Journal of Environmental Economics and Management 122 (2023) 102889

Contents lists available at ScienceDirect

Journal of Environmental Economics and Management

journal homepage: www.elsevier.com/locate/jeem

Pricing rules for PES auctions: Evidence from a natural experiment☆

Ben Balmford [a,*], Joseph Collins [b], Brett Day [a], Luke Lindsay [c], James Peacock [b]

[a] *Land, Environment, Economics and Policy Institute, Economics Department, University of Exeter Business School, United Kingdom*
[b] *EnTrade, Claverton Down, Bath, United Kingdom*
[c] *Economics Department, University of Exeter Business School, United Kingdom*

ARTICLE INFO

JEL classification:
D44
D47
D62
Q21
Q25
Q53

Keywords:
Market design
Procurement auctions
Multi-unit auctions
Payment-for-Ecosystem-Service schemes

ABSTRACT

Payments for Ecosystem Service (PES) schemes increasingly use auctions to target funds to low-cost providers, aiming to increase value-for-money. To date, PES auctions have most often employed "Pay-as-Bid" (PaB) pricing, in which successful participants are paid the amount stipulated in their bid(s). Alternative pricing rules exist, such as the "Uniform Price" (UP) rule, in which successful bids receive the same per unit payment determined by the marginal bid. Despite being successfully applied in other settings, the use of UP pricing in PES auctions has been limited. We explore the impact of UP pricing in the context of a scheme incentivising farmers to reduce nutrient run-off. Following our intervention, the auction through which contracts were allocated to farmers switched from PaB to UP. Our analysis provides the first real-world, causal evidence on the effect of alternative auction pricing rules in this context. We find that UP pricing reduced mean bids, by 40%. *A priori* the impact on payments made to the farmers is ambiguous, yet we find these to be reduced by a similar amount. Moreover, the UP format reduces the incidence of costly bidding behaviours, updating and sniping, by approximately 50% and 30% respectively. These significant and substantial changes suggest wider adoption of UP pricing in PES auctions is likely warranted.

1. Introduction

A primary concern for many Payment for Ecosystem Service (PES) schemes is that they deliver value-for-money; maximising the ecosystem service procured from the funder's limited resources. To deliver on the value-for-money objective, scheme designers have increasingly turned to auctions as a mechanism for allocating PES contracts (Latacz-Lohmann and Schilizzi, 2005; Ferraro, 2008; Cramton et al., 2021). Despite the wide variety of auction formats used elsewhere in the economy, PES implementations have remained stubbornly fixated on the "Pay-as-Bid" (PaB) pricing rule (Rolfe et al., 2017). This paper describes the outcome of a natural experiment in which the pricing rule used in a PES auction was switched from PaB to the "Uniform Price" (UP) rule. In contrast to the single-unit, sealed bid, one-shot auctions commonly studied in the literature, the auctions we studied featured

☆ We are extremely grateful to the EnTrade team for facilitating this field trial, and in particular Guy Thompson, Amy Coulthard, and Jez Graham. We are grateful for the comments of two anonymous referees and our editor, Andreas Lange, which improved the paper enormously. We would additionally like to thank Ethan Addicott, Tatyana Deryugina, Sabrina Eisenbarth, Ben Groom, Elisabeth Gsottbauer, Nick Hanley, Kelsey Jack, Todd Kaplan, Daan van Soest, Alex Teytelboym, Christian Vossler, and participants at EnvEcon 2020, BIOECON 2021, AERE 2022 and EAERE 2022 for their insightful comments and suggestions. Finally, thanks to Graham Redman, author of the John Nix Pocketbook, for his assistance. Ben Balmford gratefully acknowledges the support of South West Water for sponsoring his PhD studentship, and the Dragon Capital Chair on Biodiversity Economics funding his current postdoctoral researcher position. The authors are also grateful to the ESRC for the IAA2 Sub Award "Applying recent insights in market design to achieve environmental benefits" which supported the development of the key relationship.

* Correspondence to: F19, LEEP Institute, XFi Building, University of Exeter Business School, Rennes Drive, Exeter, EX4 4PU, United Kingdom.
E-mail address: b.j.balmford@exeter.ac.uk (B. Balmford).

https://doi.org/10.1016/j.jeem.2023.102889
Received 27 October 2022
Available online 9 October 2023
0095-0696/

multi-unit supply, semi-open bidding, and repetition. Exploiting an exogenously-determined change in pricing rule, this paper shows UP pricing delivers greater value-for-money and reduces problematic bidding behaviours that might threaten the long-term success of PES schemes. This evidence suggests that the dominance of PaB pricing within PES auctions is likely sub-optimal, and that PES schemes may often be better served by a UP pricing rule.

To implement an efficient outcome at the lowest cost to the funder (which we describe as achieving value-for-money), it is necessary to identify least-cost interventions (maximising efficiency), and then to contract for each with a payment that just covers costs (minimising the surplus transferred to suppliers). Information asymmetry imperils this goal as scheme funders do not know the cost faced by each supplier. Auctions offer a possible solution for price discovery; encouraging participants to reveal information about costs. The lowest-cost bids are successful and receive payment as defined by the auction's "pricing rule". The pricing rule determines the incentives that bidders face, and hence is a key determinant of the value-for-money that auctions deliver (Ferraro, 2008). Under PaB pricing, successful bids are paid the amount specified in the bid, and bidders are therefore incentivised to shade up their bids (overstate their costs) trading-off the possibility of higher profits against the increased probability that a bid is unsuccessful (Ausubel et al., 2014; Pycia and Woodward, 2021). In contrast, under the UP rule, each successful bid is paid the amount specified in the marginal (either last winning or first losing) bid. Hence there is less incentive to bid above cost (Vickrey, 1961; Ausubel et al., 2014). The earliest PES schemes to adopt auctions used PaB pricing (e.g. the Conservation Reserve Programme, Shoemaker, 1989; Cramton et al., 2021; and BushTender, Stoneham et al., 2003). That precedent appears to have entrenched PaB pricing as the dominant pricing rule applied in PES auctions. Yet there is much debate regarding which auction format generally maximises value-for-money (e.g. Friedman, 1960; Binmore and Swierzbinski, 2000; Brenner et al., 2009; Monostori, 2014), and the evidence from both induced-value laboratory experiments (e.g. Smith, 1967; Engelmann and Grimm, 2009),[1] and real-world markets for government debt (Nyborg et al., 2002; Barbosa et al., 2022), foreign exchange (Tenorio, 1993), timber extraction rights (Baldwin et al., 1997; Athey et al., 2011), spectrum licences (Cramton, 1995), highway procurement (Krasnokutskaya and Seim, 2011), and trading cards (Lucking-Reiley, 1999; List and Lucking-Reiley, 2000), is inconclusive. Moreover, as we go on to detail in Section 2, despite widespread adoption of the PaB format, PES auctions might be better served by UP pricing given features of the PES trading environment that are rare in other settings.

A small number of studies have implemented UP pricing within real-world PES schemes. Jack et al. (2009), Brown et al. (2011) and Pant (2015) use UP auctions in various contexts to establish take-it-or-leave-it offers for wider scheme roll-out.[2] (Jack, 2013) compares the performance of different pricing mechanisms for tree planting; contrasting a UP auction with a take-it-or-leave-it offer set at the marginal bid from the UP auction. Our work extends that literature by providing the first direct comparison of the performance of different pricing rules in PES auctions using field data.[3]

The setting we study is a UK agri-environment scheme paying farmers to deliver water quality improvements. Agri-environment schemes are by far the highest value and most prevalent PES schemes (Salzman et al., 2018), and as such are a particularly important PES setting in which to explore the impact of auction pricing rules.[4] These particular auctions allocate contracts to plant cover crops to reduce downstream nitrogen run-off, and are facilitated by EnTrade, a private company who act as the auctioneer.

Working on behalf of various regional water companies in the UK, EnTrade run PES auctions for water quality improvements across a number of geographically-distinct catchments. Our study draws on data from two such schemes. The first is in the Poole Harbour catchment, in which Wessex Water, EnTrade's parent company, is the regional water company. Biannual auctions in Poole Harbour were established in summer 2016 and used PaB pricing through to 2018. In autumn 2018, discussions between the project research team and EnTrade, pertaining to the possibility of another water company establishing a similar auction, resulted in EnTrade switching to a UP auction format in Poole Harbour. Importantly, the timing of this switch was exogenous. EnTrade had no intention of changing the pricing rule and only did so to implement the field trial proposed to them by the project research team. We benefit from a further source of identifying variation. UP pricing was only implemented in the Poole Harbour auctions, while the PaB rule was maintained in EnTrade's schemes for other water companies. Indeed, the data regarding the second series of auctions is from one of these other catchments, and covers the same time span as the Poole Harbour auctions. Owing to the commercially-sensitive nature of this second scheme, we are not privy to its identity, and instead refer to it as the "control catchment". Treatment (switching to UP pricing) was *not* randomly assigned across these catchments. Rather, the field trial occurred in Poole Harbour as the downside risks of experimentation (e.g. that value-for-money declined) fell on Wessex Water, rather than a third-party water company.

