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Advancing ecosystem services auctions: Insights from an international Delphi panel

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ABSTRACT

Auction theory has made major contributions to overcoming allocation problems involving asymmetric information and common-pool resources, leading to multiple Nobel Prizes and serving as a foundation for multi-billion-dollar markets. Despite evidence that related mechanisms could enhance the performance of payments for ecosystem services (PES), adoption has been sporadic and inconsistent. One possibility is that the relevant peer reviewed literature has low visibility or consensus design elements are not sufficiently accessible to interested experts. To overcome this barrier, we adopt a straightforward approach: we asked the PES auction subfield to describe itself. In collaboration with an expert panel ($n = 32$) whose affiliations span more than two dozen universities and research bodies across three continents—including top-ranked economists, ecosystem services theorists, and practitioners with experience designing and implementing PES programs with and without auctions—we synthesize a birds-eye view of ecosystem services auctions for an interdisciplinary audience. Through an iterative, mixed-method Delphi consultation, we identify broad consensus about fundamental elements of theory and practice, including what functions auctions tend to perform well, common challenges, and key factors influencing their performance. By selecting topics that panelists appeared to disagree about for further discussion, we also highlight open questions and potential research frontiers. We conclude with a reflection on using the Delphi method to foster exchange between time-constrained experts.

1. Introduction

The concept of payments for ecosystem services (PES) suggests that landowners do not engage in environmentally harmful practices (or fail to implement beneficial ones) out of carelessness or malice, but rather due to perverse incentives and market failures (Sutton et al., 2016; Taye et al., 2021; Turkelboom et al., 2018). Stated another way, environmentally friendly management, even if socially optimal, can impose opportunity costs that may not be financially sustainable in the face of market competition (Bingham, 2021; Uthes and Matzdorf, 2016). Thus, PES aims to compensate landowners for these costs in exchange for implementing management to produce ecosystem services (ES) like carbon storage, pollinator support, or water purification.

Real-world PES face a number of challenges, and few schemes fully satisfy sophisticated criteria like spatial targeting (selectively allocating contracts to locations with high ES density), additionality (verifying that payments increase ES production relative to a plausible non-payment baseline), or conditionality (ensuring that payments are only disbursed if providers fulfil contractual obligations) (Wunder et al., 2020, 2018).[1] Furthermore, the true cost-effectiveness of PES is difficult to ascertain, largely because information about counterfactual management intentions and opportunity costs is private (Bingham et al., 2021; Juutinen et al., 2019; Knoke et al., 2023; Villegas-Palacio et al., 2016).

Auctions are economic games of incomplete information in which bidders make strategic offers in hopes of obtaining something they

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[1] A glossary of key PES and auction-related terms is available in the appendix at the end of this article.

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value, like profits, a good, a service, or a contract (Klemperer, 1999; Milgrom, 1987). In doing so, they reveal information that can be used to make inferences about their private costs and values. The strategic incentive to disclose private information is part of what sets auctions apart from more familiar instruments like fixed payments, flat subsidies, and even bargaining (e.g. Bingham, 2021; Kindu et al., 2022). Exploring the unique strategic puzzles posed by auction mechanisms has become one of the most successful fields in economics, producing no fewer than four Nobel laureates (Vickrey, Smith, Milgrom, and Wilson) and shaping our understanding of issues ranging from asymmetric information and price formation to the provision of public goods (Teytelboym et al., 2021). Beyond the academy, auctions provide a foundation for several multi-billion-dollar markets, including for broadcast spectra (Janssen, 2020; Teytelboym et al., 2021), digital advertising space (Arnosti et al., 2016; Milgrom, 2021), and emissions allowances (MacKenzie, 2022). Despite encouraging scientific results, efforts to integrate auction mechanisms directly into practical PES programs have proceeded slowly (Whitten et al., 2017).

Extending auction theory to the ecosystem services context is not a trivial task, but economists and PES scholars have made substantial progress (Latacz-Lohmann and Van der Hamsvoort, 1997; Schilizzi, 2017). They have tested different formats, time horizons, pricing structures, and information-sharing rules (Glebe, 2021; Messer et al., 2017; Whitten, 2017); devised techniques for generating spatially coordinated outcomes, targeting multiple ecosystem services, and integrating climate risk (Banerjee et al., 2021; Lewis and Polasky, 2018; Liu et al., 2024; Nguyen et al., 2024); experimented with methods for beneficiaries to purchase ES directly from landowners (Chakrabarti et al., 2019; Li et al., 2022; Roesch-McNally et al., 2016); and even examined how mechanisms interact with local contexts to shape socioeconomic and ecological outcomes (Andeltová et al., 2019; Cooke and Corbo-Perkins, 2018; Leimona et al., 2023). While some lines of inquiry are quite technical, others are more basic. For example, Bingham et al. (2021) suggest that the nexus between participation, collusion, and trust (believed to be critical for both auction performance and post-auction PES compliance) is likely under-theorized, while Kindu et al. (2022) argue that the PES context invokes unique layers and configurations of uncertainty that are not confronted by auctions in other domains.

While these questions are interesting and important, applying auctions to ecosystem services is not exactly an esoteric proposition. Thanks to an array of pilot studies, field experiments, and deployments within a handful of large-scale environmental subsidy programs, we know that auctions can efficiently allocate PES contracts across a wide range of geographic contexts, auction types, and environmental objectives (Bingham et al., 2021; Whitten et al., 2017). Yet although decades have passed since the US introduced nationwide reverse auctions in the Conservation Reserve Program (CRP), most implementations today, with some exceptions in the US and Australia,[2] are still motivated primarily by research, rather than concretely enhancing the performance of real-world PES (Kindu et al., 2022). Why?

One possibility is that the very things that make ES auction scholarship exciting, like its dynamism and theoretical pluralism, also make it unusually difficult to navigate. The field's steady pace of innovation (Kindu et al., 2022; Schilizzi, 2017) sustains an aura of novelty, which can create the impression that the underlying mechanisms are more experimental than they really are. If the broad contours of ES auction scholarship, including its basic value claims and intended uses, are unfamiliar or even opaque to interested experts, adoption into practice will likely remain sluggish.

Although literature reviews can contribute to mapping discourses (Bingham et al., 2021) or linking conceptual frameworks (Kindu et al., 2022), the search for knowledge gaps and research opportunities often emphasizes complexity more than contains it. Meanwhile, policy is often less responsive to exciting new findings than it is to reassurances from experts that not *everything* is in question (Harris et al., 2019; La Brooy et al., 2020; Lloyd et al., 2021). In other words, decision-makers sometimes need affirmation that scholarly debates, however vigorous they may appear, are rooted in a shared understanding of mainstream scientific consensus. Identifying and communicating that consensus, however, requires investing in coordination and exchange.[3]

Here, we seek to build beyond literature reviews by synthesizing a birds-eye view of auction scholarship as it is understood by the experts who produce it. We designed and conducted an iterative, interactive, mixed-method consultation featuring a panel of experts ($n = 32$) whose affiliations span more than two dozen universities, research institutes, and government agencies across North America, Europe, and Australia, which currently account for a disproportionate share of the world's research output on ES auctions (Kindu et al., 2022). Our panel includes top-ranked economists and ecosystem service theorists, civil servants, and practitioners with experience designing and implementing PES programs both with and without auction mechanisms.

Using the Delphi method (Carson et al., 2013; Strand et al., 2017), our consultation identifies broad consensus about fundamental elements of theory and practice, including what functions auctions tend to perform well, common challenges, and key factors influencing their performance. By selecting topics panelists appeared to disagree about for in-depth discussion, we also elicit nuanced reflections on challenging issues, such as how auctions fit into multi-instrument portfolios, discrepancies between the incentives for researchers and practitioners, and the feasibility of emerging topics identified in recent reviews (Bingham et al., 2021; Kindu et al., 2022), including uncertainty, spatial coordination, and the role of equity in competitive market mechanisms.

1.1. *How this article is organized*

We begin with auction fundamentals and gradually progress to more advanced topics. After a conceptual introduction (section 2), we highlight key guiding questions (Table 2) and describe our consultation framework (section 3). The results section first clarifies the auction niche by highlighting consensus views on topics like advantages and disadvantages, links between collusion and participation, and auction dynamics (4.1). Next, it examines topics where the panel fell short of consensus, which we address in detail through qualitative interviews: namely, spatial coordination, competing objectives, and equity (4.2). In the discussion (5), we critically interpret our findings and their limitations, and summarize the panel's suggestions for future research. A glossary of key terms related to auctions and PES is available in the appendix at the end of this article.

2. State of the art: Auctions in the ecosystem services context

For most people, the word "auction" evokes a familiar scene: a fast-talking auctioneer endeavors to sell a unique item, perhaps a valuable piece of art, by calling out a series of increasing price proposals to a room of potential buyers ("bidders"). Each time the auctioneer announces a new, higher price, the number of bidders signaling that they are still interested shrinks. When only one remains, the auctioneer announces that the item has been "*Sold!*" to that bidder at the last-named price.

Known to experts as an ascending-price, open-bid seller's auction (sometimes an "English auction"), this iconic ritual has been used since antiquity to facilitate property rights transactions because it reliably

[2] For example, some state- and national-scale tender programs in Australia (Rolfe et al., 2017; Sangha et al., 2024) and The Nature Conservancy's Bird-Returns Program (Golet et al., 2018). While the EU contributes significantly to research output, real-world implementations tend to be small-scale and experimental (Coiffard et al., 2024; Kindu et al., 2022).

