irreversible) development now and in a future period; the principal solves a stochastic dynamic programming problem to

make a spatially explicit selection for period 1, basing payout on ES benefit and option value. At the end of period 1, the principal optimizes again to select which parcels to retain (revising the payment based on the current benefit function) and which to release. (*The same optimal allocation can be achieved whether the regulator pays landowners to conserve [reverse], or landowners pay the regulator for the right to develop [forward], per Coase* [73,74].) *Issues:* Like most reverse-auction-based mechanisms, bidders are assumed to have reasonably accurate knowledge of their opportunity costs, and double-bidding also asks them to quantify future uncertainty. Bidders may find it difficult to make an accurate assessment (see Sections 3.3.1 and 3.4.3).

The Bobolink Project. *Problem addressed:* Stakeholders may be willing to pay for increases in the provision of public goods like ES, but marginal WTP varies from individual to individual. Additionally, mechanisms based on donations or crowdfunding often lack features to ensure efficient procurement. *Premise:* Chakrabarti et al.'s [67] successful field experiment combines an IPA mechanism with a standard UPA to link supply and demand in a two-stage mechanism (Tables 1–3). *Summary:* The IPA aims to approach a Lindahl equilibrium through voluntary contributions. For a general introduction to IPAs, see Swallow [75] and Smith and Swallow [39] (*these sources explore applications of Lindahl's* [76] *framework; for more on Lindahl pricing, see* [77–79]). Individuals successively bid their marginal WTP for additional units of a public good; the principal checks if the aggregate bids for unit n meet n's provision point; if so, the principal moves to $n + 1$, etc., until the provision point is not met for some unit and the remaining bids are refunded (see Liu and Swallow [41] for different market-clearing rules.) All bidders may pay different prices for the same provision, but none more than they bid. In the first stage, the Bobolink Project used an IPA to establish a budget, which provided the constraint for the second stage. In the second stage, the researchers conducted a budget-constrained UPA to procure nesting habitat at least cost. Donors pledged to fund different provision levels; the auctioneers only collected pledges corresponding to the provision that had been secured through the UPA. Landowners indicated that transaction costs were lower for the Bobolink Project relative to an alternative state-administered PES scheme (p. 9). The project was so successful that it became self-sustaining and was handed over to local nonprofits, who carried it forward after the conclusion of the research grant. *Issues:* Donations in an IPA are unlikely to approximate true Hicksian WTP: due to incentives to free ride, the Lindahl equilibrium is not a Nash equilibrium [39] (p. 48). Moreover, the multi-part Lindahl-framed solicitation was time-consuming for donors [67].

While not exhaustive, these examples—combinatorial auctions, ECOSEL, D-PLPN, combining targeting and network bonuses, and the Bobolink Project's IPA-UPA pairing—illustrate the growing diversity of auction design innovations applicable to the ES context.

3.1.2. Field Experiments

This subsection briefly introduces six field experiments that we reference frequently throughout this article to illustrate auction concerns and design considerations (Table 2 also mentions the Bobolink Project, introduced in Section 3.1.1 above). These experiments are diverse both geographically (including results from North and South America, Europe, and Africa) as well as theoretically, featuring a range of mechanism designs (DPA, UPA, and IPA), varied implementation decisions (e.g., related to compliance and payment), and different sets of objectives.

Table 2. Comparison of selected field experiments.

Location, Experiment Year(s)	Main Interests	Mechanism	Rounds	Compliance Monitoring	Conditionality	Time Horizon	Reference, Pub. Year
Germany (Lower Saxony), 2007–09	Bidding behavior, cost-effectiveness, additionality	Bids ranked by price/area; budget-constrained sealed-bid UPA	1	Yes, *outcomes* (plant diversity threshold)	Yes, *outcome-based*	1 year	[80] (2011)
Tanzania (Uluguru Mountains), 2008–09	Price discovery, pro-poor targeting, cost-effectiveness	Bids ranked by price/area; budget-constrained sealed-bid UPA	2	Yes, *outcomes* (tree survival)	No: upfront payment	3 years	[81] (2013)
Bolivia (S. Altiplano), Peru (N. Altiplano), 2010–11	Multicriteria targeting (genetic diversity, agricultural knowledge, exchange networks), equity, and pricing rules	Multicriteria ranking (price/area, number of farmers, number of groups); multiple pricing rules tested (UPA, DPA, conditional); budget-constrained sealed bids	1	Yes, *actions* (area planted with selected landrace) & *outcomes* (total landrace production level)	Yes, *action-based*	1 year	[19,20,34] (2011, 2013)
Malawi (Ntchisi District), 2008	Leakage and livelihood impacts (original experiment focused on allocational cost-effectiveness)	Bids ranked by price/area; budget-constrained sealed-bid UPA	1	Yes, *outcomes* (tree survival)	Yes, *outcome-based* (payment scaled by outcome)	3 years	[28] (2017)
Indonesia (West Lampung), 2006–07	Socioeconomic and institutional links to auction-winning and compliance; perceptions of fairness; impacts on community social dynamics	Bids ranked by price/area; budget-constrained sealed-bid UPA	7	Yes, *actions* (construct sediment retention structures)	Partial, *action-based* (50% upfront; 50% at end of contract conditional)	1 year	[82,83] (2017)
Kenya (Upper Tana River watershed), 2011	Gender, risk perceptions, bidding behavior, and effect of compliance rules	Bids ranked by price; budget-constrained DPA	1	Yes, *actions* (maintain soil moisture) and *outcomes* (tree survival)	Partial: 10% upfront + comparison of *action-based* and *outcome-based* contracts	6 months	[13] (2019)
USA (New England), 2013–15	Field test of novel "Bobolink Project" mechanism; market outcomes, cost- effectiveness	Demand-side IPA + supply-side bids ranked by price/area, budget-constrained sealed-bid UPA	1 demand side + 1 supply side	Yes, *actions* (habitat-friendly management) and outcomes (bird population)	Yes: demand-side conditional on obtaining a contract at specified price, supply-side conditional on contracted management *actions*	~6 months	[67] (2019)

Germany. Ulber et al. [80] conduct a quasi-experimental field test using a DPA to allocate conservation contracts to farmers, monitoring control fields corresponding to BAU management (p. 466). The scheme achieved ES additionality relative to the controls, but bids were markedly higher than estimated opportunity costs, raising cost-effectiveness questions.

Peru and Bolivia. Narloch et al. [20] conduct a conservation auction in the Andes testing multicriteria cost-effectiveness targeting of (1) area as a proxy for genetic diversity, (2) individual participation as a proxy for traditional knowledge, (3) and group participation as a proxy for inter-community geneflow (p. 419); the overall aim was to conserve neglected traditional quinoa landraces identified through participatory workshops and expert consultations. They also considered distributional equity at individual and group levels. The bids selected by each rule differed significantly, indicating trade-offs: e.g., area and individual participation competed with group participation and produced "highly unequal" payment distributions (p. 417). Narloch et al. [19] re-examine the case, exploring payment rules and fairness issues.

Malawi. Jack and Cardona Santos [26] use a randomized experiment to compare how a UPA for tree-planting contracts impacted within-farm leakage and livelihoods relative to a contract lottery and a no-contract BAU control (see Section 3.2.2) (See [84,85]). Inputs and training were provided upfront; payments were conditional on tree survival. By targeting low opportunity cost (i.e., higher likelihood of surplus land/labor), the auction engendered marginally less leakage and household labor shortages than the lottery. Neither produced significantly more trees than BAU, so planting may have occurred anyway.

Tanzania. Jindal et al.'s [81] pilot auction for tree-planting contracts was designed to reveal cost information to guide price-setting for a carbon PES (see Section 3.3.2). The researchers collected household- and village-level socioeconomic data and interviewed both winners and losers, finding pricing trade-offs between pricing (DPA vs. UPA) and bid targeting (cost-effectiveness vs. pro-poor targeting) rules. Payments were upfront, but a two-year follow-up found high compliance.

Indonesia. Leimona and Carrasco [82] describe a multi-round UPA designed to set prices for a soil conservation PES in a setting where farmers have limited education and assets and small plots (p. 632) (*This study builds on* [86]*, which was used as guidance for the Tanzanian case; see also* [87,88].). They collected socioeconomic data and assessed participants' understanding of (a) *technical factors* about the process; (b) *social relationship factors* like information-sharing and relationships; and (c) *environmental perception factors* related to providing ES (p. 635). McGrath et al. [83] examine the interaction between participant characteristics, fairness perceptions, and community impacts in the experiment.

Kenya. Andeltová et al. [13] test a DPA in a setting with prevalent gender inequalities, comparing process- and performance-based contracts (p. 13; see Section 3.2.2). Gender differences in risk perception, tolerance, and environmental outcomes were linked to labor disparities, as women were more likely to maintain trees and contribute to family caretaking (see Sections 3.3.1 and 3.5). Despite (or perhaps because of) this imbalance, female bidders said they would accept the same contract again (p. 21).

3.2. Theme 1: Performance

We structured *performance* into three subthemes: (1) economic criteria (2) PES-framed assessments (additionality and conditionality), and (3) normative views.

3.2.1. Economic Criteria

Efficiency and cost-effectiveness. Auctions' core value claim is that (under the right conditions and if well designed) they allocate contracts cost-effectively. That is, someone who does not have a driving interest in cost-effective allocation or discovering truthful opportunity cost information will probably choose another instrument. Consequently, this subtheme—which deals mainly with efficiency and cost-effectiveness—is implicated throughout this review, so this section functions mainly as a placeholder and brief introduc-

tion to a topic that will be encountered in every other section of this article (see Sections 1 and 2 and introduction to Section 3).