Given the nature of our data, we first employ difference-in-difference (DiD) methods to identify the impact of UP pricing on bids in Poole Harbour auctions. As we go on to detail, EnTrade introduced additional changes to the Poole Harbour auction at the same time as the pricing rule change, which obfuscate our claim to causal identification of the independent effect of the pricing rule. We

[1] Schilizzi (2017) provides a recent and thorough review of laboratory experimental research specifically in the context of PES auctions.

[2] Lybbert et al. (2013), van Soest et al. (2018), Channa et al. (2019) use the Becker–DeGroot–Marschak mechanism, which has similar incentive properties to a UP auction, to establish the costs facing service providers.

[3] Narloch et al. (2013) compare outcomes under both PaB and UP pricing rules in the field but with an experimental design which precludes bidders from bidding in response to particular pricing rules. Iftekhar and Latacz-Lohmann (2017) also attempt to understand the impact of the two pricing rules, though they use a computer simulation to predict bidder behaviour, rather than implementing the rules in real-world auctions. Both PaB and UP pricing rules are used for auctions in other environmental (non-PES) contexts, e.g. for: fishing boat retirement (Schilizzi and Latacz-Lohmann, 2012), fishing quota (Lynham, 2012; Marszalec et al., 2020), water extraction rights (Hartwell and Aylward, 2007), air pollution permits (Lopomo et al., 2011), and car ownership rights (Chen and Zhao, 2013), but the same scheme has not used both pricing rules and hence a direct comparison is not possible.

[4] We follow the broader literature in defining PES schemes as payments conditional upon particular behaviour changes which generate ecosystem services. Within this broader set, we identify agri-environment schemes as paying for particular management practices on agricultural land. Such schemes normally pay for reversible management practices, and are therefore typically associated with repeated short-term contracts.

cannot exclude the possibility that these other modifications to the auction are responsible for the changes in bidding behaviour that we observe. As such, a cautious interpretation of our findings is that they represent the cumulative impact of the suite of auction changes, including the pricing rule change, that define our treatment. At the same time, it is difficult to find theoretical reasons as to why the other auction modifications should affect the outcomes that we investigate, and where possible we mitigate against any such risk.

We find that switching from PaB to UP pricing resulted in a significant (30%–45%) decrease in mean bids. Subsequent longitudinal fixed effects analysis of the Poole Harbour data show this result to hold if costs are included as an explanatory variable,[5] and suggests that this effect is not driven by the pricing rule affecting: individual participation decisions; which fields are entered into particular auctions; nor the choice of which cover crop species (the "technology" used to deliver nitrogen reductions) farmers opt for. Instead, it seems farmers update their bidding strategy in response to the incentives they face; substantially reducing the amount of shading included within bids.

Of greater importance for PES auction design is the impact on value-for-money. We compare payments per unit of nitrogen in Poole Harbour under auctions using PaB with those using UP pricing. Clearly, payments received in a given auction are not independent across bids. For this reason, we use a Monte Carlo approach, to simulate 1000 auctions with each pricing rule to ascertain the impact of the change in pricing rule on payments. Our results suggest that the median amount paid per unit of nitrate reduction was about 40% lower in UP than PaB auctions, and that the difference is not only substantial but highly significant. In short, UP pricing resulted in far better value-for-money for the funder than the PaB rule.

In addition, we find preliminary evidence in longitudinal fixed effects estimates examining bidding behaviours to suggest that the increase in value-for-money offered by the UP auction would be long-lasting: both bid-updating and sniping fell, by 60% and 30%, respectively, as compared with levels observed under PaB pricing, suggesting that the costs of participation are lower.[6] Indeed, anecdotal evidence suggests farmers prefer UP auctions (Thompson, 2021). In the Monte Carlo simulation, participation rates appear to be slightly higher in UP than PaB auctions, although this result is not significant.

Our findings suggest that the widespread reliance on PaB pricing in PES auctions may be misguided. Our research provides compelling evidence of significant advantages to UP pricing and suggests that its more widespread adoption is likely to improve the value-for-money that PES auctions deliver.

The remainder of the paper is organised as follows. In the next Section 2 we outline the PES context and its implications for pricing rule selection. In Section 3 we discuss the specifics of our setting, the institutional arrangements, and the natural experiment. In Section 4 we present our hypotheses, and Section 5 formalises our empirical strategy. Finally, we present the results (Section 6) and offer some concluding remarks (Section 7).

2. Pricing rule selection in the PES setting

PES schemes are unusual compared to other settings in which multi-unit auctions occur: bidders are part of close-knit communities, and PES payments tend to make a relatively small contribution to participant incomes, so that participation is a key concern for delivering value-for-money (Rolfe et al., 2017). These characteristics suggest that the PES setting may be well-suited to UP pricing for multiple reasons.

First, PES auctions are generally conducted in information rich environments, imperiling value-for-money under PaB pricing (Evans and Reeson, 2022). In close-knit communities, information may rapidly spread through various formal and informal channels (e.g. the UK's £50 m Woodland Carbon Guarantee Auction reveals the average successful bid; Woodland Carbon Code, 2023). Moreover, PES auctions often provide an extended bidding window (typically a few weeks) to encourage participation, during which participants receive feedback about whether their bids are provisionally winning, and can adjust them accordingly (Banerjee et al., 2015; e.g. for natural flood management in the UK, Munday, 2018; wetland restoration in Canada, Hill et al., 2011; and improved grazing management in Australia, Rolfe et al., 2009).[7] To achieve value-for-money under PaB pricing, bidders must make close-to-cost bids; however, in such an information-rich environment bidders have incentives to substantially shade their bids above cost.

Second, since bidding in PaB auctions requires strategic thinking, we conjecture that PaB pricing increases participation costs relative to a UP rule, and therefore harms longer-term value-for-money. In contrast, to a first approximation, UP bidding merely demands that a participant truthfully reveals their cost. Bidding in a UP auction, therefore, is both easier and intrinsically unhostile, likely encouraging participation. Similar concerns may be exacerbated by an extended bidding window which affords bidders the opportunity to "game" the auction. Strategic bidding may manifest as participants updating their bids throughout the bidding window, and potentially bidding in the last few hours – so-called sniping – to beat less attentive bidders to contracts. Neither bid updating nor sniping are incentivised by UP pricing as initial bids should approximate costs. Finally, the tight-knit communities in which these schemes occur mean rival bidders commonly interact in other settings. Maintaining participation may therefore hinge, in part, upon a sense of fairness (Loft et al., 2020). The UP rule, which eliminates antagonistic sniping bids and in which every successful bid is paid the same per amount unit, may be perceived as fairer.

[5] We are unable to include cost within the DiD framework owing to multi-colinearity.

[6] We cannot identify if the reduced updating and sniping are in response to the reduced incentive to strategically engage with the auction due to the pricing rule, because a greater proportion of bids in the UP auction are successful due to the bids being lower, or as bid updating is more time-consuming in the UP auctions.

[7] The information environment is similar for schemes that offer longer-term contracts (e.g. 10 years) and offer funding through auctions that are repeated more frequently (e.g. every year) but within an auction do not offer feedback, as in the Conservation Reserve Programme (Shoemaker, 1989). Indeed, learning during the CRP eroded its value-for-money (Reichelderfer and Boggess, 1988).

Table 1
Details of how each Poole Harbour auction was run.

Auction	Pricing rule	Constraint	Information feedback	Maximum bid (per kg of N)	Updating process	# potential farmers
Jun-16	Pay-as-Bid	Quantity, 35,000 kg	Linear dial	No reserve	Revise existing bid	280
Jan-17	Pay-as-Bid	Quantity, 18,000 kg	Linear dial	£2.50, publicly known	Revise existing bid	280
Jun-17	Pay-as-Bid	Quantity, 27,000 kg	Linear dial	£2.50, publicly known	Revise existing bid	280
Jan-18	Pay-as-Bid	Quantity, 18,000 kg	Speedometer	£2.50, publicly known	Revise existing bid	280
Jun-18	Pay-as-Bid	Quantity, 18,000 kg	Speedometer	£2.50, publicly known	Revise existing bid	280
Feb-19	Uniform price	Budget, £40,000	Dot	£2.00, publicly known	Delete & resubmit	280
Jun-19	Uniform price	Budget, £38,000	Dot	£2.00, publicly known	Delete & resubmit	280
Apr-20	Uniform price	Budget, £65,000	Dot	£1.60, publicly known	Delete & resubmit	318
Jun-20	Uniform price	Budget, £42,000	Dot	£1.40, publicly known	Delete & resubmit	318

3. Institutional setting

We leverage an exogenous change in pricing rule for one of EnTrade's PES auctions, in the Poole Harbour catchment, to better understand the ability of UP rules to deliver value for money.

The EnTrade schemes are typical agri-environment PES programmes, conducted in a small and relatively tight-knit community (farmers within specific catchments) in which bidders tend to be relatively small-scale operations whose main business focus is *not* the provision of ecosystem services. The schemes pay successful farmers for privately costly actions (planting cover crops on land that would otherwise have been bare over winter, requiring labour, machinery, and seed inputs)[8] which deliver ecosystem service benefits – reducing nitrogen run-off by converting highly-leachable inorganic nitrogen to organic nitrogen. Each individual has the option to supply multiple units, potentially planting cover crops on multiple fields. EnTrade auctions act as a mechanism of price discovery, allocating contracts and determining payments.