[3] The ES auction field's most recent dedicated attempt to facilitate this kind of process took place at a workshop in 2013 (Whitten et al., 2017).

reveals who is willing to pay the most for something (Klemperer, 1999; Morcillo, 2021). To accomplish this, it uses a series of structured interactions between competing, goal-oriented agents—in other words, a game.

Game theory describes the seller's auction in terms of agents making binding offers to purchase a good, with the aim of obtaining it at a price lower than their own maximum willingness to pay (generating a net utility gain) (Klemperer, 1999; Vickrey, 1961). Because only one agent can achieve this outcome, it is a *non-cooperative* game, and because each agent *ex ante* lacks information about their competitors' budgets and values, it is also a game of *incomplete information* (Myerson, 1981). Most walk away having neither won nor lost anything, aside from the time spent, because losing (i.e. suffering a net reduction in utility) requires offering a price they are unwilling to pay. The equilibrium strategy is simple: to maximize your expected payoff, make offers up to, but not exceeding, your maximum willingness to pay. Because nobody has an incentive to deviate from this strategy, the game reveals each unsuccessful bidder's maximum willingness to pay, and places a lower bound on that of the winner (Leimona et al., 2023; Liu, 2021).

Thus, while the seller's auction may not be a typical market (it only consists of a single transaction), it can reveal detailed information about the distribution of demand for unique goods lacking market data. For convenience, we group auction mechanisms featuring many buyers whose interactions exert an upward pressure on prices under the broad heading of "forward" auctions (Bingham et al., 2021; Kindu et al., 2022). Although forward auctions do shape ecosystem services provisioning (e.g. by facilitating land sales), most research in the environmental context focuses on a related variant: "reverse" auctions (Coiffard et al., 2024; Kindu et al., 2022). Instead of many buyers competing to purchase a low-substitutability good from a single seller (pushing the price up), a reverse auction usually involves many suppliers competing to sell a high-substitutability good to a single buyer (pushing the price down) (Table 1).

Conservation tenders are the classic example. Imagine an agency wants to procure nesting habitat for an endangered bird in a landscape mosaic of privately-owned parcels. Its objective is to procure the largest possible area for a fixed budget, so it needs to identify the parcels with the lowest cost per unit area.[4] Unfortunately, each landowner's willingness to accept a contract is private—a function of a complex mix of management intentions, capabilities, aesthetic preferences, opportunity costs, and other hidden variables that the agency has no way of knowing. To overcome this information asymmetry, the agency invites landowners to submit confidential bids stating the lowest payment that would convince them to accept a contract. The agency promises to accept the bids in ascending order, from cheapest to most expensive, until it runs out of money (Coiffard et al., 2024).

In this type of "pay-as-bid" or "discriminatory" price auction (DPA), the best strategy is to price your bid no lower than your true cost; otherwise, acceptance would generate a loss ("winner's curse").[5] Of course, it can still be advantageous for bidders to "shade" their bids higher than their costs, accepting a higher risk of rejection in exchange for a larger profit if the bid is accepted (Boxall et al., 2017).[6]

Opportunity costs can be revealed more accurately by slightly adjusting the payment rule. Rather than paying each bidder what they asked for, the agency can pledge to pay everyone a uniform rate to be set by the first bid the agency rejects (Duke et al., 2017; Liu, 2021). Because bids are accepted in ascending order, this rule guarantees that all winners will be paid more than they asked for. In uniform price auctions (UPAs), the dominant strategy is to honestly bid your true cost (Box 1). Economists call mechanisms satisfying this condition "incentive compatible" or "strategy-proof" (Masuda et al., 2022).[8] Thus, in the process of allocating contracts, UPAs also generate data that can be used to guide larger, simpler incentive programs (Box 2). Because all successful bidders are compensated at the same rate, some view UPAs as particularly equitable instruments (but see section 4.2.3 for contrasting views).

3. Methods

The Delphi method is a technique for soliciting collective best-guess predictions from expert groups, often about emerging issues where data is lacking (Filyushkina et al., 2018; Hufschmidt et al., 1983; Okoli and Pawlowski, 2004). The process begins by recruiting an expert panel, whose members are surveyed individually about the topic (Carson et al., 2013; Scolozzi et al., 2012; Strand et al., 2017). Next, the results are analyzed and a new survey containing information about the panel's aggregate responses from the previous round is circulated. This cycle, wherein each panelist is asked to re-evaluate their individual opinion in light of the panel's collective judgment, repeats until a stop criterion is met.

Our implementation aimed to elicit a broad self-assessment while distinguishing between settled knowledge and open questions by (1) nudging the panel toward consensus through increasingly restrictive response formats in written surveys across two rounds of interactions; (2) identifying topics that were resistant to these nudges; and (3) exploring them in depth through third consultation round consisting of qualitative interviews. Thus, after the initial survey round, the direction of the study was largely determined by the panel itself.

Although we aimed to design a protocol flexible enough to permit the panel to self-select topics, particularly for in-depth interviews in Round 3, the initial questionnaire must be constructed before the experts have been consulted. Our protocol was informed by a review of Delphi applications to other topics (Supplementary Information 1).[10] After selecting a preliminary set of topics based on two systematic reviews conducted concurrently with planning this study (Bingham et al., 2021; Kindu et al., 2022), we used the methodological review to refine these topics into questions suitable for a Delphi panel (Supplementary Information 1).

3.1. Sampling

The panel was recruited from three groups: (1) experts contributing to auction pilots in two EU projects supporting this study (n = 10; see acknowledgments); (2) researchers identified via a systematic review (Bingham et al. 2021) (n = 10); and (3) subject matter experts recruited through snowball sampling using group (2) as a seed (n = 14).

The initial panel included 34 experts whose affiliations included national research agencies, international research institutes, environmental consultancies, forest owner's associations, and 27 universities across North America, Europe, and Australia. Many panelists were professionally distinguished, including a number of scholars ranked in the top 10 % of their disciplines globally, department heads at flagship

[4] For simplicity, we assume habitat quality for nesting is homogeneous. For real-world examples, see Golet et al. (2018) for reverse auctions, and Chakrabarti et al. (2019) for a combination of forward and reverse auctions.

[5] Winner's curse also can arise from cost estimation errors (e.g. a bidder offers to plant trees for $1 each, only to learn after their bid is accepted that the combined cost of seedlings and labor sums to $3 per tree).

[6] The CRP uses discriminatory pricing (Cramton et al., 2021; Hellerstein, 2017; Wallander et al., 2017).

[8] The strategy-proofness of certain UPAs may not be obvious to bidders (Li, 2017), but the dominant strategy can be demonstrated through workshops and information sessions (Box 1, Box 2).

[10] *Supplementary Information 1:* further background on the Delphi method and elaborated methods. *Supplementary Information 2:* written questionnaires. *Supplementary Information 3:* summary of interim results panelists received before participating in qualitative interviews. *Supplementary Information 4:* anonymized interview transcripts.

Table 1
Comparison of forward and reverse auctions.

Auction direction	Buyers	Sellers	Pressure on price	Examples
Forward			↑	Seller's auction, individual price auction
Reverse			↓	Conservation tender, procurement auction

Table 2
Main themes, related literature, and response formats.

	Response formats in each consultation round		
Theme	**Round 1**	**Round 2**	**Round 3**
Niche and trajectory[1,2]: Advantages Disadvantages Risk factors Expected drivers	1.1 Open (structured) *List the three most important factors…*	2.1 Rating (slider matrices) *Here are the most popular suggestions. Adjust the sliders to rate their importance on a scale from 1 to 10.*	
Participation and collusion[1,3,4]	1.2 Open (semi-structured) *Make an estimate and describe your reasoning.*	2.2 Dichotomous choice *We synthesized a framework based on your responses. Choose one:* • *Agree* • *Disagree and explain*	3. Qualitative interviews and focus groups *Here's a summary of the results so far. We'd like to hear your thoughts, especially about topics where the panel seemed to disagree, any topics we should have asked about but didn't, and the process as a whole.*
Influence of non-participating stakeholders[1,2,5] Biophysical models and cost-effectiveness[1,2] Knowledge base *vs.* real-world performance[1,2,6-9]: Spatial coordination Uncertainty and risk Multiple objectives Equity Link between theory and practice[1,2,5,10]	1.3 Rating (Likert scales) *Choose one:* • *Strongly disagree* • *Disagree* • *Agree* • *Strongly agree*	2.3 Dichotomous choice *At least 2/3 of the panel agreed that… Choose one:* • *Agree with majority* • *Disagree and explain*	

1. Bingham et al. (2021) *2.* Kindu et al. (2022) *3.* Jindal et al. (2013) *4.* Schilizzi et al. (2017) *5.* Rolfe et al. (2022) *6.* Banerjee et al. (2021) *7.* Leimona et al. (2023) *8.* Lundhede et al. (2019) *9.* McGrath et al. (2017) *10.* Whitten (2017) *11.* Whitten et al. (2017) *12.* Boxall et al. (2017)

Note: All items could be skipped and included optional comment fields. See Supplementary Information 2 for exact wording.

institutions, IPCC authors, appointees to national scientific councils, and advisors to heads of state. For diversity, we also recruited experts in natural resource management and PES, such as auction consultants with backgrounds in ecology and forestry, and non-economist civil servants responsible for administering a then-ongoing auction pilot. The panel's experience encompassed theory and laboratory experiments, as well as designing, executing, and evaluating real-world auctions, including advising and coordinating with government agencies, NGOs, stakeholders, and landowners on the ground.