Transaction costs. A closely related subtopic that is less universally discussed in our sample is the issue of transaction costs. The revenue equivalence theorem suggests that given certain conditions (e.g. bidder risk neutrality, commodity homogeneity) the same revenue is achievable irrespective of auction design [15]. Although the theorem informs market design, it also sets a high bar, and its conditions are commonly violated in the ES auction context—including, crucially, its assumption of zero transaction costs [15] (p. 553). In reality, auctions feature a number of unique and often difficult-to-quantify transaction costs, including collecting information, designing the tender process, administering the program, and monitoring compliance (for the auctioneer) and learning how to participate, formulate a bid, and estimate one's own opportunity costs (for the bidder) (see Section 3.5.2). In the field experiments in Tanzania and Indonesia, for instance, the researchers held mock auctions and practice rounds to familiarize participants with the bidding procedure [81,82]. In the laboratory, transaction costs are often neglected for experimental reasons [89], but there are exceptions: Messer et al. [90], for instance, include a submission fee for each parcel submitted to mimic transaction costs. In practice, however, transaction costs are a significant factor in instrument selection [91], incentive type [92], mechanism design decisions like number of rounds [93], and bid selection rules like targeting [94]. In ECOSEL, data and model development demands represent significant transaction costs that could conceivably determine the mechanism's viability [40,95]. In the Bobolink Project, the complexity of the Lindahl-based solicitation required time and effort from donors that simpler solicitations avoid [67] (see Section 4).

(*Schilizzi [14] notes that weighing transaction costs when comparing auctions with other policy instruments is both a "common cause of concern" and one that has mostly received "lip service" due to experimental challenges; one strategy that can be used in the laboratory involves identifying threshold values [with their uncertainty] that define the relative preferability of an auction versus an alternative instrument—but applying such results to predict behavior in field settings involves another set of highly uncertain estimations [p. 578].*)

3.2.2. PES Criteria

Additionality. One in five articles in our sample explicitly considered additionality. It is cited as a success indicator for the CRP [10], but by systematically enrolling those with the lowest opportunity costs, some reverse auctions may be minimally additional [96] (see Section 3.3.3). Using an agent-based model (ABM), Lundberg et al. [94] show that context determines the relative additionality of fixed payments vs. UPA vs. DPA, developing an algorithm for matching mechanism to context, which is defined by baseline compliance, cost-ES correlation, cost heterogeneity, and budget (p. 347; see Section 3.4). (*For an auction-framed approach to ABM, see* [97]. *For a useful ABM-based analysis of asset specificity in repeated auctions published after we finalized our sample, see* [98].) Conte and Griffin [99] show that private benefit heterogeneity could also impact DPA additionality and overall cost-effectiveness. Leakage is also context-dependent: in Malawi, resource inequalities lowered auction leakage relative to random allocation [26], and motivational crowding may induce leakage in some settings [15] (see Section 3.5). Additionality is not just an outcome measure: additionality metrics inform BushTender's WDP [91], and onerous additionality requirements can limit participation, constraining supply [30]. In forward auctions, the belief that bids will produce additional benefits shapes contribution decisions [67].

Conditionality. Only after a clear standard has been defined and compliance actually assessed does conditionality become critical, so it is infrequently mentioned outside field studies. Process-based (e.g., [13]) and performance-based (e.g., [100]) compliance standards allocate risk and agency differently: the latter gives land managers the scope to determine how to produce an output given their costs and capabilities, but carries the risk of nonpayment if those outputs do not materialize [101,102] (Baird et al. [103] classify as performance-based any bid selection mechanism that takes environmental benefits

into account [p. 424]). Softer standards can encourage participation: Narloch et al. [34] use action-based contracts in the Andes, but also monitor non-contractually-stipulated outcomes. When outcome-based standards are used, supportive interventions may be preferable to sanctioning noncompliance [30].

The prior probability that noncompliance (1) occurs, (2) is identified, and (3) is sanctioned, can influence design [15,94]. Resource constraints matter too: the experiments in Kenya and Malawi satisfied strict conditionality [13,26], but in Tanzania, participation was encouraged through upfront payments while the researchers tried to discourage shirking by suggesting that compliance could influence future eligibility [81] (p. 74). A two-year follow-up found that winners experienced social pressure to comply (see Section 3.5). In Indonesia, Leimona and Carrasco [82] split the difference, paying 50% upfront and making the remainder conditional on compliance with a process-based standard. Where monitoring is infeasible, success may hinge on non-economic factors like mutual trust [104] (see *Trust* in Section 3.5.3). In the US, the Bobolink Project considered bidirectional conditionality: as in a standard IPA, acceptance of buyers' contributions was conditional on habitat procurement level (see e.g., [41]), while sellers' payments were conditional on compliance with a process-based standard [67].

Sometimes, it may be useful to use different compliance standards for program evaluation and payment disbursal. In Kenya, for instance, Andeltová et al. [13] monitored soil moisture to verify compliance with watering prescriptions, but considered managers compliant whether or not those prescriptions improved growth or survival: that is, compliance was evaluated based on actions rather than outcomes, but outcomes were still measured. (*For more on potential trade-offs between stewardship effort and participation when incentives are linked to uncertain outcomes, see Schilizzi and Latacz-Lohmann* [105].)

3.2.3. Normative Criteria

Auctions may face efficiency–effectiveness–equity (EEE) trade-offs [94,106], as observed in the Andes and Tanzania [20,81]; for instance, the latter may have negatively impacted the land rights of local women (p. 78). In Kenya, Andeltová et al. [13] found that targeting the participation of women may simultaneously improve key dimensions of gender equity as well as auction effectiveness—albeit at the risk of exacerbating gender-based labor disparities (see Section 3.5.3). Evaluated in terms of "access to project decision-making, trainings and cash", gender inequality may well have been exacerbated by another allocation mechanism too, since women were more likely than men to assist in maintenance [13] (p. 21). In Indonesia, farmers with larger parcels tended be more successful, possibly due to economies of scale [82]. Some argue that targeting distributional equity might undermine the motivation to use competitive mechanisms in the first place [15,19,20], though some laboratory research suggests that it might be possible to circumvent this trade-off in some cases [104] (see Section 3.5). Although conservation agencies tend to think in terms of political fairness and view inefficient expenditures of public funds as inequitable [90,94], Wünscher and Wunder [12] consider re-framing informational rents as poverty-alleviating transfers.

Equity discussions are often couched in terms of participants' expectations rather than researchers' ethics (e.g., [107]). There are practical reasons for ensuring that stakeholders *perceive* allocation and price-setting processes as fair and transparent [38,41,64,82] (see Sections 3.5.3 and 3.6). "Incorporating justice into conservation" is pragmatic, since interventions perceived to be just are more likely to succeed [83] (p. 45). Still, these concepts are nuanced, multidimensional, and relative, shaped by issues like scale, social ecologies, and understanding. (*For more on distributional, procedural, and contextual equity, see* [108]. *For designing auctions around different principles of fairness, see* [34]. *For the importance of perceived fairness and transparency as viewed by landholders and auction administrators, see* [109]. *For conflicting views of equity, see* [8,110].)

3.2.4. Summary

Additionality concerns are implicit in much of our sample, but conditionality is given shorter shrift: worth mentioning, but often treated as incidental to designing and testing efficient mechanisms. Nonetheless, conditionality entails costs that vary as a function of how parcels are situated in enmeshed physical, social, and ecological landscapes, with potential implications for mechanism design and auction dynamics. Gender relations, education, trust, and wealth distribution can directly influence both the propensity and capacity for compliance (see Section 3.5). Normative issues are mostly discussed in relation to field studies in lower-income countries, and often framed as participant expectations that must be met for pragmatic reasons.

Key lessons

- There are multiple, potentially independent dimensions along which auctions can be viewed as having succeeded or failed.
- Economic efficiency is the classic motivation for using auctions, with the possible exceptions of UPAs for price discovery (see Section 3.4.2) or forward auctions to access decentralized funding (e.g., ECOSEL, IPAs).
- Conditionality issues cross knowledge domains (contract design, governance, etc.), receiving inconsistent treatment in the auction literature—but are likely to become more prominent with increased uptake of auction tools by policymakers.
- It is important to recognize that equity and fairness are multidimensional concepts when evaluating ES auctions—for instance, by distinguishing between distributional, process, and contextual views.
- Using auctions to promote distributional equity may conflict with the mechanism's fundamental logic of efficiency-through-competition.

3.3. Theme 2: Information Dynamics

3.3.1. Incomplete and Asymmetric Information: Basic Issues

The efficiency of reverse auctions hinges in large part on the interaction between "institutions and information" [90] (p. 233). This section introduces uncertainties typical of the decision spaces within which actors involved in the auction process—including the researchers studying it—operate (see Section 3.5). These include uncertainties about site quality, provision, and social surplus; the prior intentions of different actors; mechanism details; and uncertainty about the future.