EnTrade's auctions are conducted through their online platform. Eligibility is defined at the field level. Individual fields must be located sufficiently close to the water body such that planting cover crops delivers water quality improvements within five years. Interested farmers propose planting a particular cover crop, by a particular date, on any (specified) eligible field, and state the amount they would like to receive (as a per hectare payment) for doing so, and can bid differently across fields.[9] EnTrade then use a hydrological model to translate actions into predicted reductions in nitrogen leaching ("saved nitrogen"). Bids are evaluated on the basis of cost per kg of this anticipated saved nitrogen, accepting cheaper bids first until some target is reached.

The auctions operated with a semi-open bid format with continuous feedback regarding whether a bid was provisionally accepted. Upon submitting a bid an individual farmer got instantaneous feedback on whether their bid would be funded if the auction ended at that moment.[10] Farmers were also notified via email if the provisional success status of their bid changed as the auction progressed. For the duration of the auction (i.e. during the bidding window) farmers could update their bids as frequently as they liked, or withdraw a bid altogether. To reiterate, while this is unusual compared to auctions in other economic settings, it is commonplace in PES auctions (Banerjee et al., 2015).

Bids which were successful at the end of the auction were allocated contracts. The payments made to farmers were dictated by the auction's pricing rule, as is described for each auction in the following subsections. Compliance was ascertained through spot-checks and verification via geo-tagged images and a mobile phone application. Funding was only released once projects had been verified, and compliance rates were generally very high.

3.1. The poole harbour auction

The first dataset comes from the Poole Harbour catchment, which is situated on the south coast of the UK (see Fig. 1(a)). Following a 2013 report, Wessex Water were required by regulators (The Environment Agency and Natural England) to reduce the levels of ambient nitrate. Rather than upgrade the relevant water treatment works (at a cost of £9.7 million; Ong and Cuttle, 2021), Wessex Water invited EnTrade to implement an agri-environment auction for cover crops.

The Poole Harbour auctions started in June 2016, and from 2017 there have been two auctions each year – one in the spring and the second in the summer, offering contracts for the following winter.[11] The eligible fields were limited to those within the green area in Fig. 1(b) and as such 280 farmers[12] (in 2020, 318) who were expected to have field(s) that may be eligible for funding could

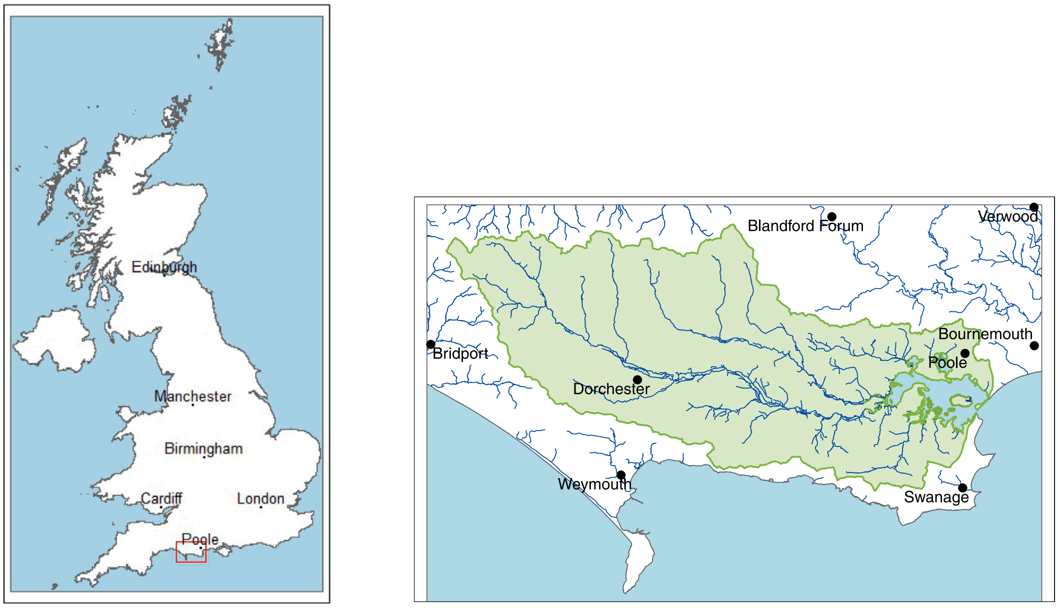
[8] Additionality is therefore not a concern in this setting. That is in contrast to some other PES settings (e.g. avoided deforestation) where for some level of service delivery marginal benefits outweigh marginal costs, and hence some service is provided absent payments.

[9] Some farm businesses are operated by more than one individual, and which individual bids may vary between years. Throughout the paper, we concern ourselves only with how the bidder (i.e. farm businesses) behave, not with the behaviour of specific individuals within a business.

[10] Farmers did not know the precise supply decisions of other farmers, only their own bid(s).

[11] Any proposal that was successful in the spring auction was then unable to be put forward in the summer. However, eligibility was not predicated upon, nor fields ruled out by, success in previous years. Thus, a field funded by the spring 2017 auction was not eligible for the summer 2017 auction but could be entered in the spring 2018 auction (and if unsuccessful there, could be entered into the summer 2018 auction).

[12] Of these, some are expected to be livestock farmers for whom cover crops are unsuitable, and others are likely to grow winter wheat which would again rule them out for funding.



(a) Position of the Poole Harbour catchment within the UK

(b) Map of the Poole Harbour catchment

Fig. 1. Maps showing the position of the Poole Harbour Catchment.
Notes: Poole Harbour catchment is on the south coast of the UK (Fig. 1(a)). The catchment (highlighted in green in Fig. 1(b)) drains east into Poole Harbour. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

enter a bid in the auction. There is evidence that the initial auction in 2016 had very different outcomes to subsequent auctions, and so this auction is typically dropped from analyses.

The pricing rule implemented in Poole Harbour was PaB for the auctions in 2016–18, and then UP for the auctions from 2019 onwards. Under PaB pricing, all successful bids were paid the amount specified in the bid. Under the UP all successful bids were paid the amount in the marginally successful bid in £ per kg saved nitrogen. The timing of the switch in pricing rule was exogenous with respect to market conditions and the goods which could be exchanged.

Other specific arrangements around the auction changed between years, some of which were coincident with the change in the pricing rule. These are detailed in Table 1. The most pressing changes relate to the reserve price and constraint that was applied. The introduction of a reserve price, and then its lowering, likely resulted in the highest bids being censored. However, it is never binding in determining payments, and therefore any effect can only be through anchoring (e.g. Ferraro et al., 2022). Moreover, our longitudinal fixed effects estimates, show that our core results are robust to excluding bids from 2017 and 2018 above the £2.00 reserve used in 2019, and excluding all bids from 2020.[13] It seems unlikely that the reserve price could be driving the large effects we observe. A second change involved a shift from a quantity constraint measured in kilos (18,000 kg) to a budget constraint measured in pounds (£40,000), which was always communicated to bidders. This switch actually serves to make the auction *less* competitive. So, unless a budget constraint is somehow more easily understood by bidders, and this makes them perceive the auction as more competitive, bids and payments would all else equal be *higher*. In the Monte Carlo analysis of payments we make the conservative assumption that bids are unaffected by the constraint change and apply the original quantity constraint.

Other minor changes include the exact way in which information was fed back (see Fig. 2), and the method for bid updating was also altered. However, a bidder still has the option, and necessary information, to update their bid as they wish. The exact length of the bidding window varied between ten days and three weeks.

As we go on to describe, these changes broadly did not occur in the control catchment, the one exception being the switch from a linear dial to a speedometer for feedback. The estimates we derive should therefore be interpreted as the cumulative impact of these changes, which we argue are likely driven by the switch in pricing. Moreover, theory suggests that the availability of instantaneous feedback and unlimited updating should result in similar outcomes under both pricing rules. In the PaB auction all bidders can discover the marginal bid, and bid at that amount subject to their costs. In the UP auction, where bids should better reflect costs, the marginal bid and overall payments remain unchanged. Hence if a treatment effect is found in this setting it is quite likely that it would extend to other PES contexts in which less feedback is offered or there is less scope for repeated bid updating.

[13] If anything, this results in a lower estimate of bids in PaB auctions than may actually be accurate. Bids which we exclude in the 2017 and 2018 auctions as they are above the £2.00 reserve imposed in later auctions may well have been submitted but at a price just below the (imagined) £2.00 reserve, if the farmer faced a cost of less than £2.00 for delivering the nitrogen reduction.

(a) “Linear dial” (b) “Speedometer” (c) “Dot”

Fig. 2. How bid feedback was offered in auctions.
Notes: In 2016 and 2017, farmers saw a linear dial (Fig. 2(a)), for 2018 the dial used was more like a speedometer (Fig. 2(b)), and in the treatment years, 2019 and 2020, farmers only saw if their bid was provisionally successful, not where their bid was placed in the distribution (Fig. 2(c)).