Thirty-two panelists (94 %) returned to participate in Round 2, of whom 26 (81 %) indicated openness to participate in Round 3. One was excluded because they contributed to data analysis and interview design. The rest were invited and 15 (60 %) participated.

3.2. Consultation protocol

Stop criterion. Following Bond et al. (2015), we classified items with ≥ 80 % agreement as "endorsed." We terminated the survey when the most recent round failed to improve agreement for any non-endorsed item (i.e. response distributions remained static; Fig. 1).[11]

Round 1 questionnaire. The Round 1 questionnaire's first section (1.1) contained structured open-ended questions where panelists made a forecast about ES auctions, then suggested advantages, disadvantages, and risk factors (Table 2). Next, a semi-structured open-ended question asked panelists to suggest a minimum participation threshold for mitigating collusion and explain their reasoning (1.2). The final section (1.3) consisted of Likert items evaluating the knowledge base for some advanced auction functions, such as generating specific spatial configurations in landscape treatments.

Interim analysis. We analyzed the completed surveys so that preliminary results could be shared with the panel in Round 2 (Supplementary Information 1). Responses to the structured open-ended questions (1.1) were clustered into "factor categories" and ranked by frequency. We used content analysis to synthesize a conceptual framework from responses to the question about participation and collusion (1.2). We weighted Likert responses (1.3) by degree and identified items satisfying a 60 % agreement threshold as potential consensus topics for Round 2. As an experiment, we also retained one item that did not reach this threshold.

Round 2 questionnaire. To help the panel asses the interim results, the first page of the Round 2 questionnaire disclosed the identities of participating panelists (Supplementary Information 1). We also introduced more restrictive response formats: structured open-response items (1.1) were replaced with rating tasks (2.1), while the semi-structured open-response (1.2) and Likert items (1.3) were replaced with dichotomous choice items (2.2, 2.3) (Table 2). In rating tasks (2.1), panelists used sliders to score the importance of the most popular factor categories, with slider start positions indicating an estimated score based on frequency analysis (Supplementary Information 1). For the dichotomous choice items (2.2), we highlighted the response indicating the consensus candidate from the previous round. All items were accompanied by optional comment boxes.

Interim analysis. We analyzed the direction and magnitude of slider adjustments (2.1) using descriptive statistics, and evaluated dichotomous-choice items (2.2, 2.3) based on whether consensus grew, remained static, or reversed. Response distributions for non-endorsed items were static after Round 2, satisfying the survey stop criterion.

Round 3 interviews. To investigate the non-endorsed items, we organized a series of qualitative interviews (Fig. 1 and Table 2). Prior to each interview, participants received a brochure summarizing the interim results (Supplementary Information 3). We conducted four focus

[11] This criterion was satisfied after Round 2.

Box 1
Bidding strategies and outcomes in a reverse auction with uniform pricing[7]

Bidder i with opportunity cost c_i submits bid of value b_i in a reverse auction. The values of the other bids are unknown to i. The distribution of these bids determine the cutoff point b^*: all bids greater than b^* will be rejected, while all bids less than b^* will be accepted and receive a payment equal to b^* (a "second-price" auction). Given that b^* is unknown, should i select a value for b_i that is higher, lower, or equal to their opportunity cost c_i? The possible outcomes associated with each strategy are summarized in the following payoff matrix:

Strategy	Probability of acceptance relative to $b_i = c_i$	Payoff by outcome	
		$b_i > b^*$ (Rejected)	$b_i < b^*$ (Accepted)
$b_i < c_i$	↑	0	$b^* - c_i < 0$
$b_i = c_i$	—	0	$b^* - c_i > 0$
$b_i > c_i$	↓	0	$b^* - c_i > 0$

Of the three strategies, $b_i < c_i$ is most likely to result in acceptance, but at the cost of a negative payoff: payment b^* is insufficient to cover the costs c_i (winner's curse), so rejection is a better outcome than acceptance. Strategies $b_i = c_i$ and $b_i > c_i$ both generate identical profits if the bid is accepted, because values of c_i and b^* (which determine the profit) are independent of the chosen b_i. Of these two strategies with identical payoffs, $b_i = c_i$ is more likely to be accepted. Thus, $b_i = c_i$ never produces an outcome that is worse than the other strategies (weak dominance).

[7] Adapted for reverse auctions from Bingham et al. (2021) and Levin (2004).

Box 2
Uniform price auctions for price discovery in Tanzania[9]

Background: With population growth, poverty, and market forces driving rapid deforestation in Tanzania's Uluguru mountains—a biodiversity hotspot influencing the water supply of Dar-es Salaam—interventions capable of addressing both environmental and socio-economic objectives are needed.

Auction: Jindal et al. (2013) used reverse auctions to allocate tree-planting contracts while conducting socio-economic surveys to evaluate the distributional effects of auction-based payments. After several informational sessions and practice rounds, participating households gathered in a local marketplace and submitted bids identifying the lowest price each would need to be paid to plant seedlings on their land.

Results: Although winners were paid upfront to facilitate the participation of poorer households, a follow-up almost two years later found that compliance rates among auction winners remained high. Most planted trees survived.

Design considerations: Using uniform pricing allowed the researchers to obtain detailed data about the distribution of opportunity costs across households, while reducing the risk of bid shading.

Impact: Because the auction served as an incentive-compatible opportunity cost elicitation, bid data were used to design a much larger subsidy scheme. Such open-enrollment programs are often less burdensome for beneficiaries and administrators alike (they usually do not require practice rounds or synchronized bidding, for instance).

Key takeaway: Although adopting uniform pricing meant paying more for a smaller benefit within the catchment, this reduction in local environmental cost-effectiveness carried socioeconomic co-benefits (poverty alleviation), and was likely offset by generating truthful cost estimates to improve the efficiency of the regional subsidy program.

[9] For additional context, see Jindal (2017) and Jindal and Vardhan (2018). For a comparisons with similar experiments, see Bingham (2021).

groups of 2–4 panelists each and interviewed the rest individually using the same schedule via videoconference. After panelists responded to each question, the interviewer briefly summarized agreements and sticking points from previous sessions for the current session to consider.

4. Results

This section begins with consensus topics, like the main advantages and disadvantages of auctions, then moves on to more advanced issues, like emerging mechanism design innovations. In the last subsection, we explore three non-endorsed items (which were related to spatial

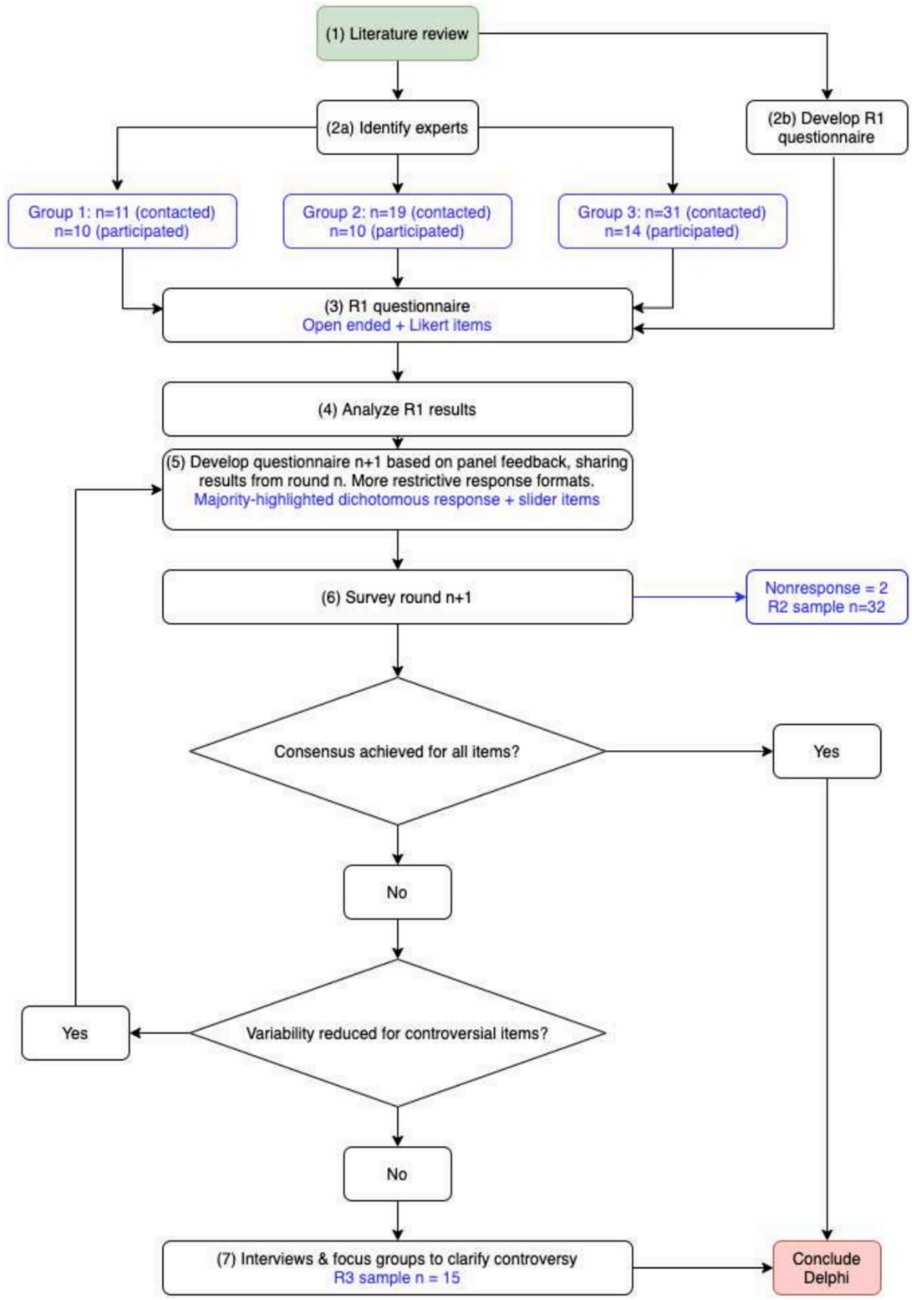

Fig. 1. Research framework. Start node in green. Stop node in red. Results specific to this implementation in blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

coordination, risk, and equity) through an analysis of written comments and interview transcripts.[12]