Site priority and ES provision. The simplest reverse auctions allocate contracts to the lowest bidders, but low cost does not necessarily correspond to value-for-money, especially if there is substantial heterogeneity in either ES production [65,101,111] or private benefits from conservation [112]. Environmental benefit indices (EBI) are metrics used to prioritize sites and weight bids in terms of value-for-money. In the US, the CRP calculates an EBI by scoring the environmental benefits offered by a given parcel against six weighted factors—an approach mostly oriented toward conservation rather than weighing multiple management alternatives [10,113]. (*In 2021, these factors were related to wildlife habitat, water quality benefits, on-farm benefits from reduced erosion, benefits likely to last beyond the contract period, air quality benefits, and cost* [114]. *Each factor is composed of several weighted subfactors.*) In Australia, EcoTender's extension to multiple objectives was enabled by the Environmental Systems Modelling Platform (EnSym) to estimate ES stocks and flows in response to management alternatives [11] (p. 115). ES indicators can facilitate bid ranking, but may be expensive at finer spatial scales; additional granularity may yield diminishing returns, particularly where "landholder engagement, information sharing, and trust-building" is feasible [115] (see Sections 3.3.3 and 3.5.3). Developing standardized measures for certain ES (e.g., those based on biodiversity) represents an important technical problem: without reliable outcome-measuring systems, investor interest in novel MBIs may be difficult to attract and maintain [91]. Asymmetric information about biophysical processes often favors procuring agencies, who can model ES response to management alternatives more reliably than landowners [10,101]. However, sharing ES quality information may

improve self-designed bids more than it exacerbates rent seeking [112] (pp. 571–585). Providing environmental rankings for different practices and allowing landowners to submit bids for a variety of them may be effective [116] (Banerjee and Conte call this *bid menu format*). In forward auctions, provision points are more likely to be reached if bidders are confident their contributions will create environmental additionality: the Bobolink Project built confidence through documentation and rebates [67], while bidders in a mock ECOSEL auction favored an FSC-certification scenario despite higher reserve prices [66]. Communicating site quality and management trade-offs to non-expert donors may be challenging, however [66,67].

Regulatory intentions. Just as agencies struggle to assess threat (see Section 3.3.3), landowners may find regulatory intentions difficult to gauge. If the government fails to achieve its goals through an auction, might it impose regulations even more burdensome than the proposed contract? Holmes [106] finds that threatening to do so can constrain bid inflation, but following through entails adverse selection costs (p. 590). If the perceived risk of regulatory intervention is acute, landowners could theoretically deflate bids and risk winner's curse to protect option values. Of course, there is a broad spectrum between an explicit threat and the felt danger that unspecified regulatory action could follow a failed auction; the salience of such fears are likely context-dependent. Some even desire regulatory intervention: Cooke and Corbo-Perkins [107] interview landowners who deliberately underbid their costs, trading winner's curse for permanent development restrictions (i.e., negative option value). Although landowners' informational rents are typically framed in a negative light (e.g., [100,117]), this is an economic judgment, not a moral or political one. If the principal's objectives include stimulating rural economies or supporting marginalized communities, it may tolerate higher rents—although there is admittedly tension between this framing, auctions' competitive-efficiency basis, and Tinbergen's rule of one policy objective per instrument [12].

Auctioneer preferences and mechanism design. Sharing information about auctioneer preferences can increase rent seeking in iterative auctions [17], though declining to disclose how many rounds will be performed could impede strategic bidding [93]. Similarly, sharing past results can increase rent seeking unless bidders believe that the budget is unpredictable [90]. Lundberg et al. [94] simulate learning in DPAs by allowing agents to copy neighbors' successful bids, which rapidly increases conservation costs when provision costs are randomly distributed (p. 355). (*Learning effects may not undermine auction cost-effectiveness in the presence of asset specificity if "land users face liquidity constraints and high time preferences"* [98] *(p. 1), but they could shape the comparative efficiency of repeated budget- vs. target-constrained auctions* [9].) Obscuring auction-relevant information from bidders can also have social implications in field settings, however: since information quality influences reported satisfaction and perceptions of fairness, erring on the side of more disclosure may boost participation and satisfaction [72,83,92,104] (see Section 3.5.3). Bidding entails time, effort, and potentially emotional investment with uncertain payoff, so prospective bidders may struggle to gauge the risks and benefits of participation if they do not understand the mechanism [96]. Bidding also involves trading off the risk of losing with that of winner's curse [118], so bid shading can reflect uncertainties about implementation, transaction costs, future expenses, and past experience [30,80,90,92].

Information silos within actor categories. Private information between bidders is just as important as principal–agent asymmetries. Uncertainty about the number of competitors and their bids can influence the relative cost-effectiveness of UPAs and DPAs, for instance [89] (see Section 3.4.1). When spatial bonuses are used, difficulty estimating how competition and future enrollments might impact both win probability and payout can shape bidding strategy [63,64], although evaluating information availability is difficult outside laboratory conditions [90] (p. 213). In forward auctions, prosocial behaviors like contribution decisions may be influenced by the observed behaviors of other buyers [41,66].

3.3.2. Price Discovery

When used as *cost-revealing* or *price discovery* mechanisms, auctions entice landowners to reveal private information about expected costs or foregone gains [19,20,82]. The (D-)PLPN mechanisms highlight price discovery as a discrete function [18,46]—and that function is sometimes prioritized over the cost-effectiveness of the transaction itself [119]. One-shot auctions can be implemented to guide subsidy design [94]; the Tanzanian auction was designed to collect data to estimate supply curves for setting prices in a subsequent PES scheme [81]. Incentive compatible in principle, a well-designed UPA can allow the principal to pay some informational rent (equivalent to the summed differences between each accepted bid and the first rejected bid) to obtain truthful opportunity cost information [12,15] (see also [16,120]). This is not a foolproof strategy: significant bid shading was identified in the UPA in Germany [80], and in Indonesia, low price/compliance correlation suggested suboptimal incentive elicitation [82] (see Section 3.1). This could be attributable either to difficulties understanding the mechanism on the part of participants, or to difficulty on the part of the auctioneers in identifying high-risk bids.

3.3.3. Moral Hazard and Adverse Selection

Moral hazard. Moral hazard occurs when a contracted provider shirks or neglects cost-control or risk-mitigation measures [117] (p. 389). It is mainly a concern when contracts prescribe interventions that are difficult to monitor or verify (e.g., predator control), but it can be mitigated if (a) the costs of the activity are truthfully elicited and (b) there is a way to measure its effects [101] (pp. 6–7). Of course, if outcomes are easy to measure, then a performance-based standard might be possible, conceivably avoiding the dilemma. Site visits can provide opportunities to build rapport with landowners, which may reduce the risk of moral hazard [15,115]. (*For interactions between contract and auction design with respect to adverse selection and moral hazard, see* [121]).

Adverse selection. Although auctions are ostensibly efficiency-oriented tools [20,93], Arnold et al. [117] find DPAs to underperform both externality-correcting taxes and doing nothing at all. The reason has to do with adverse selection, which occurs when low-value parcels mimic high-value parcels, or alternatively when low-cost producers mimic high-cost producers (p. 389). In the first case, the reliability with which parcels can be ranked by value-for-money depends heavily on the EBI metric. In the second case, unlike site quality (which can be observed and assessed), opportunity costs and future management intentions represent information that is private to bidders. Those most likely to provide an ES for free can submit highly competitive bids, potentially extracting rents equivalent to the entirety of the payment (zero additionality). Mechanism design modifications or the inclusion of a screening feature are suggested as potential solutions. Distinguishing high- and low-threat parcels is difficult [112,117], and threat targeting can induce harmful behaviors like jeopardizing previously-secure resources as a profit-seeking strategy [75]. Adverse selection risk is influenced by contextual variables like budget, regulatory threats, correlations between opportunity cost and ES provision, and baseline compliance [94,106] (see Section 3.5). *(For a theoretical and experimental analysis of the interaction between pricing rules and compliance behavior in imperfect monitoring environments, see* [122].)

3.3.4. Collusion and Free Riding

Collusion subverts the competitive dynamic underpinning auction efficiency [21,91]. In the laboratory, collusion can be measured by comparing bidding under different communication treatments, for instance [63,64]. In the field, however, it is difficult to identify and thus challenging to prevent. In Tanzania, Jindal et al. [81] analyzed bidders' seating arrangements and conducted statistical tests for between-bid similarities, but failed to identify evidence of collusion. Of course, ruling out collusion is like proving a negative: it is hard to know when you have been outsmarted. When auctions are repeated or feature continuous bidding, bidders can use historical information to make inferences about reserve prices to calibrate their bids; in multi-round auctions, they can respond to other bidders' price

signals [21,91,93]. (*In the first phase of the CRP, for instance, bidders learned to estimate the value of a regional threshold below which any bid was automatically accepted [Maximum Acceptable Rental Rates, MARR], leading to bid shading and significant increases in program costs* [123] *[p. 602].*)

Collusion probably becomes more difficult as the complexity of targeting and bid selection rules increases. To game (D-)PLPN, for instance, colluders would have to know other bidders' opportunity costs and accurately estimate environmental benefit functions parcel by parcel [18,46]. Even then, coordinated underbidding to obtain contracts risks winner's curse, implicating thorny logistical and political problems like developing a profit-sharing system in case of success and maintaining solidarity in the face of risk (p. 31).

In forward auctions, collusion is less of a concern. Although coordination in IPAs has not been studied extensively, competing effects can be imagined: it might foster pro-social behavior, allowing groups to secure higher provision—or encourage free riding if one's preferred provision level has already been funded [41]. ECOSEL relies on bidders coordinating to fund a consensus bundle: the core risk is not collusion but discoordination [66].