Table 2
Details of how control catchment auctions were run.

Pricing rule	Constraint	Information feedback	Maximum bid (per kg of N)	Updating process	# potential farmers
Pay-as-Bid	Fixed quantity throughout	Linear dial in 2017, speedometer 2018 onward	Constant through all auctions, redacted owing to commercial sensitivity	Revise existing bid	Fixed throughout

3.2. *The control catchment auction*

The EnTrade-operated auctions in the control catchment ran contemporaneously with the Poole Harbour auctions, but in another catchment elsewhere in England. Funding came from a different water company, but was again driven by a desire to lower the costs of complying with a regulatory obligation to reduce nitrogen run-off. These auctions ran once per year from 2017 onward, and throughout maintained PaB pricing. Since the identity of this catchment is commercially-sensitive, we refer to it as the “control catchment” as it acts as the control in our DiD framework.

Beyond the pricing rule, the auction processes in the control catchment were extremely similar to that implemented in Poole Harbour before the switch to UP pricing. The details are summarised in Table 2. As in Poole Harbour, contracts were awarded for cover-crop planting on otherwise bare land near the water course. There was a reserve price which was the same in all four auctions in the control catchment, but different to that used in any Poole Harbour auction.[14] Feedback was offered through the linear dial in 2017, and then through the speedometer in 2018–2020 (i.e. there was no switch in the control catchment to the feedback dot). The control catchment auctions operated with a fixed quantity constraint in all auctions.

The processes implemented within auctions, and a range of intermediate outcomes, were extremely similar in both catchments before the switch in pricing rule in Poole Harbour. Indeed, as is highlighted in Appendix Figure A1, while the auctions in the control catchment tend to involve fewer farmers (Appendix Figure A1a), they are otherwise extremely comparable to Poole Harbour auctions. The distribution of: bids submitted by each farmer (Appendix Figure A1b); each cover crop included in bids (Appendix Figure A1c); and nitrogen savings offered by each bid (Appendix Figure A1d); all appear very similar.

4. Hypotheses

There is theory on multi-unit auctions (e.g. Ausubel et al., 2014; Pycia and Woodward, 2021), however, this is unfortunately not directly applicable to the PES setting with bid updating. Nonetheless, pricing rules shape bidder incentives, and these different incentives inform our expectations. To reiterate, under PaB pricing an individual’s best bidding strategy is to shade up their bid, overstating their costs on all of their items (fields) and particularly on their lower cost units. In contrast, in a UP auction bidders are expected to bid at cost on their low-cost units. With multiple units, bidders can exert market power, overstating their costs on higher cost items in an attempt to increase the marginal bid, and hence increase the profits they accrue on their lower cost items.[15] Of course, as the number of bidders increases, this incentive decreases because the probability that a particular bidder determines the price (marginal bid) declines. As bidders shade up across all units in PaB auctions, rather than just the highest cost units under UP pricing, our expectation is that:

Hypothesis 1. Bids are lower in UP than in PaB auctions

For policy-makers, the key outcome is value-for-money. The marginal cost of accepting a bid in the UP auction is not the amount specified in the bid (as it is in the PaB auction), but rather the extra cost of paying that bid amount to *all* would-be accepted bids. Therefore, even if UP bids are lower, it is unclear whether mean *payments* are higher or lower in the UP or PaB auctions, and we explore if:

[14] The commercial sensitivity of the reserve price prevents us from disclosing the value.

[15] Note, there is no rationing of successful bids at the margin in these auctions, and hence the point raised by Kastl (2011) – that bidders may actually be incentivised to *overstate* their supply at prices they think could be marginal does not apply.

Hypothesis 2. Payments change under PaB and UP pricing

As PES auctions aim to maintain value-for-money over many auction iterations, we examine the impact of the switch in pricing rule on the participation costs that bidders face. We cannot directly ascertain how the pricing rule affects participation costs, but rather seek to understand two proxies for the cost of bidding: updating and sniping. Updating bids is costly owing to the time it takes farmers to formulate a revised offer. Farmers manage complex business operations, and therefore face a high opportunity cost of time. The prevalence of sniping would hint at further participation costs as farmers must be active at a specific period in the auction.[16] Moreover, sniping is part of a sophisticated bidding strategy, and suggests bidders must have engaged in complex reasoning; again, this is costly. Finally, sniping is likely to result in provisionally-winning bids being relegated, not because they are high-cost, but rather because the provisionally-successful bidder was not active during the last moments of the bidding window. This likely causes auction efficiency to suffer[17] and may frustrate individuals who get displaced late on.

The different pricing rules impact the incentive farmers face to engage in these costly participation strategies. Under PaB pricing, achieving the optimal degree of shading relative to other bids promotes updating and sniping. Indeed, our expectation is that:

Hypothesis 3. Bids are updated less frequently in the UP auction

And that:

Hypothesis 4. A lower proportion of bidding activity (bid submission and bid updating) occurs in the last 24 h of a UP auction compared to a PaB auction

Note, the switch to the UP pricing rule coincided with more bids being accepted in part because mean payments were lower, and so fewer submitted bids were rejected. Lower rejection rates decrease the need for bidders to update bids. Similarly, there were small changes to the user interface for bid updating concurrent with the switch in pricing rule, making updating slightly more time-consuming. We are not able to identify whether these mechanisms, or the incentive to simply report one's true cost in UP auctions, underlie changes in updating and sniping frequencies. Rather, we estimate the combined effect of UP pricing and concurrent changes on these problematic bidding behaviours.

5. Empirical strategy

The data provided to us by EnTrade is exceptionally rich, including details on: level of bid; type of cover crop; time and date of bidding; bid revisions; anonymised identity of the bidder; and anonymised identity of the field parcel. Accordingly, we can track individual bidders and fields through and across auctions. We exploit this fine-grain detail in order to understand bidding patterns and timings, while controlling for pseudo-replication between observations in the regression specifications.

Our analyses focus on two different datasets from each auction series. The first is the level of each final standing bid. In all cases, these bids are expressed in £2016 per kg of saved nitrogen.[18] The second concerns the history of all bid submissions and updates through each auction. Throughout, we identify the average treatment effect on the treated, conditional upon participation.

5.1. Identifying the effect upon bids

To present our empirical strategy, we make use of the following notation. Individual farmers are indexed $i = 1, 2, \ldots, n$, and each farmer has J_i fields indexed $j = 1, 2, \ldots, J_i$. In an individual auction, t, a farmer makes a decision regarding whether to enter a specific field which we denote by d_{ijt}, and which takes a value 1 if field j of farmer i is entered into auction t, and 0 otherwise.

To assess Hypothesis 1 we employ a DiD strategy using a two-way fixed effects (TWFE) estimator, with the data from both Poole Harbour and the control catchment for years 2017–2020. While there have been many recent advances in DiD estimators, TWFE recovers the average treatment effect on the treated when particular assumptions hold. Specifically, there are relatively many clusters; outcomes for treated and control units follow parallel trends before treatment; treatment is binary, non-reversible and occurs at the same time for all treated units; and there is no anticipation of treatment; all of which hold in this case (Rico-Straffon et al., 2023; Roth et al., 2023).[19] A fully-flexible model for such estimation is:

$$\begin{aligned} Bid_{ijt}|(d_{ijt}=1) = \beta_0 + \beta_1 Year_t + \beta_2 Catchment_t + \beta_3 Year_t \times Catchment_t + \\ \beta_4 After\ intervention_t + \beta_5 After\ intervention_t \times Year\ minus\ year\ of\ intervention_t + \\ \beta_6 After\ intervention_t \times Catchment_t + \\ \beta_7 After\ intervention_t \times Year\ minus\ year\ of\ intervention_t \times Catchment_t + \epsilon_{ijt} \end{aligned} \tag{1}$$

[16] Without sniping, one may expect farmers to bid at the time which costs them the least. High degrees of sniping would require more bidding in a constrained window, which chance alone dictates is unlikely to be coincident with when a farmer faces their lowest opportunity cost.

[17] We do not attempt to recover the underlying cost distribution and therefore cannot directly speak to the relative efficiency of auctions, however, sniping is consistent with inefficiency.

[18] We adjust for inflation in bids in later auctions using estimates for yearly inflation as measured by the Office for National Statistics' CPI series "CPI INDEX 00: ALL ITEMS 2015=100" time series data, with code "D7BT", within the "Consumer price inflation time series (MM23)" dataset. The estimates used in this paper were released on 20th January 2021, and are downloadable from https://www.ons.gov.uk/economy/inflationandpriceindices/datasets/consumerpriceindices.

[19] The interested reader is directed to recent reviews by de Chaisemartin and D'Haultfœuille (2022a), Roth et al. (2023) examining recent proposals for estimators which are robust to independently relaxing these assumptions, including those proposed by Cameron et al. (2008), de Chaisemartin and D'Haultfœuille (2020), Callaway and Sant'Anna (2021), Canay et al. (2021), Sun and Abraham (2021), de Chaisemartin and D'Haultfœuille (2022), de Chaisemartin and D'Haultfoeuille (2022c).