4.1. *Areas of agreement*

Short summary: Auctions offer well-known economic advantages like cost-effectiveness and price discovery, but they can also activate social co-benefits like stakeholder engagement and transparent contract allocation. Although research has outpaced practice, well-understood field-tested mechanisms are available for deployment on the ground. At the same time, auctions are not yet out-of-the-box solutions for PES: matching auction design to specific application contexts can involve trade-offs and benefit from specialist input. The overriding disadvantage and risk factor for using auctions in the ES context centers on participation rates, which are often low for reasons that are poorly understood (see Rolfe et al., 2022). Although participation influences collusion risk, the precise nature of this relationship also depends heavily on context. In practice, auction-based PES usually do not engage explicitly with environmental uncertainty, spatially-coordinated interventions, or equity at the mechanism level. Looking ahead, the panel expects future developments to be driven mainly by changes in policy and new technologies.

[12] *Method reminder:* To help readers follow our iterative consultation, we include short reminders of the iterative process that led to each result in footnotes like this. Note that while we refer to relevant literature in summarizing qualitative results, panelists were not asked to support their views with citations.

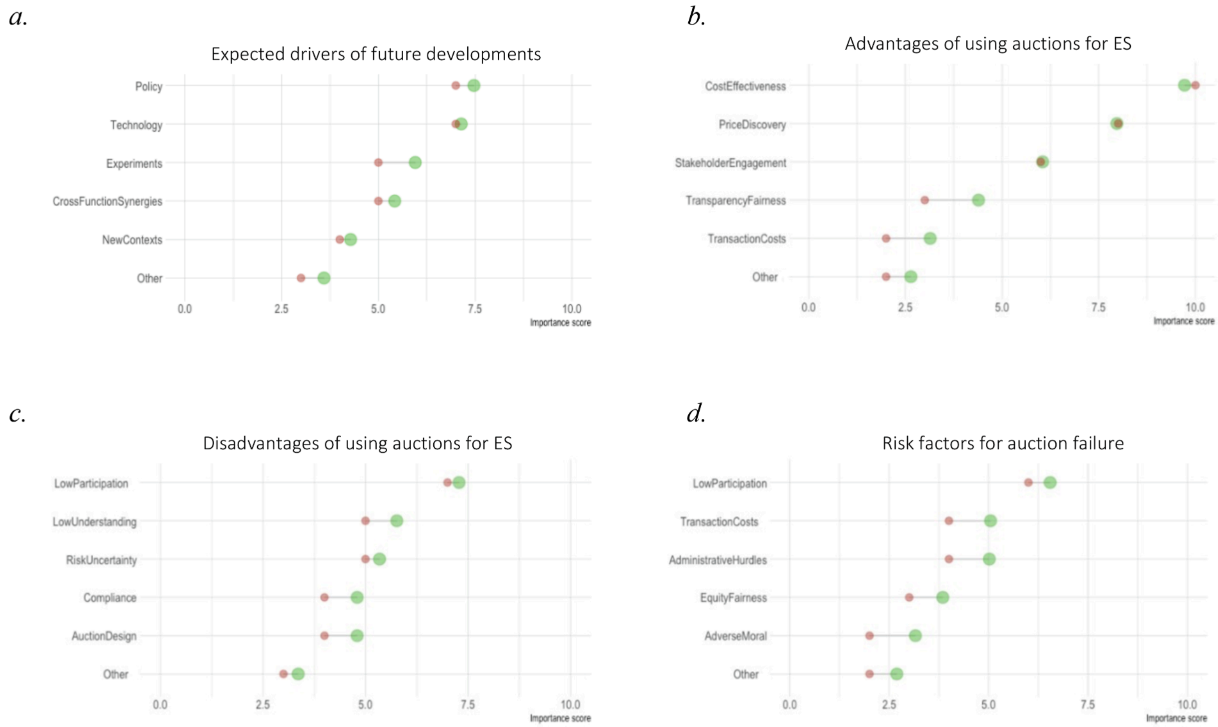

Fig. 2. Rating the importance of ES auction factor categories. Examples of factors in each category (see Supplementary Information 2 for exact wording): *Policy*: Receptiveness, market creation. *Technology:* Cheaper monitoring, better measurements. *Experiments:* Upscaled field, web, administrative experiments. *CrossFunctionSynergies:* with e.g. ES certification, decision support systems, merging administrative data with field experiments. *NewContexts:* Applications to new ES, context-matching. *CostEffectiveness:* Assuming auction well-designed. *PriceDiscovery:* i.e. cost revelation. *StakeholderEngagement:* Linking buyers to sellers, extension. *TransparencyFairness:* Process, price setting. *TransactionCosts:* Learning, verification. *LowParticipation:* Cost, cognitive burden, outreach. *AdministrativeHurdles:* Design, technical capacity, outreach. *EquityFairness:* Resource advantages, economies of scale. *AdverseMoral:* Adverse selection, moral hazard. *LowUnderstanding:* of mechanism, rules, obligations. *RiskUncert*: Winner's curse, contract duration, post-contract support. *Compliance:* Monitoring, contract stringency. *AuctionDesign:* Matching mechanisms to objectives and context, scale issues, influence of secondary goals like avoiding large payouts.

4.1.1. *Advantages, disadvantages, risk factors, and expected drivers*

Panelists used sliders to rate the importance of advantages, disadvantages, and risks associated with ES auctions, as well as drivers they expected to shape the field moving forward. Each slider's start position represented an importance score based its popularity in the previous round (Fig. 1).[13] The final ranking closely aligned with the suggested score: on average, the panel adjusted each slider slightly upward, with the result that the relative rankings remained unchanged. Agreement was generally stronger for higher-ranked categories than lower-ranked ones (Supplementary Information 5).

These rankings suggest several interesting patterns. In general, auction research tends to emphasize the operation of the mechanism itself, including performance metrics like cost-effectiveness, information dynamics like cost revelation and communication effects, and behavioral processes like participation and compliance (Bingham et al., 2021; Kindu et al., 2022). While such mechanism-oriented considerations rank high as advantages, disadvantages, and risk factors (Fig. 2b-d), they are conspicuously absent from the top drivers of future developments (Fig. 2a): rather than focusing on classic auction theory, future drivers center on the context in which the mechanism operates. Similarly, the top advantages the panel attributed to auctions (efficiency, price discovery; panel *b*) can be demonstrated theoretically, whereas practical concerns dominate the list of disadvantages and risk factors (panels *c, d*).

While some responses seem contradictory (i.e. similar factors appear as both advantages and disadvantages) (Fig. 3), panelists offered some clarification in qualitative comments. Auctions' efficiency advantage, for instance, depends on the scope of the analysis: while auctions might reduce some transaction costs, like those associated with asymmetric information, they can also introduce others, requiring participants to learn how to estimate costs and place strategic bids under an uncertain payoff (Jindal et al., 2013; Schilizzi, 2017). Similarly, *fairness* is often considered an advantage of the process because the results are verifiably determined by *a priori* rules; however, auctions are not necessarily fair in a distributional sense, since wealthy bidders can sometimes leverage economies of scale to out-compete smallholders (Blackmore et al., 2014; Leimona and Carrasco, 2017). These tensions echo common concerns in the PES literature (Jones et al., 2020; Lliso et al., 2021; Ruoso and Plant, 2021).

Taken together, these findings suggest that there is relative consensus around the fundamentals of auction theory, but much less around the exogenous contextual variables that shape practical implementations. Thus, the high rank assigned to experiments as a potential driver of future ES auction developments (Fig. 2a) suggests a need for more contextualized experiments to support enhanced performance in specific domains by guiding narrow theoretical refinements and mechanism design modifications. In interviews, some panelists hinted that experimental work is seen as crucial partly because bigger trials could attract policy interest and facilitate more widespread adoption of auction tools.

The information-revealing properties for which auctions are famous

[13] *Method reminder:* Panelists suggested advantages, disadvantages, risks, and drivers in structured open-ended response items (Round 1.1). In the interim analysis, we grouped their responses into "factor categories" and calculated a suggested importance score for each category based on its popularity (Supplementary Information 1). Panelists were informed that the slider start positions were based on this score, and were invited to adjust the score as they wished.