3.3.5. Summary

ES auctions can be viewed as processes of accumulating and rearranging information between silos: information about *intentions and the status quo*, and therefore costs, benefits, and threats; the biophysical processes that produce ES and the expected *effects of management alternatives* on provision; about the dynamics of the *auctions as games*; and about the *other actors* engaged in them, including the kinds of coordination and competition they can undertake. Note that price discovery means something very different for forward and reverse auction formats (crudely, WTP vs. WTA).

Key lessons

- Although opportunity cost, benefit, and threat to future ES provision are related, they should not be conflated when analyzing auction dynamics and outcomes.
- Auctions can either be about getting a pretty good price (DPA), or deliberately overpaying in order to learn what a really good price would be (UPA). (*Note: this is a difference of orientation, not performance: rents in DPAs are not necessarily lower than in UPAs, but the former aims to minimize them, whereas in the latter the principal agrees in advance not to "extort all possible rents" in exchange for truthful opportunity cost information* [120] *[p. 22]. For comparing information rents in these two formats, see* [124] *and* [42].)
- Collusion can inflate prices in reverse auctions; in forward formats, prices are mostly vulnerable to distortion by cheap/free riding.
- Failing to limit adverse selection and moral hazard can compromise auction cost-effectiveness to the point of creating perverse outcomes worse than doing nothing.
- Sometimes information asymmetries can be exploited for the gain of one party, but in other cases disclosure improves outcomes (for instance, enabling bidders to tailor bids to the auctioneer's preferences to increase win probability or seek bonuses for, e.g., agglomeration).

3.4. Theme 3: Design

3.4.1. Communication

Bidder–bidder communication effects are a popular subject for laboratory experiments, particularly those interested in coordination and collusion, e.g., (see Sections 3.3, 3.4.3, and 3.5.3). However, auctioneer–bidder communication can impact bidding behavior too: using an induced-value experiment structured as a public good dilemma combined with an effort-level game, Vogt et al. [104] find auctioneer–bidder chat fostered the development of a social gift exchange over repeated auctions. (Relatedly, successful interactions between principal and auction winners can create social capital that favors repeated winning, potentially leading to "lock-in" effects" [125].) Contrary to the game-theoretic prediction, this dynamic increased outcome equity without efficiency losses: auctioneers' willingness to accept higher-priced contracts was balanced out by winners' willingness to invest more effort in service provision. In field settings, communicating high-quality information

about the auction process to bidders can improve perceptions of fairness and modulate community impacts [83]. Auctions can be an occasion for extension, outreach, and public education—important co-benefits that are often overlooked [15]. In an auction to improve stormwater management where material inputs were provided for free, Mayer et al. [111] found although that most bidders submitted zero-dollar bids, the intervention appeared to produce additional benefits, demonstrating auctions' potential extension function for promoting BMP adoption even when total payments are quite low.

3.4.2. Scale

Scale concerns are salient for mechanism design. We consider four dimensions: budget, space, time, and participation level (see Sections 3.5 and 3.6). To highlight the links between them, we introduce these dimensions in arbitrary pairs.

Budget and participation level. Variable budgets can deter rent seeking [90], and larger ones can increase participation due to expectations about payouts or winning probability [63]. However, auctions do not have to be big to be successful: small budgets and few participants can still induce competition and produce cost-effective outcomes, although perhaps not very impactful ones [15] (p. 53). The likelihood of enrolling expensive bids increases with the budget/participants ratio, with potentially negative implications for cost-effectiveness [96]. Absent a reserve price, a large budget can interact with a small bidder pool to award "enormously" overpriced contracts [80] (pp. 46–70). Conversely, too much participation for the available budget risks high administrative costs, negative sentiments among unsuccessful bidders, leakage due to motivational crowding, and deterring future participation [15] (p. 83; see Section 3.6). Lundberg et al. [94] offer a detailed, simulation-based perspective on how budget level may interact with other contextual and design variables to modify outcomes—albeit one that neglects qualitative issues like high rejection rates discouraging participation in future auctions. Forward auctions are born budgetless: they are designed to establish ES provision levels by allowing voluntary contributions to set the budget [40,119].

The Tanzanian auction's small, closely connected potential bidder pool implied an elevated risk of collusion, but also fostered compliance: unsuccessful bidders did not want to see winners shirk because they knew "low bidders had prevented them from winning" [81] (p. 78). In lower-income countries, constraints on budgets and institutional capacity may encourage experimentation and innovation in auction design [12,15]; oversized budgets could risk equilibrium impacts on local economies (e.g., on wages, prices, and labor allocation) [26] (p. 647).

Geography and time. Target area and contract duration should be informed by eligible participant numbers, parcel sizes, program objectives, ES modelling capacity, and heterogeneities in cost, benefit, and provision [26,94]. Difficult-to-predict processes emerging from landscape mosaics can complicate both WDPs [18,40,95] and post-contract management [107] (see Section 3.4.3). If large landowners exploiting economies of scale to monopolize contracts is a concern, bid caps might be considered [82].

Field trials mostly rely on contract durations of a few years at most (Table 2), whereas conservation programs may prefer longer commitments. Everard [10] considers the CRP's 10–15 year contracts a good balance between renewal flexibility and long-term planning. Time horizon can impact bidding patterns by modifying risk profiles and option values, but the net effect varies: prices could rise with contract duration in some contexts [81,95] and fall for indefinite contracts in others [107]. In lower-income countries, budget and contract duration may modulate trade-offs between procedural and contextual equity [83]. D-PLPN's two-part bid design effectively puts a price on option value [18]. In addition to contract duration, the timeline for the auction process itself matters too: inducing competition requires a degree of synchrony that is largely unique to auctions [15].

3.4.3. Advanced Functions

Spatial coordination. The simplest way to incorporate spatial information into auctions involves targeting benefit (e.g., the CRP's EBI [113,126]; see also [92,115,119]), threats to future provision, or both (see Section 3.3). However, objectives like fire resistance or habitat corridors emerge from landscape mosaics; accessing them requires the principal to weigh the positioning of potentially heterogeneous parcels in relation to one another to solve the WDP [101]. Spatial coordination is typically introduced either by (a) stimulating coordination between bidders themselves (bottom-up), (b) optimizing spatially explicit WDPs (top-down), or both. These designs generally assume that landowners have an accurate understanding of their own opportunity costs. (*Computational tractability is an issue for combinatorial problems with discrete, spatially explicit bids, since arithmetic increases in the number of bids exponentially increases the number of possible bundles* [65,93] *(p. 1626). For a useful non-auction-specific review of coordination incentives—including threshold bonuses, which are not discussed here—see Nguyen et al.* [127].)

Bottom-up approaches attempt to combine iterative bidding formats, agglomeration bonuses, communication, and pricing rules to encourage coordination without enabling excessive rent seeking. In Reeson et al. [93], increasing the win probability for contiguous parcels in a multi-round DPA induced coordination without exacerbating rent-seeking when the total number of rounds was not disclosed. Banerjee et al. [17] score contiguity in an iterative DPA with heterogeneous parcel values; disclosing the spatial objective had no net effect on efficiency. In Krawczyk et al.'s [64] multi-round auction experiment with heterogeneous parcel values, a DPA cost-effectively facilitated long corridor creation where a UPA typically failed to: in the latter treatment, a single high-priced parcel in a critical location can create a missing link/hold-out problem that can only be overcome by accepting an extremely high uniform payment (pp. 41–42). As above, the experiment also found that communication enabled coordination but also collusion, and thus minimal net changes in efficiency. Liu et al. [72] report similar paradoxical effects, although participants' understanding of the incentive system may have played a role; they caution that auctions with spatial criteria may deter potential participants due to increased mechanism complexity, and stress the need for further research. Iftekhar and Latacz-Lohmann [89] also find a DPA to produce more cost-effective coordination than a UPA, though the DPA was more sensitive to bidder uncertainty (pp. 17–18). In the UPA treatment, landowners submitted bids individually and the auction terminated with the formation of a wildlife zone; in the DPA treatment, landholders formed group bids (transaction costs of group formation were neglected). Economic cost-effectiveness was maximized when landowners and auctioneer both knew the parcels' values, but budgetary cost-effectiveness was maximized when only the auctioneer knew the parcels' environmental values.

The (D-)PLPN mechanisms offer top-down alternatives for heterogeneous parcels, using a VCG variant for price discovery, then optimizing: since the "value generated by an individual parcel, and hence the payment [...] is a function of land uses on all parcels", the final selection can be made after a single round [18] (p. 6249). (D-)PLPN ignore management cost functions for different within-parcel provision levels, relying instead on binary *develop/conserve* decision variables. It is not immediately obvious that this limitation would be trivial to overcome; doing so might require modifications to the opportunity cost elicitation and optimization models, which could offset cost-effectiveness gains achieved by expanding the feasible region. ECOSEL is a forward mechanism that can readily incorporate spatially explicit optimization [40].

Risk and uncertainty. Along with scale, good category, and property rights allocation, risks and transaction costs are among the primary variables determining mechanism selection [91,128]. Most research is focalized through buyers, even if the ultimate goal is to provide insights into bidders' behavioral patterns. Studies exploring how risk impacts bidding include Wichmann et al.'s [118] experiment on bidder responses to different risk categories (cost and losing) and configurations, Lundberg's [94] algorithm for choosing pricing rules based on the risk landscape, and Palm-Forster et al.'s [92] comparison of BMP-

promoting tools under uncertainty. Considered from the buyer's perspective, common approaches to integrating risk include simple discounting [40,95] and screening mechanisms [117], and—among the most serious attempts at risk integration—D-PLPN [18].