Farmer i's bid for field j in auction t, conditional upon their participation (denoted $Bid_{ijt}|(d_{ijt} = 1)$), is estimated as being a function of: the year that a particular auction takes place ($Year_t$); an indicator variable for the catchment ($Catchment_t$, 1 = Poole Harbour); an indicator variable for the pricing rule employed in the Poole Harbour auctions that year ($After\ intervention_t$, 1 = UP); and a continuous variable reflecting the number of years between the auction and intervention in Poole Harbour ($Year\ minus\ year\ of\ intervention_t$ regardless of which catchment the auction is in, this takes a value of 0 for auctions conducted before intervention).

As is the case in implementing all regressions regarding bids (Eqs. (1), (2), and (3)), ϵ_{ijt} is estimated using cluster robust standard errors, clustering at the farmer level. Standard errors are clustered at the farmer level as this is the level at which we anticipate errors to be correlated.[20]

In this set-up, the estimate of β_3 assesses any divergence from parallel trends in the pre-intervention period. β_6 captures any step-change in bids as a result of the pricing rule change. β_7 is the effect of UP pricing on changing the trend of bids after intervention. Given the relatively few repeat observations we have for each catchment, we also parameterise models which impose assumptions on the data generating process by removing particular terms in the regression equation (e.g. assuming that the difference in trends after intervention is the same in both catchments, and removing the term associated with β_7). If one is prepared to accept these additional assumptions, we can more precisely estimate the effect of the pricing rule change on bids.

We run robustness checks using only the Poole Harbour data. These explore whether the effect is being driven by the costs of cover crop planting not accounted for by inflation nor by comparison to the control catchment; or changes in the reserve price. To this end, we run regressions of the form:

$$Bid_{ijt}|(d_{ijt} = 1) = \beta_0 + \beta_1 Pricing\ rule_t + \beta_2 Cost\ controls_t + \beta_3 Year_t + \epsilon_{ijt} \tag{2}$$

Where: $Pricing rule_t$ is an indicator variable for the pricing rule used in that auction (1 = UP); $Cost controls_t$ is an index relative to 2016 for the estimated cost of cover crop seed and machinery inputs at the time of the auction;[21] and $Year_t$ is defined as before. To ascertain the impact of the reserve price changes, this regression is initially parameterised using all bids entered into the auctions in 2017–2020, then with excluding bids in 2017 and 2018 above the £2.00 reserve price used in 2019, and finally additionally excluding bids in 2020 auctions with their lower reserves. The costs control variable must be dropped from the regression in which data from 2020 is excluded owing to multi-collinearity.

Given we find UP pricing lowers bids, we investigate which mechanisms mediate this effect. At least four avenues are possible: (1) different farmers choose to enter the PaB and UP auctions; (2) the same farmers participate but choose to enter different fields; (3) the same farmers enter the same fields but choose to use different technologies (cover crops); or (4) the farmers respond to the incentives they face and reduce the shading included in bids. These possible mechanisms are explored through longitudinal fixed effects estimates for the Poole Harbour bidding data. These regressions take the form:

$$\begin{aligned} Bid_{ijt}|(d_{ijt} = 1) = \beta_0 + \beta_1 Pricing\ rule_t + \beta_2 Cost\ controls_t + \beta_3 Year_t + \\ \beta_4 Proposed\ mechanism_{ijt} + \epsilon_{ijt} \end{aligned} \tag{3}$$

In addition to the variables defined for Eq. (2), $Proposed\ mechanism_{ijt}$ is a variable which accounts for either the farmer, the field, or the cover crop that is entered into a particular auction.

5.2. Identifying the effect upon payments

We next turn to identify the impact of pricing rule on payments (Hypothesis 2). Our approach to identifying the effect on payments differs from that on bids, because the payments received by different bids in the same auction are not independent. Rather, payments are calculated by the application of the pricing rule to all bids within the auction, so each bid's payment is a function of all other bids in that auction. Therefore, we explore the impact of pricing rule on payments through a Monte Carlo simulation using data from Poole Harbour from 2017–2020. In brief, we view the observed participation and bidding decision of each farmer as being a random draw from their possible responses to a particular pricing rule. We randomly draw one realisation of a farmer's PaB behaviour and one realisation of their UP behaviour, and construct a pair of simulated auctions by repeating the draw for each of the 39 farmers that ever participated in 2017–2020. First we consider the extensive margin. If a given farmer chose not to participate in the randomly selected auction, then no bids are entered. If they did participate, we next consider the intensive margin, entering all bids that they made in that randomly selected auction. We then apply a target constraint of 18,000 kg, and PaB pricing to the simulated PaB auction, and UP pricing to the simulated UP auction.[22] For each auction, we calculate the mean payment (in £2016), and for the pair of auctions the difference between mean payments. We repeat that 1000 times to build up a Monte Carlo sample of the range of possible auction outcomes compatible with our observed data. The parameter of interest is

[20] Recent work (see Roth et al., 2023 for a review) has suggested that the most conservative approach is clustering at the level of independent assignment to treatment. Unfortunately, that is not possible with the data that we have. Alternative methods exist for estimating standard errors, yet these require imposing strong additional assumptions.

[21] The data that underpin these estimates come from the "John Nix Pocketbook for Farm Management", which is the authority on the price of agricultural inputs in the UK. We thank Graham Redman, the pocketbook author, for his assistance in preparing these estimates.

[22] As with the real-world auctions, the UP is set as the marginally winning bid and we do not ration bids in either pricing rule. Most auctions purchase slightly more than, rather than exactly, 18,000kgs. Some auctions, by chance, purchase less than the full target (of the 2000 Monte Carlo iterations, there are 22 such auctions in the PaB, and 4 in the UP), yet this does not systematically bias the observed distribution of mean payments.

Table 3
Summary statistics of auction outcomes.

Auction	Mean bid (std. dev.) (£/kg N)	No. farmers	No. bids	% Bids successful	N bought (1000s kgs)	% Non compliant
			Pay as Bid			
Jun-16	1.93 (1.00)	17	126	77.0	34.5	2.1
Jan-17	1.65 (0.51)	13	117	40.2	19.2	10.6
Jun-17	1.90 (0.41)	17	111	68.5	31.3	2.6
Jan-18	2.07 (0.25)	11	69	55.1	16.1	5.3
Jun-18	1.71 (0.37)	14	101	63.4	18.6	0.0
			Uniform price			
Feb-19	1.14 (0.28)	12	126	83.3	31.8	3.8
Jun-19	0.81 (0.23)	16	63	98.4	32.2	9.7
Apr-20	1.09 (0.30)	19	171	80.7	48.9	3.6
Jun-20	1.02 (0.22)	16	103	94.2	33.9	5.2

then the median difference in mean payments, and the empirical 95% confidence interval around this (taken as the values at the 2.5 and 97.5 percentiles). We also calculate an exact p-value as the percentile where the difference in mean payments under the two pricing rules is approximately 0.

5.3. Identifying the effect upon costly bidding behaviours

To assess Hypothesis 3 regarding updating, we model the probability that any given action (bid submission or update) is an update conditional upon participation ($P(update|action)_{ijt}|(d_{ijt}=1)$) as a function of the pricing rule in the auction, and a continuous variable for the year that auction takes place, with data from Poole Harbour. Hence:

$$P(update|action)_{ijt}|(d_{ijt}=1) = \beta_0 + \beta_1 Pricing\ rule_t + \beta_2 Year_t + \epsilon_{ijt} \tag{4}$$

As such, β_1 can be understood as the estimated impact of the change in pricing rule on the probability that a randomly selected action is an update (rather than bid submission).[23]

The effect of the pricing rule on sniping is estimated similarly, to provide insight on Hypothesis 4. We define "sniping" as any action (either an initial submission or an update) which occurs in the last 24 h of an auction window. We model the probability that a given action is sniping conditional on participation ($P(snipe|action)_{ijt}|(d_{ijt}=1)$) as a function of the pricing rule used, and a continuous variable for the year that auction takes place, again for Poole Harbour auctions:

$$P(snipe|action)_{ijt}|(d_{ijt}=1) = \beta_0 + \beta_1 Pricing\ rule_t + \beta_2 Year_t + \epsilon_{ijt} \tag{5}$$

Similar to Eq. (4), the estimate of β_1 is the impact of the change in pricing rule on the probability that an individual action is sniping.

In Eqs. (4) and (5) we cluster the standard error at the level of a unique bid; that is, a bid which is made on a particular field in a particular auction, and may then be updated through the auction. We run these analyses with and without 2016 data to mitigate against any effect being driven by learning (over and above any learning effect that occurs through time more generally). To reiterate, we identify the total effect of auction changes on bid updating and sniping.

6. Results

6.1. Auction summary statistics

We first consider overall auction outcomes in Poole Harbour. As is clear in Table 3, while the auctions are always open to numerous bidders, in each auction relatively few tend to bid. The apparent increase in 2020 bidders is in part due to the fact that across the two auctions, six newly-eligible bidders participate. Moreover, we also see relatively high turnover in bidders between auctions. Across all auctions, 40 different bidders ever participate, despite the maximum in any one auction of 19.[24] We conjecture these patterns are because the net benefit of winning a contract to a particular bidder changes through time and is idiosyncratic with respect to other bidders. Nonetheless, it is indicative of participation being costly, else the (potentially slim) positive probability of winning a profitable contract would ensure all bidders bid in every auction.