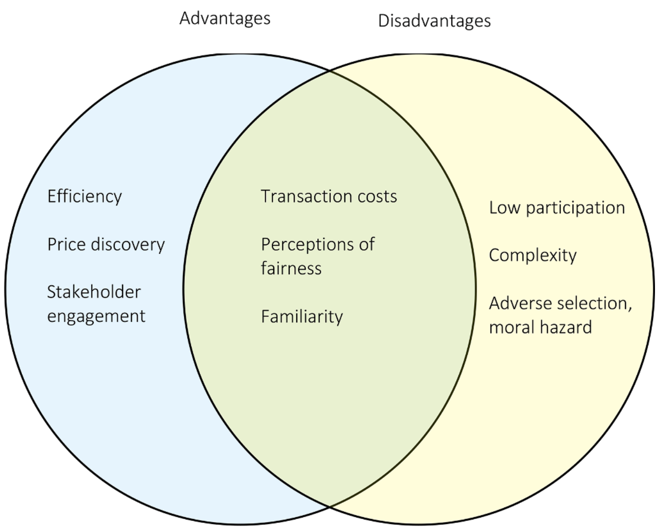

Fig. 3. Suggested advantages and disadvantages of auctions for ecosystem services.

can be a double-edged sword in the environmental context, where bidders face a much more complicated task than simply assessing how much they are willing to pay for a good (Supplementary Information 3). Instead, they may have to gather information about the costs and benefits of different management alternatives, possibly with dissimilar environmental-economic risk profiles (Kindu et al., 2022). These informational demands might deter adoption by agencies and participation by ES providers, especially if sophisticated PES criteria like additionality and spatial targeting are involved. When bidders and agencies overcome these barriers, however, the fact that information has been systematically collected and evaluated can give auctions a transparency advantage over alternative instruments, increasing trust and potentially compliance (Bingham et al., 2021; Leimona et al., 2023).

Participation has emerged as a fundamental issue for the mainstreaming of ES auctions, impacting virtually every aspect of auction design, dynamics, and performance (Howard and Valcu, 2021; Rolfe et al., 2022, 2018). Our panel ranked low participation as the top disadvantage associated with past auctions, and the top risk factor for future ones (Fig. 2c,d). One panelist even objected to scoring disadvantages and risk factors at all, on the grounds that all of the factors ultimately led back to participation.[14] Participation decisions are sensitive to context and can be influenced (for example) by perceptions of the regulator's capacity to incentivize conservation, the risk of underbidding one's costs (i.e. winner's curse), and the degree of political support, including the reliability of funding (Bingham et al., 2021; Blackmore et al., 2014; Kindu et al., 2022; Wichmann et al., 2017a). In turn, participation impacts performance: higher participation rates can increase the environmental impact of auction-based PES by expanding the pool of available interventions, and boost efficiency by making it more difficult for bidders to collude to extort informational rents.

Based on an analysis of panelists' suggestions, we proposed a conceptual framework for how the participation-collusion relationship is structured in practice (Box 3). The framework was unanimously endorsed by the responding panel.[15]

In comments and discussions, panelists emphasized that the context dependence of the participation-collusion relationship is notable for a field often dominated by theoretical and laboratory work. Compared to other domains, ES auctions often look less like abstract pricing mechanisms than situated social processes.[16] Even for a fixed number of bidders, collusion risk would likely be influenced by variables like cost heterogeneity, since colluders often expect a roughly equal apportionment of gross, but not net, benefits (Supplementary Information 3). In fact, collusion itself may be a red herring: when there are too few bidders, the risks posed by colluders extorting informational rent might be eclipsed by the risk that the auction will be perceived as a failure due to overpayment or underparticipation. In either case, the remedy is to overcome the participation challenge.

4.1.2. Auction theory, practice, and dynamics

The panel endorsed seven statements about how auctions work in theory and practice (Table 3), including its most explicit affirmation that ES auction practice is lagging behind scientific research.[17] Many panelists elaborated on the problem in comments—for example, speculating that researchers might be incentivized to over-innovate and produce too-complex mechanisms that conflict with the need for simplicity in policy and application. This disconnect helps explain why items 8–10 fell short of the endorsement threshold: even though moderate majorities felt that we know enough to design spatially coordinated (75 %) or multi-objective (69 %) auctions, there was a strong consensus that real-world experience is lacking.

We should highlight a few qualifications from the panel's commentary (Supplementary Information 3). First, there a number of ways that non-bidding stakeholders can indirectly influence outcomes: if they are eligible to bid, choosing not to depresses the participation rate; if they are not eligible, they may seek to persuade those who are, or to influence program designers or administrators. Mostly, however, non-bidders exert no influence simply because they tend not to be aware of the auction at all.

Although biophysical models shape cost-effectiveness assessments by linking actions to outcomes, natural science may be a minor contributor to auction performance. When costs and benefits are both heterogeneous, cost-effectiveness is driven by which is more so, and environmental model outputs are typically more homogeneous than bids. Despite the importance of environmental uncertainty, however, a few panelists objected to the premise that risk should be incorporated into mechanism design (item 5), since auctions themselves aggregate bidders' beliefs about the likelihood of different scenarios by asking them to make risky decisions (e.g. balance the risk of losing versus the risk of winner's curse) as a means of exploiting information asymmetries

[14] For an illustration, see Kindu et al. (2022 section 3.2.2 and Fig. 7).

[15] *Method reminder:* In Round 1, we asked panelists to suggest factors influencing the minimum number of participants needed to mitigate collusion. In the interim analysis, we synthesized these suggestions into a general conceptual framework (Supplementary Information 1). In Round 2, panelists were asked to either endorse the framework or reject it and leave a comment. The framework was endorsed by every panelist who responded (i.e. excluding "no answer"; 90% of the full panel).

[16] While the anecdotal suggestion that two bidders could mitigate collusion risk was controversial, the issue is academic: the panel agreed that a two-bidder auction would probably not be satisfactory in the real world.

[17] *Method reminder*: In Round 1, panelists responded to a series of Likert items (Table 2). We weighted the responses by degree and identified the majority opinion for each item. In Round 2, we asked the panel to revisit these items, highlighting the majority opinion and replacing Likert scales with dichotomous choice items. If panelists chose the minority position, they were asked to provide a written comment explaining their perspective. Items that reached at least 80% agreement were classified as endorsed. The three non-endorsed items were investigated through qualitative interviews in Round 3.

Box 3
Conceptual framework for evaluating minimum participant needs

For field auctions, the minimum number of participants needed to mitigate the risk of bidders successfully colluding and undermining efficiency is a function of four main clusters of factors.

(1) The **social and geographic distance between actors**, including social capital, communication networks, and shared sociocultural norms;
(2) **The odds of winning,** a function of the ratio between the available budget and the expected payment, between the number of potential and actual bidders, and/or between the number of units available and the number of units to be procured (reserving the option to reject all bids can also amplify bidders' strategic dilemma);
(3) **The design and management of the auction**, including the use of uniform or discriminatory pricing, multiple rounds or repeated auctions, and the confidentiality of reserve prices, bids, and outcomes; and
(4) **The participation of consultants** shared by multiple bidders.

Other relevant factors include the **heterogeneity** of bids and actions; the **market power of** colluding **subgroups**; program **goals**, including the specific ES at stake; and **national context**, with likely differences between developed and developing countries.

Anecdotally, this number ranges between 2 and 100 in panelists' individual experience.

Table 3
Degree of support for ten claims about ES auctions.

Statement	Level of agreement >90 %	>80 %	>65 %
1. Although the preferences of non-bidding stakeholders may indirectly impact auction outcomes, they usually **do not** directly influence the auction itself.	•		
2. Innovations accepted by the scientific community are **not often adopted** in practice (the link between auction theory and practice is suboptimal).	•		
3. The cost-effectiveness of auctions **depends heavily** on the accuracy of biophysical models predicting how management alternatives affect ES provision.	•		
4. The current knowledge base is probably **not sufficient** to reliably design auctions that can account for longer-term sources of uncertainty and risk, such as climate.		•	
In practice, real-world auctions typically **do not** successfully…			
5. … account for uncertainty and risk on seasonal or shorter timescales.	*	•	
6. …promote greater equity in the distribution of environmental/economic benefits.	*	•	
7. … produce spatially coordinated outcomes.	*	•	
The current knowledge base **is sufficient** to reliably design auctions that can…			
8.… produce spatially coordinated outcomes.			•
9.… optimize across multiple objectives.			•
10.… promote greater equity in the distribution of environmental/economic benefits.			

• = support across entire panel. * = support among responders (excluding "no answer"). Wording adjusted for brevity and to reflect consensus-disagree positions; see Supplementary Information 2 for exact phrasing.

(Wichmann et al., 2017a). Of course, administrators implicitly make trade-offs between short- and long-term risk in the design and contracting phases, shaping bidder behavior as a consequence (Glebe, 2021; Olita et al., 2023; Wichmann et al., 2017a).

4.2. Beyond consensus: Uncertainty and disagreement

This section introduces three topics that generated stubbornly divergent response distributions during surveys: spatial coordination, multi-objective designs, and equity. To understand why, we held a series of interviews and focus groups in Round 3 (Supplementary Information 4).

4.2.1. Is the knowledge base sufficient to reliably design spatially coordinated auctions?

Most panelists believe that we know how to design auctions that can generate spatially coordinated outcomes (Table 3). The remainder—about one quarter of the panel—consider spatial coordination within reach but not yet reliable. For example, one wrote:

> "The majority is clearly wrong, given the existing literature and evidence… it's a very active research area, so I'd say that we'll soon be able to agree. For now, it's premature."