Multiple objectives. A single intervention can impact ES and policy goals differently, so accounting for multiple criteria is a topic of substantial interest. Incorporating risk (e.g., [18]), spatial coordination (e.g., [17,46]), or participation (e.g., [96,105]) could be viewed examples of "multi-objective" mechanisms; see Section 3.6 and the other paragraphs of Section 3.4.3 for these topics.

In the Andes, Narloch et al. [20] explore several trade-offs between targeting area, individual-, and group-level participation, and Narloch et al. [34] find that mechanism design and payment rules can be manipulated to limit trade-offs between cost-effectiveness and (at least some dimensions of) fairness (p. 114). Bid targeting indices can use expert judgment to weight multiple objectives *a priori* (e.g., using the Analytic Hierarchy Process), potentially accommodating many objectives but not necessarily producing an optimal solution [115]. The CRP is an example of a large public program using an additive index [10]. Combinatorial auctions offer another approach [65], although landowner perspectives would likely influence basket design—for instance, by being predisposed to see trade-offs vs. synergies between biodiversity and production [30] (p. 87). Roesch-McNally et al. [66] analyze stakeholders' use of the multi-objective ECOSEL mechanism to make trade-offs in a mock forward auction. ECOSEL can optimize a large number of objectives in principle, but the difficulty of interpreting Pareto maps and selecting alternatives increases rapidly with the number of objectives. (*For practical reasons, participatory Pareto methods typically focus on just a few key objectives* [40,71,129]. *ECOSEL appears to assume a single large landowner but may be extensible to joint management areas with many landowners using Pareto decomposition methods, as in* [71].)

3.4.4. Summary

Land management decision-making requires navigating diverse interests; trade-offs abound. Recent research has sought to bring auctions to bear on this problem through sophisticated mechanism design, payment rules, and bid selection procedures. These approaches differ in their degree of (de)centralization, the stage at which objectives are balanced in the decision-making process, and the degree of engagement with uncertainty and risk. Despite impressive technical innovations, field trials are needed.

Key lessons

- Using auctions to generate spatially-coordinated benefits is an active and theory-rich niche that emphasizes advanced mechanism design and bid selection features.
- Spatial coordination can be introduced in either a centralized, top-down (e.g., administrator obtains truthful cost information for all bids, and then optimizes) or decentralized, bottom-up manner (e.g., iterative bidding with contiguity incentives).
- Multiple objectives can be addressed through either *a priori* or *a posteriori* approaches; the former typically involve weighting criteria, while the latter utilize optimization (though this is not to suggest that *a priori* approaches exclude optimization methods like goal programming).
- Combinatorial auctions and ECOSEL-style approaches may provide landowners with greater flexibility to submit bundles tailored to their own capabilities. In combinatorial auctions, trade-offs are made by the principal in selecting bids, but bundle composition may not be optimal.
- Risk and uncertainty are inconsistently integrated into the mechanism design process, with the notable exception of D-PLPN.

3.5. Theme 4: Context

Because they are meant to be generalizable, laboratory experiments commonly omit a number of factors with substantial implications for real-world auction performance. This

section addresses issues like culturally situated considerations relating to signification and exchange, institutional capacity, and value systems.

3.5.1. Country Development

While we acknowledge that the developed–developing country dichotomy can be problematic [130–134], these concepts structure auction discourse; thus, we stick with the lexicon typical of our sample, drawing a coarse distinction between developed/developing and high/low-income countries, e.g., [12]. Examples of large-scale auction-based public programs are mainly found in higher-income countries, while auctions in lower-income countries mostly take the form of small-scale field experiments—although the number of such experiments continues to grow alongside the prevalence of PES schemes more broadly [12,13]. On the one hand, this could offer opportunities for well-designed auctions to improve the impact of limited budgets. On the other, PES in lower-income countries are more frequently designed with social policy objectives in mind, so competitive efficiency-oriented tools may not be ideal [81]. The differences between countries at opposite poles of income/development scales may not be extreme for auction practice, but they are unlikely to be insignificant. Wünscher and Wunder [12] offer a useful introduction to the problem space:

> "Imperfect markets and information about production systems, high subsistence incomes, high variability in prices and yields, and risk-averse behavior all constitute characteristics [of low-income countries] that conservation tenders may be particularly suited to address. Conversely, lack of expertise and infrastructure can hamper tender design and the dissemination of information to potential participants. Some of these challenges can be dealt with, but solutions unavoidably increase transaction costs which, in turn, may affect scalability." (p. 672).

Our sample reflects a clear interest in exploring how auctions interact with these contexts. Notable dimensions of this interaction include economic inequality [22,34]; social hierarchies and tradition [13,19,20]; understandings of the mechanism, contracting, and its underlying market logic [81,107]; and institutional capacity and logistics [12,15]. These issues may be entangled: developing country contexts often pair strong demands for equity-sensitive designs with sharp constraints on the resources and capacity needed to develop and implement them [83]. Where large auction-based public programs exist, it may be beneficial to integrate ES purchased through these mechanisms into national accounts (e.g., estimating GDP contributions) [11]. The following subthemes are closely linked to these contexts.

3.5.2. Institutional and Policy Factors

General considerations. Baird et al. [103] stress that institutional capacity typically constrains performance-based interventions like reverse auctions that account for environmental benefits. Part of capacity is budgetary: consistency can create reliability and familiarity, boosting participation—but too much consistency can induce rent seeking, since stochastic budgetary changes may influence the perceived risks associated with bid shading [90]. Where adequate capacity exists, the inertia of current approaches and preferred policy styles can modulate friction: Liu et al. [72] discuss challenges associated with introducing new land management tools in the rural Chinese policy context, which features centralized decision-making, limited action space for NGOs, and a strong preference for policy "realism" over theoretical work or experiments based on "contrived" laboratory conditions (p. 866). Policymaker receptiveness can also influence researchers' tolerance to explore innovative or unconventional mechanisms (e.g., [75]) and modulate the theory-practice relationship by providing funds for field experiments or data for program evaluation. Receptiveness matters: auctions are more likely to be implemented (and succeed) in policy environments featuring "a commitment to efficiency objectives", and institutional actors may be called on to play a public education role [15].

Auction niche. Auctions are often framed as responses to the shortcomings of alternative instruments (e.g., [18,40]), but policy tools' cost-benefit profiles depend on factors like regulatory regime, property rights allocation, policy conflicts, and contract law [100,101,106,135]. Narloch et al. [19,20] and Pirard [128] distinguish reverse auctions from other MBIs mainly on the basis of price discovery, disincentives to free-ride or rent-seek, and transaction costs. As with offsets and credits, the requisite level of governmental involvement is another distinguishing factor: institutional actors are usually needed to establish markets and the "methodologies and eligibility rules" they rely on [113] (p. 178). Auctions can often be distinguished from offsets in terms of stakeholders, funding source, and impacts on other ecosystems (p. 177). Offsets impact two areas in one exchange (degraded and conserved); auctions only focus on one at a time. The locus of decision-making is also relevant: unlike open enrollment programs, in an auction the principal decides who gets a contract [101]. Auctions can impose substantial informational and administrative burdens on the principal, and present bidders with unique transaction costs [91] (p. 18). Simple fixed taxes may be less accommodating to heterogeneities, but can sometimes sidestep DPAs' pesky adverse selection problems and improve cost-effectiveness if set correctly [106,117]. (*See Vergamini et al.* [136] *for a contrasting view that finds DPAs to be more cost-effective than flat payments when bidders make two-attribute (price plus benefit) bids.*)

Auctions can be bundled with other policy interventions (e.g., for valuation or price setting as in Tanzania [81] or to generate data for environmental accounting as in [11,137]) as well as extension services [15]. Farley et al. [38] consider a cap-and-auction tool for an institution tasked with managing common pool resources: bidders compete for development rights and public bodies capture rents that can be reinvested or returned to taxpayers. The objective is *proportional equivalence between benefits and costs*, achieved when all users of common goods pay the same price without capturing "unearned profits" and revenue is spent on the good (pp. 72, 77–78).

3.5.3. Sociocultural and Relational Factors

Trust and understanding. Price discovery and social acceptability hinge on constellations of trust, distrust, and understanding. In the PLPN example, if bidders *distrust* that the principal will honor its payment calculation after they reveal their costs, they are unlikely to bid truthfully; if enough bidders *trust one another enough* to collude, they might win collective rents [46] (p. 31). Trust may be a reason to prefer bottom-up approaches to spatial coordination over one-shot optimization, which asks participants to place their trust first in the black box of linear programming, then in the agency to faithfully report its output; if participants decline to offer this trust, selecting clustered winners could create the appearance of favoritism or corruption [17]. Whether they stem from perceptions of project partners or unstable policy environments, trust issues can also depress participation [30]. Mechanism and contract design can interact with community trust networks by stimulating competition at specific scales (e.g., individual bidding vs. group contracts), potentially undermining (for example) prosocial collective action norms [15,34]. Although auction research mostly adopts the perspective of a suspicious principal (who does not trust landowners to accurately represent their costs or comply unless incentivized), prospective bidders also need to trust that future payments will be disbursed as promised [72]. In some contexts, simply rejecting a bid after the bidder has invested in preparing it might be seen as a violation of this nature [19,20].