Table 3 also highlights two further aspects which are noteworthy. First, the percentage of bids which are successful varies somewhat. Generally around two-thirds of bids are accepted in the PaB auctions (except in January 2017 when 40% of bids are successful). For the UP auctions, this figure is considerably higher, with more than four-fifths of bids successful in all UP auctions,

[23] Our estimate does not distinguish between the first update to a bid and subsequent updates. As such, an auction with two bid submissions and two updates would result in the same estimates regardless of whether those two updates are twice to the same bid, or once to each bid.

[24] Compared to the 39 farmers used in the Monte Carlo exercise, there is one additional farmer who only participated in 2016.

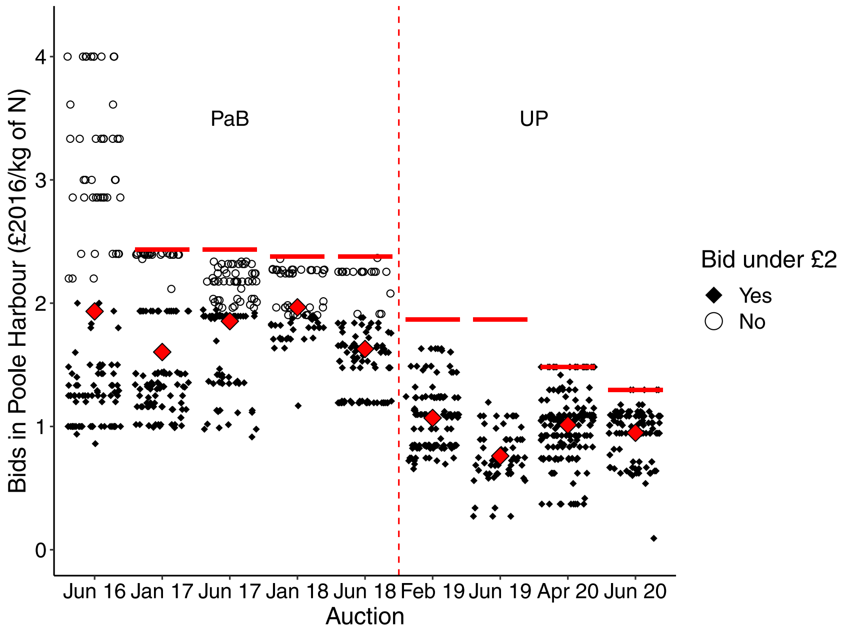


Fig. 3. Final bids in each auction.
Notes: To the left of the red dashed line auctions operate as PaB; to the right as UP. Red diamonds represent mean bids each year, horizontal red lines show reserve prices (£2016). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and just a 1.6% rejection rate in June 2019. Second, and potentially partially responsible for the increase in the rate of bid success, is the increase in the quantity of nitrogen removal which is bought in UP (~30,000kgs) compared to PaB auctions (~18,000 kg).[25] This itself is somewhat driven by the budget in UP auctions being more than was actually required to meet the 18,000 kg target; in part owing to the lower mean payments we go on to find result from the switch in pricing rule.

6.2. Effects on bids

The bids that are placed for each field are displayed in Fig. 3, with the bid amount in 2016 prices on the vertical axis, and the series of auctions segregated across the horizontal axis. Each point represents a distinct field–auction combination, and are hollow if the bid – not adjusting for inflation – was above £2.00 (the reserve price that was implemented for the 2019 UP auctions). Red diamonds display the mean bid for each auction. The red dashed vertical line separates the PaB auctions (to the left) from the UP auctions, while the solid horizontal lines show the reserve prices (again, £2016), where appropriate.

Multiple patterns are clear. First, in all auctions there is a range of bid amounts. This is somewhat surprising given that in all auctions bidders received feedback about the status of their bid and could update it accordingly. With that information, one might have expected that the range of bids in PaB auctions narrowed as participants adjust their bids towards the marginally-winning bid.[26] The range of bids is greatest in 2016, while in later auctions this range narrows considerably, driven by the highest bids being considerably lower. This is likely caused by a combination of bidders learning that extremely high bids are unsuccessful, but still incur participation costs to submit them; and by the auctioneer introducing reserve prices in auctions from 2017 onward. It is worth highlighting that while the reserve prices may influence the highest observed bids, the maximum bids in 2019 following the switch in pricing rule are well below the reserve price, so clearly this alone does not fully explain the observed changes in the highest bids.

A further pattern across all auctions is the presence of bids clustered at the same level and showing clearly defined horizontal "lines" of bids in Fig. 3. Rather than reflecting that bids are submitted at the marginally-accepted price at the time of submission, these lines reflect individual farmers submitting multiple fields at the same price or multiple farmers settling on focal amounts (e.g. £1.00/kg of N). This is despite the fact that farmers actually submit bids as £/ha of activity, albeit being informed as to what

[25] There are two exceptions amongst the PaB auctions. In 2016 there was only one auction, therefore the June 2016 auction attempted to purchase close to two auctions' worth of nitrogen. In June 2017 a third party buyer also wanted additional nitrogen removal, which was purchased through this auction, hence the larger quantity then. April 2020's higher budget (and resulting extra saved nitrogen) reflects the start of the new Asset Management Plan period within the UK water industry, in which Wessex Water was required to deliver additional nitrogen reductions.

[26] A more nuanced prediction is the bids which win collapse to the marginally winning bid, with higher bids simply representing farmers with higher costs whose bids are rejected, but for whom there is no incentive to reduce their bid. Yet clearly this too is not borne out, given the wide range in bids which *are* successful.

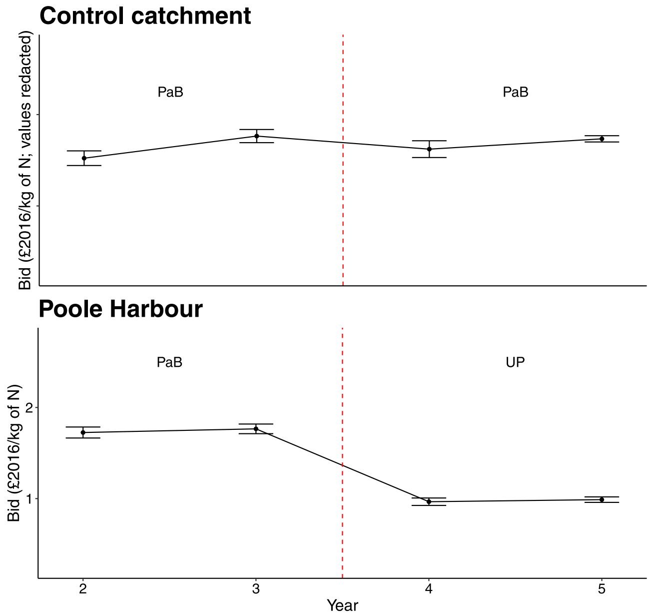


Fig. 4. Bidding trends in the Poole Harbour and control catchment auctions.
Notes: Points display the mean bids in a given catchment for a particular year (for Poole Harbour these are averaged across the two auctions in each year). Error bars are calculated as $mean \pm 1.96 \times std.err$. For the control catchment data, the vertical axis labels have been removed so as to ensure commercially sensitive data about the bids in that catchment remain confidential. While the scale remains the same, the axis ticks do not correspond to the same bid amounts. The vertical red dashed line represents when the switch in the Poole Harbour pricing rule occurred – to the left PaB, to the right UP; the control catchment used PaB throughout. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

that translates to as a £/kg bid. Hence, it seems farmers are formulating beliefs about what bid amount may be accepted as a £/kg price.

Turning to consider Hypothesis 1, Fig. 3 identifies a noticeable step-down in bids moving from PaB to UP pricing for the Poole Harbour auction, a finding consistent with the incentives bidders face. That same pattern is also illustrated in the bottom panel of Fig. 4 where the two auctions in each year (excluding the 2016 auction) have been aggregated to give a mean bid in each year. That presentation allows comparison with bidding patterns in the control catchment that is shown in the top panel. Note that to maintain confidentiality of commercially-sensitive information, the labels of the vertical axis for the control catchment have been removed. While the scale remains the same as for the Poole Harbour plot, the axis ticks correspond to different bid amounts. The figure suggests that in the two years for which there are PaB auctions in both catchments, the average change in bids was comparable – both increasing slightly from 2017 to 2018. Upon switching to the UP pricing rule, bids in the Poole Harbour catchment sharply decline, while those in the control catchment remain comparable to previous years. Table 4 reports estimates from the DiD regression (Eq. (1)), progressively relaxing assumptions about what changes between catchments (in columns (1) to (5), respectively). Note that where specific parameters could be used to back-calculate commercially-sensitive information regarding bids in the control catchment, we report only absolute t-values (middle panel). As suggested in Fig. 4, results of the regression analysis using Eq. (1) show non-significant differences in bids across the two catchments before intervention (β_2; absolute t-value = 0.91, $p = 0.37$), and, more critically, no significant difference in pre-intervention time trends (β_3; absolute t-value = 1.19, $p = 0.237$). These results, the similar auction processes (Tables 1 and 2), and the similarities in intermediate outcomes across catchments prior to intervention in Poole Harbour (Appendix Figure A1), lend support to the assumption of parallel trends in the post-treatment period absent our intervention.