In interviews, panelists agreed that spatially coordinated mechanisms perform well in the lab (Banerjee, 2018) and in a few field pilots (Liu et al., 2024; Windle et al., 2009). "We know what ought to work, but it doesn't always when we run the experiments," one panelist noted. If challenged to demonstrate that spatial mechanisms can work in the real world, success "wouldn't be automatic, but it's certainly not like we can't do it." The main impediment is probably the dearth of field data due to funding and low uptake.

Other challenges include *design costs*, *trade-offs* between coordination and collusion, and *thin markets*. *Design costs* derive from metric complexity and information requirements: e.g., the correlation between ecological values and economic costs can vary in strength and sign, so the principal needs detailed knowledge to prioritize one spatial configuration over another. *Trade-offs* emerge because in disclosing a spatial preference or introducing incentives for coordination, the principal risks facilitating rent-seeking and collusion, possibly offsetting the benefits of a spatial allocation (Conte and Banerjee, 2024; Howard and Valcu, 2021)—and if spatial auctions fail to show a clear cost-effectiveness advantage, then much simpler instruments are available. Finally, *thin markets* occur when spatial preferences or complex eligibility requirements limit the size of the bidder pool (possibly introducing missing links), or when owners of critical parcels extort high prices. Since higher participation can buffer both collusion and thin markets, the best way to improve the reliability of spatially-coordinated mechanisms might be to focus on the participation problem.

Of course, auctions do not necessarily need to solve spatial coordination single-handedly. "See what you scoop up with the auction," one panelist suggested, "then attack the missing links with another instrument." However, there is little guidance about how auctions fit into multi-instrument portfolios (but see Box 2):

> "You want people to coordinate for a cross-boundary outcome. Are auctions the best or only way? For some outcomes, a certain type of auction could do the job, or a certain contract design—maybe

Box 4
Interpretations of equity in the auction context

1. Autonomy; perceived fairness of setting own price	5. Similar profits (net payment less winners' individual costs)	9. Win ratio: contracts awarded to more bidders vs. one large landowner "scooping the pot"	13. Non-exacerbation of existing inequities (auction is not a net income transfer to the wealthiest landowners)
2. Equal pay for equal output	6. Support participation of marginalized groups	10. Bid caps: limit maximum payment per unit area or benefit	14. Avoid adverse impacts on land/labor distributions (especially in developing countries with insecure property rights)
3. Equal pay for equal action	7. Best use of public funds; cost-effective procurement	11. Distribution of environmental benefits (e.g. increasing public access to contracted land)	15. Intergenerational equity
4. Equal opportunity for the same contract	12. Agency: stakeholders directly influence management (forward auctions)	12. Transparency: No rigging/corruption when verifiably run according to the rules	16. Equity as a fuzzy constraint: doesn't have to be equitable, but must avoid perception of egregious inequity.

collective payments with collective thresholds. And it may not be good to put them together. That's still not known, either."

In this case, theory might actually overstate the practical challenge. Because incentive-compatible spatially coordinated mechanisms are rare and optimality is difficult to prove, scholars may hesitate to promote them. But if they can reliably produce second-best outcomes—and many panelists felt they can—then they are probably good enough for policy. Without more and bigger real-world trials, progress will likely remain slow.

4.2.2. Is the knowledge base sufficient to reliably design optimal multi-objective auctions?

Auctions are market mechanisms linking buyers and sellers, each of whom is assumed to have multiple aims and preferences. In that sense, auctions are always multi-objective: the buyer considers their objectives when designing the program, the sellers when formulating their bids.[18]

But addressing competing objectives at the mechanism level—for instance, by seeking to procure baskets of potentially uncorrelated ES through a single tender—is more challenging. One strategy for buyers involves soliciting bids for a single management change to reveal opportunity costs, then using multi-criteria optimization to incorporate environmental data when selecting winners (Lewis and Polasky, 2018). The buyer might not even disclose their criteria to the bidders, and instead attempt to procure a "hidden bundle" by soliciting bids for one service (e.g. carbon storage) expecting to obtain others (e.g. biodiversity) as co-benefits.[19] Knowing this, both buyers and sellers can be strategic about which markets they enter (Summers et al., 2021).

Likewise, sellers respond to multi-attribute utility functions when formulating their bids: e.g., different plantings might entail different economic and amenity values, with the net effect being captured in the opportunity cost elicitation. However, it might also be possible to design mechanisms that help bidders identify salient attributes and make quantitative trade-offs between them using tools like combinatorial optimization, data envelopment analysis, and/or Pareto frontiers (Iftekhar et al., 2012; Lundhede et al., 2019; Marques et al., 2020). As with spatial coordination, however, there may be a tension between scholarly rigor and practical utility: theory on multi-good ES auctions is sparse, and while some mechanisms look appealing on paper, they often require important simplifying assumptions, such as bidders operating as rational profit-maximizers (Cooke and Corbo-Perkins, 2018). Meanwhile, empirical work usually uses heuristics whose solutions are difficult to assess for optimality; results are not often easily generalizable.

The panel viewed these challenges as real and persistent but not necessarily fatal, though some questioned whether multi-good ES auctions are worth pursuing in the first place. A common objection appealed to the Tinbergen principle, which holds that multiple objectives imply multiple policy instruments (Barrett et al., 2013; Mann and Lanz, 2013; Rey et al., 2019). As a practical rule of thumb, auctions are often more likely to succeed when they are big, simple, and feature homogenous goods; thus, multi-objective mechanisms might be inherently inefficient. One panelist cautioned:

> "Does it make sense to try? How do you weight [different benefits]? My immediate reaction is: take the one that has the highest weight, design the auction for that, and scoop up the others as side benefits. But I don't know. I'm open on this one."

As a word of caution, auctions that rely too heavily on optimization to select winners may be less transparent, which could impact trust, satisfaction, and compliance (Bingham et al., 2021; Kindu et al., 2022; McWherter et al., 2022). Running complex calculations in the background turns the selection process into a black box: "Their friend gets accepted, but not them, and they feel they submitted a very similar, competitive bid." This can also be a problem for spatial coordination, where awarding contracts to a cluster of neighbors might give the impression of unfair manipulation unless the selection process is easy to understand and verify.

4.2.3. Is the knowledge base sufficient to design auctions that promote distributional equity?

Unlike our discussions about spatial coordination and multi-objective auctions, the issue of equity generated fairly divergent accounts of the relevant considerations. Key issues include equity definitions, their relationship with design, and the role of second-order effects like using auctions to obtain information to guide more equitable policy later. Altogether, we identified 16 different equity-related objectives in comments and transcripts (Box 4).

Some panelists argued that equity is either outside the scope of, or even antithetical to, the competitive logic that auctions are based on.[20] Others interpreted this competitive logic as a form of process equity, since all bidders have an equal opportunity for the same contract, or as being compatible with equitable aims, like ensuring the best use of public funds. As in the broader PES literature, *equity* signifies different things to different people in different contexts, and conflicting norms are likely to be operative in any real-world auction (Schilizzi, 2014, 2011).

Why has the literature tended to steer clear of these issues? Earlier work often interprets this tendency as a domain issue (Bingham et al., 2021; Leimona et al., 2023; Markova-Nenova et al., 2023a), but our interviews hint that it may also be a strategic choice. Attempting to engage with equity at the mechanism or program design level feels like inviting

[18] For convenience, we refer to reverse auctions throughout this section (i.e. buyers want to procure ES and sellers bid to provide them).

[19] This might happen, for example, when regulations prohibit "double-dipping" (for example, selling biodiversity credits from a parcel already under a carbon contract).

[20] "[This question] is nonsensical," one panelist wrote. "Auctions, by their very nature, reward those who can do a better job of delivering environmental benefits. That's what markets are all about!".

controversy: with so many potentially salient and mutually-exclusive definitions, opening up a debate about equity could discourage risk-averse administrators from adopting auction mechanisms, despite the fact that well-executed auctions are typically viewed by participants as intuitive, transparent, and fair.

Still, most panelists felt that the idea of incorporating some dimension of equity should not be rejected out of hand. One idea might be to include equity not as an objective, but rather as a constraint—possibly a soft and relative one, like taking steps to avoid the perception of egregious inequity. Equity could also be explored as a side effect, for instance by assessing whether an auction would likely increase or decrease wealth disparities in a community. Even so, our discussions sometimes felt a bit like a brainstorming session:

> "Can we think of auctions that will improve equity? Maybe packaged auctions, collective auctions… If you're talking about traditional conservation auctions—no, I don't think that can handle equity. I don't know whether it would be possible to design auctions on different principles that might include a dimension of distributional equity. I'd have to work on it. But again: should you?"

As with spatial coordination and multi-objective designs, some tension between theory and practice may be at work. While the panel hesitated to discuss equity without a specific operational definition, real-world auction funders might not feel similarly constrained. Panelists recounted clients invoking a vague notion of equity in order to justify design choices that would undermine the cost-effectiveness of auction-based PES. For instance, an agency might prefer to maximize acceptance rates to generate social or political co-benefits like long-term engagement or supporting key constituencies, even at the cost of economic efficiency.[21] One panelist recalled surveying designers and administrators about the importance of different program considerations:

> "The results were dismal! Cost-effectiveness was always the lowest. Things like transparency, ease of application, fairness scored high. Getting more conservation for your buck seemed shockingly unimportant… If we're not asking the right questions, if they're open to [auctions] but just stuck on fairness… maybe we could adjust our research or explain our perspective."