Trust can enable collaboration, reducing monitoring costs and improving cost-effectiveness; investing in building trust-based relationships and ensuring processes are perceived as fair may enhance future participation [104,115]. It can also influence selection bias: in Malawi and Indonesia, researchers gathered data on prospective participants' level of trust in other actor categories, for instance [26,83]. In ECOSEL, where bidding determines management, (mis)trust of outsiders is particularly salient: restricting the pool of potential bidders increases the likelihood that the auction will fail, but unrestricted bidding could allow wealthy outsiders to dominate outcomes [66]. (*Landowners who trust the intentions*

of the principal may be more willing to accept contracts at lower price points [98]. *See Blackmore et al.* [109] *for agency–landholder relationships, perceived fairness, and participation. See Etchart et al.* [138] *for a novel, equity-conscious exploration of the consequences of* buyer *non-compliance with PES contracts.*)

Understanding is closely related to both trust and learning effects (and thus rent-seeking) [17], but it is also a variable with social significance. Field studies invest in carefully explaining bidding strategies and may collect data on participant understanding, which has implications for cost-effectiveness and legitimacy alike; practice bidding rounds may build familiarity [72,81], although some populations may approach auctions primarily as games and lend insufficient weight to the idea that contracts may be difficult to fulfill [82] (p. 635). There is a strong case to be made that simplicity and understandability should be central concerns when evaluating mechanism suitability [15]; it has even been suggested that the UPA concept may be too difficult to understand for some purposes [89]. Whitten et al. [30] suggest making simplicity a major mechanism design consideration on top of additional assistance like information workshops. In forward formats, helping bidders understand landowners' operational priorities and constraints can demonstrate that free riding by "waiting for farmers to 'do the right thing'" is unlikely to result in the desired provision, encouraging higher contribution levels [67] (p. 9); see also [66]. The framing of environmental objectives and consequences should be carefully considered and linked to tangible indicators or consequences [66,119].

Values and tradition. While many practical and ideological critiques of ES auctions also apply to other MBIs, others are more idiosyncratic [101]. Cooke and Corbo-Perkins [107] identify four key tensions between conservation practices and Australia's EcoTender program. First, an attempt to buy indefinite development restrictions induced systematic underbidding, with conservation-oriented landowners choosing to *pay* to obtain permanent legal protection (p. 175). Second, only a minority of bidders priced in their own labor, viewing conservation as part of their stewardship responsibility (p. 176). Third, participants attempting to manage novel ecologies in good faith faced winner's curse due to inapplicable standards and spatial discoordination (p. 177). Fourth, prohibiting communication between winners discouraged knowledge-sharing and impeded the formation of "collaborative, cross-boundary conservation networks" (p. 178). Auctions rely on market logic; in contexts featuring a strong conservation ethic, they may impose unnecessary costs and limit participants' ability to be proactive stewards. (*Whitten et al.* [30] *identify the provision of post-contract support as an often-overlooked issue in the ES auction literature that warrants additional attention; Blackmore et al.* [109] *find strong agreement between auction practitioners and landholders that agency investment in agency-landholder relationships is important for auction performance, with implications for participation. Post-contract support could conceivably shift the effort/participation trade-off identified by Schilizzi and Latacz-Lohmann* [105], *although the cost-effectiveness implications would depend on the nature and extent of support.*)

Others may view underbidding like that observed by Cooke and Corbo-Perkins as advantageous *crowding in*, because bidders price baseline stewardship into their bids: "In a context of intrinsic motivation, bids are likely to understate costs", especially if landowners can propose baskets of projects they are already motivated to undertake [22] (pp. 114–18). Where there is an expectation that stewardship be compensated, auctions seem to be viewed as fairer than other allocation mechanisms [81,82], although perceptions of fairness have strong demographic and cultural influences [34,81–83]. In Tanzania and Indonesia, participants suggested that compliance was driven more by honesty than utilitarian self-interest, though sanctioning non-compliance rather than terminating payments could alter the priority of these factors [81,83]. On the demand side, notions of the traditional can shape management objectives like selecting species or practices to conserve [19,20]. The task itself matters too, as some management interventions may be viewed negatively by key landowners (e.g., restoring wetlands in agricultural areas) [96].

Identities and hierarchies. Bidders may not view one another as equally legitimate competitors for contracts: perceptions of group membership, the legitimacy of land tenure

structures, and social hierarchies may influence perceptions of the mechanism and its impacts on networked community relationships, which can feed back into the dynamics of the auction itself [83]—e.g., by providing compliance pressure, as in Tanzania [81]. In addition, although follow-up research often focuses on winners, losers also engage in discourses about the process and its outcomes, potentially taking the view that their time, effort, and emotional labor were squandered:

> "[Feeling one's bid was unfairly rejected] is especially likely where social norms are shaped by egalitarian traditions and where concepts such as competitiveness and commoditization of biodiversity-related resources are poorly understood and even rejected [20]" (p. 423).

In Indonesia, community perceptions of auction fairness were mediated by ethnic group membership (some groups being considered indigenous and others viewed as migrants) as well as economic status: disadvantaged and less-educated groups assigned lower fairness ratings to the auction [83]. This could reflect different levels of understanding of the process or indicate that a lack of procedural equity aggravated pre-existing tensions (p. 48). Banerjee et al. [17] suggest that relinquishing information about spatial coordination priorities, even at the risk of enabling collusion, may be useful to support perceptions of fairness by reducing the risk that participants view geographically clustered contracts as evidence of a biased process (p. 411). In Kenya, gender (a) shaped auction performance due to divergent risk assessments and tolerances; (b) was impacted by auction results due to differentials in labor allocations; and (c) influenced environmental outcomes [13]. In ECOSEL, a hierarchy of stakeholder directness shaped the perceived legitimacy of contributions, with some bidders worrying that profit-motivated corporations could easily overwhelm the contributions of conservation-oriented locals [66].

3.5.4. Summary

National, sociocultural, policy, and institutional contexts directly influence auction design and outcomes. A number of studies highlight policy features relevant to specific cases, but no focused, comprehensive treatments of the interaction between policy context and auction dynamics were identified. In comparative discussions, auction methods are typically distinguished from other tools by their price-discovery capacity, relationship with free riding and rent seeking, the nature of government intervention required, and the locus of decision-making. The form and type of transaction costs associated with auction methods also appears to be unique.

Key lessons

- ES auctions in low-income countries may navigate different sets of objectives and constraints than in richer countries. Large-scale auction-based environmental policy tools are unlikely to be directly transferable from one context to the other without modification.
- There are bidirectional linkages between behavioral and sociocultural factors on the one hand and auction dynamics and outcomes on the other.
- The series of interactions that constitute an auction have symbolic value, serving to reveal or even construct social relationships and shaping perceptions of trust and fairness.
- Improvements in participants' understanding of auction mechanisms can have paradoxical effects, potentially facilitating collusion but promoting perceptions of fairness.

3.6. Theme 5: Participation

Like economic efficiency, this theme permeates much of the sample: it is not possible to conduct an auction without participants (see Section 3.1.2), and under-participation is a widespread problem for the field [96]. As a result, the previous themes could not be introduced without raising the issue of participation: for instance, we have already mentioned it as a factor relevant to economic, PES, and normative performance criteria (Section 3.2);

linked it to both standard (Section 3.3.1) and advanced (Section 3.4.3) mechanism design questions; defined participation as one of four dimensions along which auction scale should be evaluated (Section 3.4.2); and highlighted it in relation to institutional and social factors relevant to ES auctions (Sections 3.5.2 and 3.5.3). Despite its status as an unavoidable consideration in ES auction research and practice; however, few studies center participation itself as the primary object of investigation. As a result (and to avoid rehashing issues already introduced above), our discussion of this final theme is brief—but we stress that this short treatment belies its arguably paramount importance.

Although participation-focused studies are few and far between, the resources that do exist are both detailed and useful, albeit mostly calibrated to higher-income country contexts. The deterrent effect of cost risk on participation [118] can be limited by offering insurance against unexpected losses caused by compliance with management standards, though at some added cost [92]. Drawing on six Australian case studies, Whitten et al. [30] develop a five-stage landholder-centric "barriers and opportunities" framework to develop auctions in way that supports higher participation through (1) alignment, (2) opportunity, (3) engagement, (4) contracting, and (5) post-participation factors (pp. 87–88). It defines participation steps and types (as well as barriers emerging at each stage), and considers how auction and contract design variables might impact participation decision-making. Since the optimal participation level likely depends on scale issues (see Section 3.4.2), it may be possible to manipulate configurations of barriers and opportunities to "facilitate self-selection of stronger bidders", reducing administrative and compliance costs (p. 82); see also [82]. Narloch et al. [20] and Jindal et al. [81] explore strategies to target poorer households for participation and contracts.

Citing chronic under-participation in developed-country auctions, Rolfe et al. [96] (2018) differentiate between attempts to examine participation in terms of (a) the characteristics of potential bidders (e.g., [13]), and (b) auction design features (e.g., [30]), then attempt to develop a "unified" model based on a three-part decision process. Prospective participants must simultaneously decide:

1. Am I willing to change my practices?
2. Am I willing to accept contractual obligations about these changes?
3. How do I determine the price that I am willing to accept if I enter a bid (pp. 1, 13)?

These decisions, in turn, are shaped by factors like auction objectives, mechanism design, and perceptions of risk and uncertainty. Taking care not to conflate these decisions is a theoretical as well as a practical issue, particularly when spatial objectives are involved: Fooks et al. [63] model the decision to participate and the conditional price-setting decision separately, for instance. Once again, however, this is an approach that conceptualizes participants as utilitarian and which may not account for social drivers poorly captured by rational-actor models.