Formally exploring the impact of pricing rule on bids, Column (1) of Table 4 reports the results from a minimal specification, in which we seek only to identify the mean change in bids in Poole Harbour before and after intervention while controlling for any difference between catchments and any universal shift in bids in both catchments after the Poole Harbour intervention. The regressions reported in Columns (2) to (5) progressively relax assumptions about underlying time trends in Poole Harbour and control catchment bids, as well as allowing the switch in pricing rule to affect these trends. These results show clear evidence of a highly significant and substantial reduction in mean bids. We are hesitant to over-interpret any one estimated parameter alone, given we only have two years' worth of data before and after intervention in each catchment. Nonetheless, in all specifications, the clear result is that bids are substantially reduced, and this is largely significant to $p < 0.01$ and always significant to at least $p < 0.1$. UP pricing reduced bids between 29.2% and 44.9% relative to the mean bid in 2017–2018 auctions using PaB pricing (£1.78 in £2016). Given that some shading above cost may well remain in UP bids, one can view this as a lower bound estimate of the mean degree of shading reported in PaB auction bids. Overall, our analysis provides strong evidence to support the contention that changing the pricing rule in the Poole Harbour auctions substantially reduced bids.

Table 4
The effect of pricing rule on bids in Poole Harbour in 2016 prices (£/kg of N).

	(1)	(2)	(3)	(4)	(5)
	Effect size (std. err.)				
After intervention × Catchment (Poole Harbour = 1)	−0.764*** (0.104)	−0.783*** (0.096)	−0.510* (0.296)	−0.783*** (0.096)	−0.567* (0.316)
After intervention × Year minus year of intervention × Catchment (Poole Harbour = 1)	–	–	–	–	0.112 (0.192)
	Absolute t-values				
Year	–	0.79	1.72*	0.63	2.86***
Catchment	9.53***	9.73***	1.55	9.69***	0.91
Year × Catchment	–	–	1.13	–	1.19
After intervention	0.02	0.61	1.26	0.56	0.88
After intervention × Year minus year of intervention	–	–	–	0.28	1.15
Number of observations:	1027				
Number of clusters:	58				

Notes: The results reported in Columns (1) to (5) are parameterised using Eq. (1), gradually relaxing the assumptions over possible differences between catchments. In all cases standard errors are clustered at the farm level. The top panel reports effect sizes and the clustered standard errors in parentheses. The middle panel reports absolute t values to ensure that the bids in the control catchment cannot be deduced, and commercially sensitive information therefore remains confidential.
* p < 0.1, ** p < 0.05, *** p < 0.01.

Table 5
Robustness checks regarding the effect of pricing rule on bids in Poole Harbour in 2016 prices (£/kg of N).

	(1)	(2)	(3)
Pricing rule (Uniform price = 1)	−0.829*** (0.146)	−0.659*** (0.168)	−0.707** (0.292)
Cost controls:	Yes	Yes	No
Linear time trend:	Yes	Yes	Yes
Number of observations:	861	730	456
Number of clusters:	39	38	29

Notes: The results reported are parameterised using Eq. (2), using different sets of observations. Column (1) uses all bids 2017–2020; (2) excludes bids above £2.00; and (3) additionally excludes the data from 2020. Clustered standard errors in parentheses.
* p < 0.1, ** p < 0.05, *** p < 0.01

One may be concerned about stories which postulate that the estimated effect is driven by changes in the cost of planting cover crops which is not reflected in control catchment bids, or is the result of the changes in the reserve price used in Poole Harbour. We explore such issues in robustness checks, and focus exclusively on Poole Harbour data owing to the multi-collinearities present within a DiD framework. The longitudinal fixed effects estimates, presented in Table 5, all show statistically-significant and economically-meaningful reductions in bids. Moreover, these estimates are all of a similar magnitude to the DiD estimates. Taken together, the core finding of substantially and significantly lower bids, is robust to different econometric specifications and the inclusion of other potential drivers.

6.3. Possible mechanisms underlying changes in bids

Our analysis reveals that the switch to UP pricing precipitated an immediate and large decline in the bids placed in the Poole Harbour auctions. The question that remains is "why"? As discussed previously, one explanation might be the different incentive properties of the two pricing rules, leading to bidders reducing the degree of shading in their UP auction bids. However, there are rival explanations. First, different types of farmers may have different preferences over auction institutions. If that were true, then observed changes in bidding under UP could be explained simply as lower cost farmers preferring to enter UP auctions. Two further possible explanations are that the UP auction encourages farmers to submit bids on lower cost fields, or for lower cost cover crop species. Note that each of these explanations run counter to the assumption that agents are cost minimising in the PaB auctions.

We explore this question by dividing our data from the 2018 PaB auctions and 2019 UP auctions into three groups. Farmers who only bid in the PaB auctions, farmers who only bid in the UP auctions and farmers who bid in both the PaB and UP auctions. In these analyses the group bidding in both types of auction act as the comparator. If our alternative explanations are correct and the PaB auction attracts relatively higher cost bidders and the UP relatively lower cost bidders, then we would expect the bids of the PaB-only group to exceed those of the comparator and bids from the UP-only group to be less than those of the comparator.

Table 6
The effect of controlling for different potential mechanisms on the estimated impact of the switch in pricing rule on bids in Poole Harbour in 2016 prices (£/kg of N).

Mechanism controlled for:	(1) None	(2) Farmer participation	(3) Field selection	(4) Cover crop choice
Pricing rule	−0.829***	−0.775***	−0.810**	−0.835***
(Uniform price = 1)	(0.146)	(0.146)	(0.314)	(0.139)
Farmer FE:	No	Yes	No	No
Field FE:	No	No	Yes	No
Cover crop FE:	No	No	No	Yes
Cost controls:	Yes	Yes	Yes	Yes
Linear time trend:	Yes	Yes	Yes	Yes
Number of observations:	861			
Number of clusters:	39			

Notes: Data used is for the 2017–2020 auctions. Clustered standard errors in parentheses.
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

As shown in Appendix Tables A1a and A2 we see no significant evidence of that pattern (p-value > 0.2). We repeat that analysis but using field level data. Again we find no evidence to support the idea that higher cost fields are entered in the PaB auctions or that lower cost fields are entered in the UP auctions (Appendix Tables A1b and A2; p-value > 0.4). We conclude that the observed changes in bids arising on the switching of auction format are not driven by lower-cost farmers, or lower-cost fields, being more likely to participate in UP auctions.

Moreover, Table 6 reports regression results from Eq. (3) which examine possible mechanisms driving the observed impact of the pricing rule. In columns 2–4 we additionally include fixed effects to control for farmer participation, field selection and cover crop choice, respectively. By doing so we can ascertain the effect of UP pricing on bids *conditional* upon the three hypothesised mechanisms.[27] If any such mechanism were driving the impact of UP pricing, we would expect a substantial difference in the estimated treatment effect (our estimated β_1 coefficients) between the unconditioned regression (Column (1)) and the regressions which control for the purported mechanisms (any of Columns (2) to (4)). Instead, all estimates of the effect of the pricing rule change are extremely close to that reported in the baseline regression, not including any fixed effects for mechanism (Column 1). Indeed, using z-tests to compare the estimated β_1 coefficient for each model to that of the model which has no fixed effects for mechanism (Column 1), shows all p-values to be ≥ 0.75. Accordingly, the evidence points to the conclusion that bidders are simply reducing the degree of shading included within their bids, appropriately responding to the incentives of the UP pricing rule.

6.4. Changes in payments

While bids in UP auctions are lower, as highlighted in Hypothesis 2, it is ambiguous what effect this will have on value-for-money.

For each Poole Harbour auction, Fig. 5 displays the amount paid to each successful bid, and the mean payment for the auction, in £2016 per kg of nitrogen.[28] The impact of the pricing rule change is evident in the reduction in spread of payments with each successful bidder in the 2019 and 2020 UP auctions being paid the same amount. From Fig. 5 it is also clear that the mean amount paid in each auction varies and that payments made in the UP auction are generally lower than those made in the PaB auctions. Recall that any apparent effect of pricing rule in this analysis could be masked by the effect of the simultaneous changes in the auction constraint. We contend that those changes are unlikely to explain lower payments in the UP auction. Rather, their impact was likely to *increase* observed payments in those auctions. In particular, when UP pricing was introduced, the auctions also switched to being budget constrained which, combined with bids in the UP auction being so much lower, resulted in much greater quantities of saved nitrogen being bought. Purchasing from a larger proportion of the supply curve necessarily means buying higher cost nitrogen savings, hence resulting in a higher marginal price. If such impacts are prevalent, the reduction in payments observed in Fig. 5 would be substantially under-estimating how much UP pricing reduced payments relative to PaB.