The tendency of policymakers to view auctions as subsidy distribution tools rather than competitive allocation and pricing mechanisms could help explain their reluctance to incorporate auctions into large-scale environmental subsidy programs. If underlying goal of programs like the EU's Common Agricultural Policy (CAP) is providing financial support to farmers, then policymakers should use an instrument that gets money into farmers' pockets on time and without too much hassle. Unfortunately, this is not a strength of competitive market mechanisms. Confronted with a pressing need to maximize environmental impact under budgetary constraints, however, policymakers could revise their calculus in auctions' favor.

5. Discussion

Our results suggest that mainstreaming auctions in the PES context—and understanding why their adoption has proceeded so slowly—will likely require reinterpreting them as multidimensional processes that are socially, economically, and ecologically situated (Leimona et al., 2023). Unlike auctions for artwork, electricity, or broadcast spectra, the PES context often requires a degree of ongoing collaboration between bidders and administrators to facilitate participation, estimate opportunity costs, predict management effects, monitor compliance, access support through extension services, and so forth. Auction mechanisms ask only that bidders act in accordance with their own self-interest, but facilitating environmental change often demands something else: trust. Reconciling this social layer with mechanism design and environmental uncertainty will require not only interdisciplinary exchange, but also an expansion of the ongoing dialog between scholars, program designers, administrators, and land managers.

At the same time, we stress that while there is always more to learn, simple, reliable auction mechanisms are already available for integration into PES. Auctions have a well-documented track record; much of our panel has first-hand experience designing and implementing them. There is a strong expert consensus that well-designed, well-executed auctions can improve the cost-effectiveness of PES, generate valuable information about private values, engage stakeholders, and provide a transparent process for determining payments and allocating contracts—provided, of course, that people participate in them. Understanding the drivers and consequences of participation patterns represents a critical frontier for ES auctions (Rolfe et al., 2022). In a recent literature synthesis, for example, Kindu et al. (2022) propose a *meta*-framework which represents participation as a horizontal bar linking virtually every compartment of auction research (their section 3.2.2).

Notably, the panel endorsed a simple framework linking participation to collusion risk (Box 3). While collusion remains a persistent topic of interest (Arguedas and van Soest, 2011; Banerjee, 2022; Ferguson et al., 2016; Fooks et al., 2016; Krawczyk et al., 2016), and despite general agreement that it is deterred by higher participation rates, this relationship is shaped by a contextual factors requiring further study. In the meantime, the strong consensus that context matters serves as a reminder to take care using laboratory results to guide decisions in the field.

Our results also suggest some areas of focus for future mechanism design innovations and field applications. Assessments of the practical viability of multi-objective auctions and spatially coordinated mechanisms vary (Banerjee, 2018; Bingham et al., 2021, pp. 20–21; Markova-Nenova et al., 2023b; Narloch et al., 2011; Nguyen et al., 2023). Although some panelists were skeptical that these features were compatible with auctions, others felt that refinements that could greatly improve their feasibility are within reach. These mechanisms could also become more accessible as our understanding of participation issues grows.

The relationship between auctions and equity also warrants further debate. While we were unable to synthesize any clear consensus, we did identify a wide range of possible interpretations of what equity might mean in the ES auction context. Some panelists suggested ways to amplify the voices of marginalized groups; others argued that engagement with distributional equity is out-of-bounds for competitive instruments.[22] These issues call for more explicit engagement from researchers, policy experts, and ethicists (Bingham, 2021; Cooke and Corbo-Perkins, 2018; Leimona et al., 2023; Lliso et al., 2021; Thompson, 2021).

Methodologically, we found the Delphi approach well-suited to flexibly accommodating experts with diverse backgrounds (Kattirtzi and Winskel, 2020; Kaufmann, 2016; Strand et al., 2017). During interviews, panelists stressed the importance of seeking to understand a plurality of perspectives and forms of expertise.[23] Our panel encompassed a wide

[21] One panelist termed this the "Vegemite approach": "Spread it thinly, otherwise it's too salty. Everybody's happy, they'll vote for you next time… We're not looking at cost-benefit in economic terms, but in political terms.".

[22] See Schilizzi (2014) for equity norms in the auction context, related metrics, and trade-offs with efficiency.

[23] Some relevant examples from the interview transcripts (Supplementary Information 4) relate to behavioral nudges (lines 723–728), discrepancies between agricultural and conservation professionals (2194–2206), the importance of distinguishing between different types of participants (2293–2308), how non-economists can offer important insights (2432–2438), and overlooked aspects of conducting transient economic experiments in durable, tight-knit communities (2591–2596).

spectrum of experience spanning theory development, laboratory experiments, fieldwork, and administering real-world auction programs, but our sampling approach emphasized academic credentials. Although several panelists have published extensively on the perspective of auction participants, for example, our panel did not include anyone who could speak as a participant themselves.

When working with diverse panels, it important to keep in mind that the average view is not necessarily the correct one; after all, knowledge development progresses by challenging accepted wisdom. For example, someone the panel clearly viewed as a top expert on the topic ("Panelist A") decisively broke with the majority in Round 2, describing the consensus view as "clearly wrong." Delphi research typically takes it for granted that those who consider themselves less qualified to answer a given question are more likely to gravitate toward the panel's dominant opinion, but presumably this propensity is sensitive to how this opinion is identified in the first place. While we weighted Likert scales by response degree, for example, an alternative would be to weight by self-assessed expertise (e.g. Butler et al., 2015; Cressey et al., 2019; Scavarda et al., 2006; Shu et al., 2021). Had the surveys not been anonymous, the panel might have valued Panelist A's judgment more than its own collective guess. The protocol used to identify and communicate emerging consensus is an important decision that—like auction design—likely depends heavily on contextual factors, including the diversity of the panel and familiarity with the credentials of other panelists. Guidance for how to navigate this issue in Delphi research is scarce.

This study was made possible by panelists' generous contributions of time and effort.[24] These were not negligible, but we think our method offers significant time and resource savings over other approaches to stimulating exchange, though conferences and workshops can certainly be fruitful (Whitten, 2017). Panelists seemed to welcome the chance to engage in quick exchanges on challenging topics with other experts, and felt that doing so more regularly could be beneficial. Despite some limitations associated with conducting remote focus groups across time-zones, our approach offers a relatively cheap way to rapidly synthesize expert opinion, generate conceptual reference points, and potentially foster coordination for future projects.

Especially in multidisciplinary, international, and applied fields like auctions and PES, techniques for supporting structured communication between experts might offer a useful complement to more specialized, technical channels like journal articles and conferences. They might be particularly well-suited to efforts to cultivate exchange between the natural sciences, economists, and policymakers. These interfaces are vital for ES auctions, and enhancing them could catalyze innovations in mechanisms, programs, and infrastructure moving forward. We hope that our study can offer a starting point for understanding why translating auction theory into practice has proved so challenging, and possibly even provide a blueprint for subsequent work with larger and even more diverse panels.

5.1. Limitations

The Delphi method was designed to synthesize global opinions about emerging or uncertain topics, often through the use of broadly-formulated prompts. In this study, for example, we asked panelists to suggest, and later rank, some of the primary advantages they associate with the use of auctions in the ecosystem services context, obtaining a set attributes that panelists associate with ES auctions in general. Future work might explore how a similar panel—or, ideally, one comprising an even broader range of perspectives—would evaluate more concrete comparisons between auctions and specific alternatives, like command-and-control policies, flat subsidies, or Coasean bargaining processes (Bingham, 2021).

Unlike a typical survey, where the goal is to transfer information from respondents to researchers, we aimed to facilitate structured communication within a large group of time-constrained experts. The information-sharing function of the survey sometimes conflicted with standard survey design practices, especially where panelists were intended to influence one another via suggested scores and highlighted majority opinions.

In some cases, information-sharing complicated response tasks. For example, we coined the label *cross-functional synergies* to capture an unusually broad theme in written responses, and provided examples to clarify (Fig. 4). Because these examples illustrate different ways of thinking about the field's boundaries and possible futures, we hoped panelists might find them thought-provoking, but their inclusion likely introduced some noise into our results:

> *Comment 1:* I increased the score […] but the category was so broad it tempered my answer. I don't see much promise for blockchain, but I see a lot of potential for administrative experiments.
> *Comment 2:* [Changing a score] captures a lot of stuff, some of which is and some of which is NOT important. So the change is the average of several possibly not-in-the-same-direction re-scores!

Prioritizing information-sharing also precluded the use of control groups to test the suggested score effect, since communicating that score was a secondary function of the survey. By the same token, panelists sometimes answer strategically because they know that their response in one round might influence the panel's sentiment in the next:

> "I answered 'yes' in part because I'm concerned that if people say 'no', they'll just keep doing nothing. I wanted to signal that we know enough to know that [spatial coordination] is a good idea that could work in certain circumstances."