Participation decisions are not easily mapped from reverse to forward auctions: receiving money is different than spending it, particularly in environments lacking a strong disincentive to free ride [40,66,75]. When landscape-scale ES are sought, large numbers of bidders may be needed to generate budgets that enable large enough target areas. However, it is also possible to gain momentum: as the Bobolink Project became established, competition between sellers increased, driving down prices by almost 50% and increasing donations' impact [67].

4. Discussion

As illustrated by the internal references throughout Section 3, the subthemes we identified interact frequently. Moving from theory to practice, the five top-level themes are effectively inseparable (Figure 1). Information dynamics and participation (and the interactions between them) are manipulable through auction design. Atop uncertain contextual landscapes, auction administrators attempt to assemble these three elements into a structure that can support the desired objectives, but they cannot completely insulate performance outcomes from idiosyncratic—and potentially hidden—contextual dynamics

(Figure 4). Schilizzi [14] sketches a more process-oriented scheme in which *causes* (like auction format, implementation rules, or bidder characteristics) produce *intermediate effects* in the form of behaviors exhibited by the pool of potential bidders (like the decision to participate, collude, take risks, and comply with contracts). These intermediate effects then produce *final effects* representing the performance of the auction measured against economic criteria. As with all designed markets, auction performance emerges from an ongoing interplay between, on the one hand, intrinsic factors like design and implementation that are specific to the auction itself; and on the other, extrinsic contextual factors like past history, previous experience (on the part of auctioneers, participants, and potentially other stakeholders), and interactions with other programs.

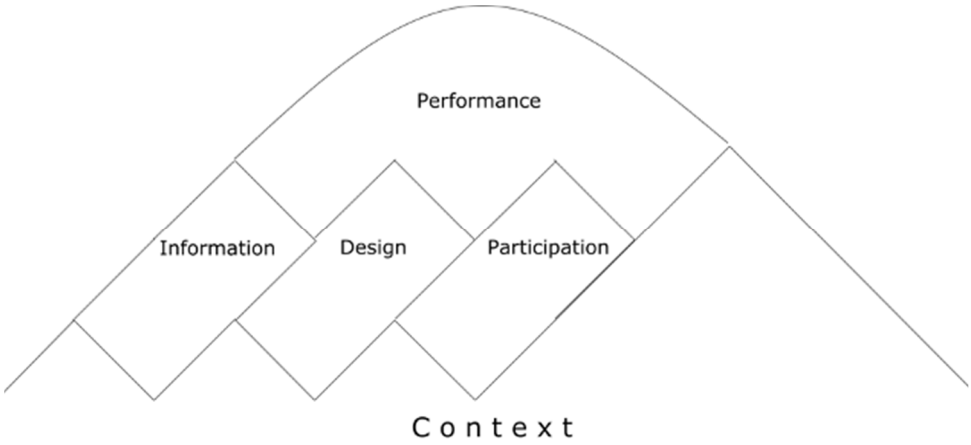


Figure 4. Conceptual representation of between-theme relationships.

Rather than interactions between discrete components, intersecting subthemes sometimes reveal descriptions of the same component from different vantage points: it is not uncommon to attack the same problem from different disciplinary perspectives and using different language in such a multidisciplinary body of literature. In such cases, we chose not to translate these treatments into a common register when reporting our results and attempted instead to highlight the conceptual diversity of the sample.

Mechanism design, for instance, favors the economic language of scarcity or absence (e.g., *incomplete information*) when it engages issues relating to strategic behaviors, while a more sociological view might stress the abundance and strength of relationships in its explanation (e.g., *trust* or *social capital*). While the functional difference between articulating these issues as absence or presence may be minimal, the former framing centers independent agents attempting to navigate uncertainty, while the latter encourages us to recognize the symbolic links between them: who is asking what of whom?

The neoclassical paradigm underpinning much of the mechanism design literature is focused on "getting the price right" and avoiding overpayment; as such, it is focalized through the principal. This echoes a tendency in the broader PES literature, where the compliance of land stewards with contracts has received immense attention but that of buyers (i.e., by providing funding continuity) has been largely overlooked [138]. If the design discussion is focalized through the principal and bidders are simplified as profit-maximizers, then reverse auctions are a set of stratagems making it difficult for them to rent-seek or shirk their obligations: implicitly, bidders are not to be trusted.

In fact, it is arguably the bidders' trust that is most in demand for a successful auction (Figure 5). Policymakers need to trust that the mechanism will work and that the administrator can oversee the process with a minimum degree of competence. However, for an optimal outcome, the bidders must trust: (a) the agency to be neutral and communicative, to monitor compliance fairly, and to provide agreed-upon support; (b) policymakers to provide baseline stability for at least the duration of the contract, including funding continuity and refraining from implementing conflicting policies; (c) the mechanism itself to

function in a fair and transparent way; and (d) their own capacity to accurately estimate opportunity costs, avoid winner's curse, and satisfy the contract—but they must *not* (e) trust each other enough to collude successfully. Would-be colluders are confronted with a stag hunt: there is a high-risk, high-payoff pure Nash equilibrium when all players collude, and a low-risk, low-payoff pure Nash equilibrium when all players defect [139,140]. Trust can also have further impacts at the program level: the agency is not obligated to trust landowners because it has the power to evaluate compliance, but it may benefit from optional trust-building [115,138]. Attending more closely to issues of trust may offer a starting point for overcoming the persistent participation issues impeding real-world ES auctions.

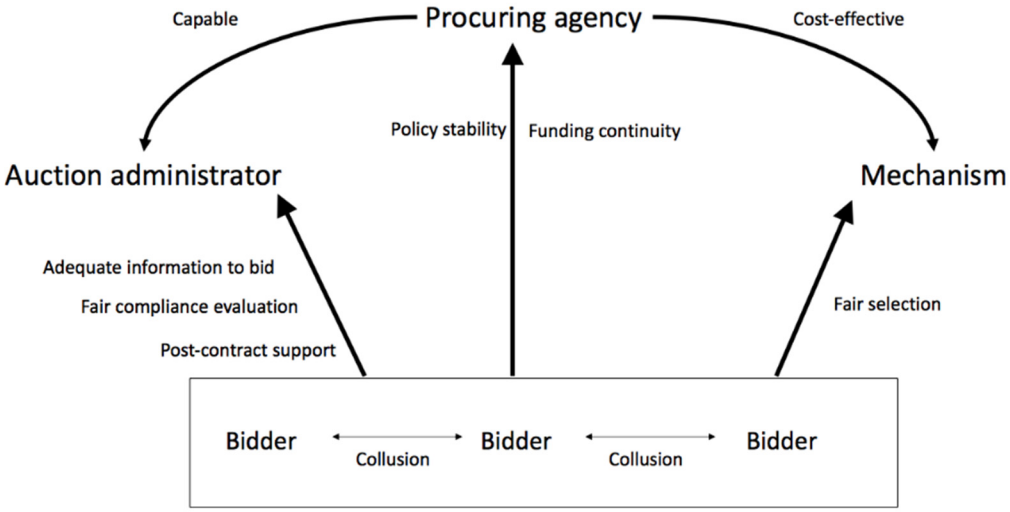


Figure 5. Potential trust relationships between reverse auction actors. Arrows move from truster to trustee.

Of the mechanisms we reviewed, ECOSEL [40,95,141] has the most tenuous connection to auction theory. However, ECOSEL also resonates conceptually with both combinatorial auctions and IPAs. Relative to combinatorial auctions, ECOSEL inverts the locus of decision-making about trade-offs. Combinatorial auctions devolve within-parcel trade-offs between objectives to decentralized landowners, then a central decision-maker weights those objectives when choosing between proposals to select winners (thus determining landscape composition) [65]. ECOSEL instead starts by running a multi-objective optimization across the entire landscape, then devolves the task of weighting those objectives to decentralized stakeholders, simplifying the computational problem implicit in combinatorial WDPs [40,95,141]. Mapping along these dimensions (centralization of decision-making and single vs. multiple management alternatives) is a helpful way to think of the relationships between these mechanisms (Table 3).

Table 3. Mechanisms by locus of decision-making and number of alternatives.

		Procurement Decisions	
Management alternatives		*Centralized*	*Decentralized*
	Single	Standard UPA/DPA	IPA
	Multiple	Combinatorial auction	ECOSEL

Standard reverse auctions and combinatorial auctions rely on a central decision-maker (the principal) to select winners and define the terms of the tender. (Note that Table 3 specifies number of management alternatives rather than number of environmental objectives, since standard reverse auctions can weigh multiple benefits, though typically by collapsing them into a single additive EBI; for a counterexample using data envelopment

analysis, see Lundhede et al. [142].) Standard reverse auctions and IPAs usually involve a single contract, like setting aside land for conservation or planting trees. Combinatorial auctions and ECOSEL attempt to make trade-offs between multiple management actions and/or environmental benefits explicit. As forward mechanisms, ECOSEL and IPAs both attempt to provide a framework through which stakeholders can directly support the provision of non-market ES, trading off ES provision scenarios against cost: i.e., they essentially crowdsource decisions about budget and thus procurement. The former seeks to maximize ES valuation (and thus seller profit), while the latter aims to ensure that donors' contributions are used cost-effectively (particularly when combined with a reverse auction, as in the Bobolink Project [67], which we might situate in the middle of the first row of Table 3).