5.2. Directions for future research

In the course of the consultation, panelists highlighted a number of topics that they felt warranted further study. This section collects some of these "questions worth asking".[25]

First, additional dialog with program designers and other stakeholders to build mutual understanding and tailor auction tools to their needs is indicated. Are they willing to consider tools designed with cost-effectiveness as a primary objective (Grand et al., 2017; Markova-Nenova et al., 2023b; Messer et al., 2016)? If so, why has uptake of auctions for ES been so slow relative to e.g. broadcast spectra (Whitten et al., 2017)? If program designers dislike market mechanisms, is this in tension with the competitive nature of industries like farming, which are ideal targets for ES auctions (Blackmore et al., 2014)? How can thinly-spread conservation bodies overcome the transaction costs involved in running auctions, and how can participants overcome the transaction costs of bidding (Kindu et al., 2022; Palm-Forster et al., 2016; Whitten et al., 2017, 2013)? How can auctions be optimally integrated into multi-instrument bundles to avoid policy conflict (Bingham et al., 2021, p. 23; Howard and Valcu, 2021; Jindal et al., 2013; Latacz-Lohmann and Schilizzi, 2014)?

Exploring auctions as multidimensional socio-economic processes means attending to context and co-benefits. Since landowners often need help understanding the ecological and management trade-offs that underpin bid formulation (Howard and Valcu, 2021; Whitten et al., 2017, 2013), extension and education are crucial but understudied elements. How can they be better integrated into auction research? Can auctions be designed with local knowledge networks in mind, either as resources to draw upon, or as targets for public education co-benefits

[24] In addition to time spent communicating with us and reviewing previous results, panelists spent, on average, 20 min per questionnaire, plus roughly one hour in focus groups and interviews.

[25] Also see Supplementary Information 4.

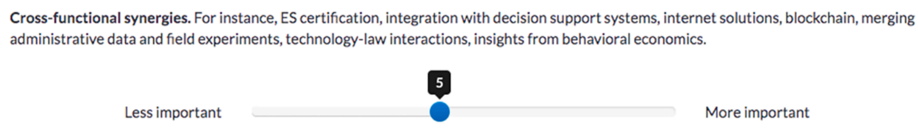

Fig. 4. Example Round 2 sub-question: "In the coming years, the most significant developments in ES auctions are likely to come from…".

(Baumber et al., 2019; Leimona et al., 2023; Rolfe et al., 2017)? How might this impact outcomes, given the significant role that risk aversion plays in shaping bidding behavior (Blackmore et al., 2014; Olita et al., 2023; Wichmann et al., 2017a)?

The role of idiosyncratic contextual factors is also receiving growing attention. How have legal and regulatory regimes influenced the development of ES auctions in North America, Australia, and the EU? International comparative work should continue, particularly with respect to developed and developing countries (Kindu et al., 2022; Wünscher and Wunder, 2017). The distinction between landowners and tenants has been largely overlooked (Bigelow et al., 2016; Ganguly et al., 2020): might bidders' relationships to their parcels influence bidding behavior and outcomes (Chan et al., 2018)?

Finally, the prevalence of small field experiments relative to major implementations in major PES programs raises questions about scale. What policy scale must auction programs achieve to move the needle on agri-environmental outcomes? How is the optimal spatial scale influenced by context and objectives (Rolfe et al., 2022)? With respect to temporal scale, how can auctions be designed to create enduring change through time-limited payments (Fitzsimmons and Cooke, 2021; Olita et al., 2023; Rasch et al., 2021; Thompson, 2021)?

6. Conclusion

Efforts to integrate auction mechanisms with PES have matured into a vibrant field at the intersection of economics, governance, and environmental management, but adoption into practice has been sporadic. To better familiarize the ecosystem services community with auction techniques, we designed and conducted an expert consultation featuring influential, internationally prominent scholars and practitioners with hands-on experience designing and implementing auction-based PES. In short, we asked the ES auction field to describe itself. What can auctions offer to PES? What are their limitations? Where are they headed scientifically and practically?

Our findings seem to be dominated by two themes. First, while auction theory in general is well-developed and has substantially outpaced practice, progress in the environmental context is limited by the sporadic uptake of auctions by policymakers and a resulting lack of field data to inform engagement with various practical issues. Efforts should focus on improving the research-policy-practice nexus. Second, auctions in the field consistently face low participation rates for reasons that remain poorly understood. Low participation is a fundamental problem with implications for virtually every component of the auction process.

In addition to these two major findings, we clarify the auction niche. There is a strong consensus that auctions can offer real advantages to PES, like improving cost-effectiveness, revealing opportunity costs, engaging stakeholders, and increasing the transparency of price-setting and contract allocation processes. But they also have relatively high informational requirements and can be more challenging for administrators and participants to navigate than simpler alternatives like open-enrollment programs. Interestingly, many well-known challenges, such as the role of uncertainty and transaction costs as impediments to participation, are not necessarily intrinsic to auction mechanisms themselves. Instead, they can likely be addressed through outreach, extension, and other elements of administration.

Overall, we hope this study can catalyze further efforts to better integrate a somewhat fragmented, profoundly multidisciplinary field with PES theory and practice more broadly. It highlights some priority areas for research and suggests a need for the development and dissemination of evidence-based best-practice guidelines. The continued expansion of the PES literature and growing policy interest in circular bioeconomies offer new opportunities and challenges for auctions, particularly where funding is limited and cost-effective interventions that transparently involve stakeholders are needed. By proactively communicating areas of scientific consensus, conducting outreach to respond to the priorities and constraints of program designers, and continuing to develop sophisticated mechanisms to account for context, the ES auction field may better position itself to contribute to sustainability policy.

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CRediT authorship contribution statement

Logan Robert Bingham: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Peter Boxall:** Writing – review & editing, Writing – original draft, Formal analysis. **Riccardo Da Re:** Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Stuart Whitten:** Writing – review & editing, Writing – original draft, Formal analysis. **Thomas Knoke:** Writing – review & editing, Writing – original draft, Supervision, Resources, Funding acquisition. **José G. Borges:** Writing – review & editing, Writing – original draft, Supervision, Software, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

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

Data availability

Transcripts provided as supplementary material

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Appendix:. Glossary of key terms

This glossary provides brief and general definitions for key PES and auction-related terms used throughout this article. Note that panelists were neither provided with, nor asked to provide, any operational definitions, so usage may vary in our data and results. This appendix has been loosely adapted from Bingham et al. (2021 s. 1.1)

additionality: A PES assessment criterion that is satisfied if ES production exceeds (is "additional" to) a plausible business-as-usual baseline (Wunder et al., 2020, 2018). Thus, it is related not only to benefits produced by the intervention, but also to the threat posed to ES in the baseline scenario (Kroeger, 2013).

bid shading: Strategically submitting a bid higher (or lower in the case of uniform pricing) than the bidder's true opportunity cost in hopes of extracting profits above one's cost in an auction (informational rents) (Boxall et al., 2017; Wichmann et al., 2017b)

conditionality: Requiring that PES payments are disbursed if, and only if, providers demonstrate compliance with the terms of the contract; i.e. payments are "conditional" on compliance (Wunder et al., 2020, 2018).

contract design: The set of decisions about the terms of an agreement, including things like payments, contract duration, conditionality, whether compliance will be assessed in terms of actions executed or outcomes produced, how compliance will be documented, the consequences associated with breaching the contract, etc. Contracts with more stringent terms may carry a higher opportunity cost and prospective ES providers might consider them riskier, impacting bidding behavior and auction outcomes (Kindu et al., 2022; Rolfe et al., 2018; Wünscher and Wunder, 2017)

cost-effectiveness: A criterion for evaluating program performance based on the cost incurred to achieve a given physical objective (e.g. the payment required to store an additional tonne of carbon, regardless of the impact that carbon storage has on broader social welfare). For economists, programs can be locally cost-effective but not efficient in terms of social welfare experienced by the wider region or country; in the PES context, these terms are often used interchangeably (Kroeger, 2013; Martin et al., 2014)

collusion: A strategy for extorting additional profits (informational rents) wherein a group of bidders attempts to subvert the auction process through systematic and coordinated *bid shading* among themselves (Blackmore et al., 2014; Dijk et al., 2018)

discriminatory pricing: A rule specifying that each accepted bid will be compensated at a rate which depends on the payment requested in that bid (and not the payments requested by other accepted bids)

efficiency: Refers to total welfare maximization (e.g. the increase in social welfare generated by storing an additional tonne of carbon, divided by the cost of storing it); often used interchangeably with *cost-effectiveness* in the PES context (Kroeger, 2013; Martin et al., 2014)

opportunity cost: The sum of costs and foregone benefits associated with one alternative relative to another: e.g., the opportunity costs of conserving a forest might include foregone timber revenue as well as the ability to convert to a different landscape that the owner prefers aesthetically or culturally (Kindu et al., 2022; Olita et al., 2023; Rolfe et al., 2018). Opportunity costs might be relatively homogenous (asking cereal farmers to briefly delay harvesting a fixed area to protect nesting habitat) or heterogeneous (asking farmers with different crops, resources, knowledge equipment, business structures, and risk preferences to implement an unfamiliar agrosilvopasture system).

spatial targeting: A PES assessment criterion based on the idea that contracts should be selectively allocated to locations with high ES density and/or lower prices associated with protecting those ES (Wunder et al., 2020, 2018)

uniform pricing: A rule specifying that all accepted bids will be compensated at a uniform rate, which is guaranteed to be greater than or equal to the payment requested in any individual accepted bid

winner's curse: In referring to reverse auctions, an outcome where the payment requested by an accepted bid is not sufficient to cover the actual cost of complying with the contract. This can result from attempting to bid strategically (e.g. in the case of uniform price auctions, a bidder may request a payment that they know to be below their opportunity costs, in the hopes that the final price will be greater than requested) or from errors in the bidder's own estimated cost of compliance (in the case of a discriminatory price auction)

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoser.2024.101647.

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