It is not immediately obvious that these two forward designs are incommensurable: one can imagine a version of the two-stage Bobolink Project mechanism that allows donors to make trade-offs between multiple environmental objectives, or alternatively, a version of ECOSEL that uses donors' money more efficiently or solicits marginal WTP for a range of overall provision levels. The decision processes that underlie bidding in ECOSEL have not yet been thoroughly investigated, however, and Lindahl-based solicitations for IPAs entail a participation-eroding time cost [67]. Each of these mechanisms constrains the potential outcome space (and simplifies donors' decision task) by fixing either the overall provision level or the objective against which provision is measured. That is, ECOSEL fixes the aggregate provision level in advance by selecting bundles from a Pareto frontier, and bidders determine which objectives are most represented in the joint production function; IPAs tend to fix the objective in advance, and bidders determine its provision level. A hybrid mechanism would presumably require bidders to make decisions along both dimensions, and thus would have to grapple with issues like cognitive load and transaction costs.

Overall, the recent ES auction literature is innovative and dynamic, but also perhaps somewhat fragmented across disciplinary perspectives and lexicons. For instance, we identified several different perspectives from which auction success or failure might be judged (strictly economic measures, PES criteria, or normative views), each of which may yield a different conclusion even when applied to the same case. Auction assessments should make clear how they are defining and measuring success, and it may be beneficial to include additional comments about dimensions that are excluded from that definition to facilitate future comparative research. Similarly, comparative research (such as efforts to build databases of PES case studies, which may include attributes like "success" or "failure") should be cognizant that the use of these terms may vary significantly from case to case [35,143,144].

Despite several large, well-established public programs using reverse auction methods (e.g., CRP, EcoTender), scholarship still developing. Debates persist about the basic characteristics of the auction tool: does it achieve dramatic efficiency gains by virtue of its unique capacity to overcome information asymmetries, or is it actually much *less* efficient than simpler tools like fixed taxes? The answer, of course, is "it depends", but operationalizing those dependencies to produce a generalizable, context-matched mechanism selection and design algorithm is a challenging task. Comparative efficiency is likely to become even trickier to evaluate if all costs, including notoriously hard-to-measure transaction costs (particularly related to information acquisition and learning), are included in the calculation.

Part of the issue has to do with the diversity of potential designs in combination with the often-overriding importance of both context and implementation. Laboratory research enables the exploration of dynamics involving variables that may be very difficult to isolate in field settings: thus, while applying findings from the laboratory to the field can be challenging, laboratory research plays a valuable role in elucidating the design parameters to which a given field implementation is likely to be sensitive. Similarly, advanced mechanisms may achieve greater efficiency on paper, but pose participation barriers and transaction costs due to information requirements or the simple pedagogical

challenge of ensuring that bidders understand the mechanism well enough to enter rational bids (but not so well that they begin to devise effective rent-seeking strategies!). Legal frameworks, cultural expectations, data availability, and notions of legitimacy and fairness can all enter the equation for field implementations.

Because auctions involve the interplay of many simultaneous parameters with the potential to influence behavior at multiple stages and scales, a kind of paradox emerges between experiences in the laboratory and in the field: moving from the former to the latter introduces so many potential confounders that it can seem impossible to confidently predict the performance of any type of auction—yet examples of field auctions considered successful by the auctioneer's criteria do not appear to be in especially short supply. Trying to understand when and why things that could plausibly go wrong in theory end up going right in practice could be an interesting line of inquiry, and offer another reason to evaluate performance from a multidimensional standpoint both when conducting field studies and when trying to synthesize existing research to derive new insights.

Survey research can shed light on how auction practitioners view cost-effectiveness [145], what variables influence bidders' propensity to participate in future auctions [146], and where these priorities align [109]. Field-based research with qualitative components can raise interesting questions about motivation, participation, ideology, and other hidden contexts that more rigidly devised, highly quantitative approaches may struggle to detect or navigate. Mixed-method approaches to testing new designs in new settings could help illuminate the nexus between design, actor, and context. A brief selection of topics that might benefit from further attention is provided below.

Practical guidance. Although the knowledge base is growing, practical evidence-based guidance for designing and implementing ES auctions given specific goals, constraints, and context appears scarce [22,30,100]. Future work might seek to identify risk factors for failure (and holistic frameworks for assessing whether, how, and to what extent auctions in different contexts can be said to have succeeded or failed), develop best practices or other design frameworks, and further clarify the auction niche.

Regulatory threat. Prospective bidders' felt danger that a failed auction could trigger regulatory intervention appears to be a potentially significant consideration that has only been characterized in a preliminary way [106].

Motivational crowding. Further research into the relationship between auction methods and intrinsic motivation for stewardship, including motivational crowding, is indicated [22,107].

Normative views. The relevance of EEE trade-offs, the ethical frameworks used to guide auction assessments, and the operationalization of justice and social equity in auction research are well-established issues requiring further attention [12,82,83].

Field trials for sophisticated designs. This review identified impressive theoretical work in advanced auction designs for achieving spatially coordinated outcomes and integrating risk, but field trials using these tools are limited or nonexistent [18,72,93,116].

Operationalizing context. Attempts to further systematize the array of contextual variables informing design and performance may be valuable [13,90].

Forward auctions. With a few narrow exceptions (e.g., [38,40,67,141]), discussions of forward auctions in ES are rare. Developing forward formats to generate higher ES prices and engage larger numbers of stakeholders, rather than (or in combination with) reverse formats aimed at gaining landowner participation at the lowest possible price, may expand the available MBI toolset.

Multi-criteria optimization. Although auction methods have been applied to a wide variety of ES, the recent literature shows limited engagement with multi-objective optimality. Efforts to use indices to score bids on ecological value (e.g., metrics like EBIs) or promote contiguity suggest that the topic is of interest [17,46,93,115]. However, most designs engage with either binary conserve–develop decisions; if multiple management alternatives are permitted, landowners are allowed to combine them as they prefer, leaving the procurement agency to predict ES implications (see Lundhede et al. [142] for a useful

exploration of using data envelopment analysis for bid selection in multi-attribute auctions). Tóth et al. [40,95] combine multicriteria optimization with auctions in ECOSEL, but in an unusual forward format that has not yet undergone field trials or been subjected to close theoretical scrutiny. It may be worthwhile to explore the integration of multi-criteria optimization with ES auctions.

Participation. The number and characteristics of participants can make or break an auction, but serious attempts to grapple with participation either from the perspective of bidder attributes or auction design are in short supply (e.g., [15,96,105,118]); ideally, further efforts should be made to integrate these two perspectives, building on Rolfe et al. [96].

Priorities for the field. There are fairly distinct threads in the literature, but it is difficult to get a global sense of the domains that are expected to drive future developments in ES auctions, or those which should be prioritized in future research or policy initiatives (though Whitten et al. [15] make a good start). Continued efforts to facilitate dialogue within the field could pay dividends moving forward.

5. Conclusions

This review attempted to take stock of the last decade of scholarship on the use of auction mechanisms for PES contract allocation. This body of literature is built on three linked conceptual families: mechanism design, PES, and policy analysis. Within it, we identified five large, composite topical themes—performance, information, design, context, and participation—often reflecting different facets or representations of closely related problems. We limited our search of the Scopus and Google Scholar databases to peer-reviewed journal articles and book chapters. Thus, only a subset of the recent ES auction literature was accessed. The inclusion of gray literature could alter some of our conclusions above—for instance, by offering more practical guidance. The search terms we used were not exhaustive and may not have captured work in closely-related areas, such as experiments that do not explicitly use the language of ecosystem services. Working with a significantly larger sample would require a different analytic approach than the one used here.

Although auctions stereotypically use competition to enhance allocational efficiency, there are other well-established uses for these tools as well, from price discovery to social policy objectives. Efforts to systematize the process of matching design to program objectives, constraints, and context are underway, but currently provide loose guidance. Impressive mechanism design innovations have increased the feasibility of spatial coordination, risk integration, and crowdfunding through forward formats, but more field trials are needed. Considering this, further investment in integrating this multidisciplinary body of work and identifying priorities for research and practice might be beneficial.

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Abbreviations

ABM	Agent-based model
CRP	Conservation Reserve Program
DPA	Discriminatory price auction
EEE	Efficiency-effectiveness-equity (usually in reference to trade-offs)
EBI	Environmental benefit index
ES	Ecosystem services
IPA	Individual price auction
PES	Payments for ecosystem services
MARR	Maximum Acceptable Rental Rates
MBI	Market-based instrument
NGO	Non-governmental organization
UPA	Uniform price auction
VCG	Vickrey–Clarke–Groves mechanism
WDP	Winner determination problem
WTA	Willingness to accept
WTP	Willingness to pay

Appendix A. Vickrey Auctions

Box A1. Vickrey auctions create a strategic dilemma with price disclosure as a weakly dominant solution. (Adapted for reverse auctions from Levin [147], p. 2).

Suppose that bidder i's opportunity cost is c_i and i contemplates submitting a bid $b_i < c_i$. The value of the lowest bid b' submitted by any other bidder is unknown to i, so three outcomes are possible:
(1a) $b' < b_i, c_i$ (1b) $b_i < b' < c_i$ (1c) $b_i, c_i < b'$
In scenarios (1a) and (1c), bidding c_i rather than b_i would not have changed the outcome (lose, or win b', respectively). In scenario (1b), i wins but suffers winner's curse, which would have been avoided if i bid c_i rather than b_i. If i bids $b_i > c_i$, there are three possibilities:
(2a) $b' < b_i, c_i$ (2b) $b_i > b' > c_i$ (2c) $b_i, c_i < b'$
In scenarios (2a,c), i loses or wins b', respectively. In scenario (2b), i loses, but would have won if i had bid c_i instead of b_i. Thus, i should bid c_i rather than another value b_i.

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