Fig. 6 displays the mean payments for each of the 1000 Monte Carlo simulations for each pricing rule, which maintain the same constraint across auctions. Individual crosses show the mean payment (in 2016 prices) for each simulation, while the box plot shows the median and inter-quartile range across the simulations for each pricing rule, and the dots highlight outliers. The information is also summarised in Table 7, which displays median outcomes (and empirical 95% confidence intervals) of the simulations.

The results are striking. While there is overlap in the distribution of mean payments in individual simulations, it is evident from Fig. 6 that payments are generally higher in PaB auctions. Indeed, we find that the median of the mean payments across PaB simulations is £1.41, nearly 40% higher than in the UP auctions where the median is only £0.89. Moreover, the median difference in mean payments between pricing rules is £0.52. The empirically calculated 95% confidence intervals (£0.08–0.93) and the exact p-value (p=0.013) also reveal this to be highly significant. Hence the switch to uniform pricing led to a highly significant, and very substantial, increase in the value-for-money of the scheme.

[27] We are unable to control for all three mechanisms simultaneously in a regression owing to the co-linearities between them: e.g. a particular field is almost always owned by the same farmer throughout all auctions.

[28] These payments are equivalent to about £60–120/ha.

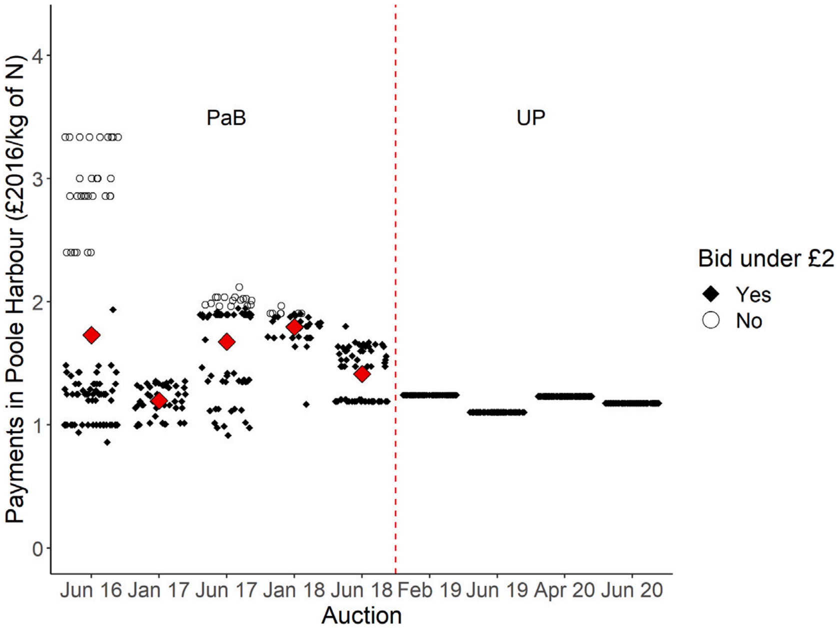


Fig. 5. Actual payments paid to successful bids.
Notes: To the left of the red dashed line auction operate as PaB; to the right as UP. The red diamond is the mean payment, included for the PaB auctions only as in the UP auctions all successful bids are paid the same amount. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

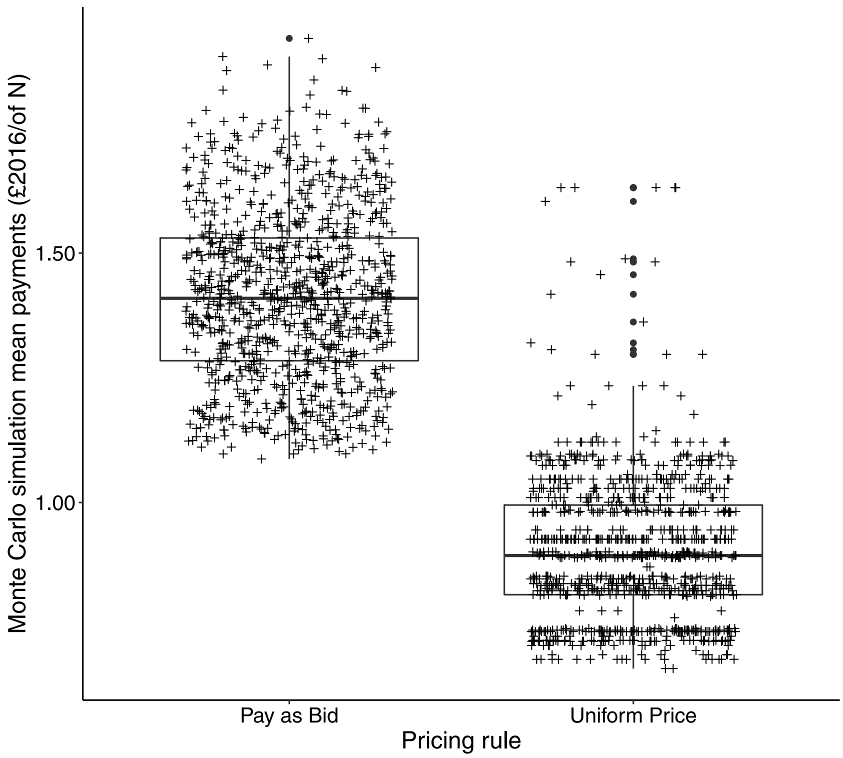


Fig. 6. Mean payments paid to successful bids in each of the Monte Carlo simulation auctions.
Notes: Each auction is represented by a cross, and the box plot summarises the distribution of these mean payments, showing the median and inter-quartile range.

Table 7
Median outcomes from the Monte Carlo simulations.

	Payments (£2016/kg N)	Number Farmers	Number bids
PaB	1.41	14	100
	(1.13–1.75)	(9–18)	(54–149)
UP	0.89	16	115.5
	(0.69–1.14)	(10–21)	(61–169)

Empirical 95% confidence intervals given in brackets.

One might be concerned that this apparent increase in value-for-money came at the expense of lower compliance rates. Yet as is made clear in the most right-hand column of Table 3, compliance rates are very high throughout all auctions, and do not systematically vary with the change in pricing rule. Moreover, as compliance was assessed before funds were released, non-compliant bids were simply not paid.

An interesting counterpoint to lower payments under UP pricing is that Poole Harbour farmers report to EnTrade a general preference for UP rather than PaB auctions (Thompson, 2021). Of course, this could be because of lower participation costs (as explored in Section 6.5). However, a further possibility concerns the perceived fairness of UP auctions.[29] To explore this, Appendix Figure A2 shows the frequency of different payments made to all fields entered in each auction (as £2016 per kg of nitrogen). It is clear that bidders in UP auctions are more likely to be successful, and there is no variation in payment rates within each UP auction. Accordingly, farmers may prefer the UP auctions because their bids are more likely to be accepted, and they perceive the payments as fairer.

6.5. Differences in participation costs

Our analyses examine the impact of the suite of changes on bidding behaviours which are assumed to be costly: bid updating and sniping. Not only does this represent a cost to participants in the short-term, over a longer horizon it could reduce participation rates and hence decrease the value-for-money offered to the funder. Fig. 7 presents bidding behaviour in each auction (separated along the vertical axis), with the horizontal axis capturing at what time point in the bidding window (expressed as a proportion of the bidding window) that action occurred. The type of action – bid submission or update – is indicated by hollow circles (submissions) rather than black diamonds (updates). Red vertical lines in each auction indicate when the last day of the bidding window starts; actions to the right of this line are regarded as sniping behaviours. The horizontal dashed red line indicates when the pricing rule changed; below are PaB, and above UP, auctions. The red circles and diamonds represent the mean proportion of the way through at which point a bid is submitted, and updated, respectively. The blue triangles are the mean proportion of the way through for any type of action.

Regarding Hypothesis 3 it seems instances of updating (black diamonds) are far more common in PaB auctions (below the red dashed line) than in UP auctions. This is corroborated in Appendix Figure A3 which shows the distribution of bids dependent on the number of updates by pricing rule (A3a) and auction (A3b). While updating a bid at all is rare in both auction formats, it seems that bids tend to be updated at all more frequently, and conditional on being updated at least once, are updated more often, in PaB auctions.

Actions are spread out over the whole bidding window in all auctions, however, there is clumping towards the right-hand side; highlighted, too, by the proximity of the red and blue points to the right. Across pricing rules, farmers are choosing to submit and update their bids relatively late into bidding windows. Nonetheless, and in line with Hypothesis 4, the density of all points right of the red vertical lines, seems higher in PaB than UP auctions. Moreover, the mean timing of activity (blue triangle) is shifted slightly left in UP than PaB auctions overall.

Formal statistical analysis, presented in Table 8, supports the conclusion that updating and sniping are more common in PaB than UP auctions. Conditional on an action occurring, in the PaB auction there is a nearly 60% chance this action is an update. In the UP auction it is less than 25%. Again, this is both significant, and economically meaningful. This result is underscored by a chi-squared test of the distributions displayed in Appendix Figure A3a which finds significant differences between them ($p<0.001$). Furthermore, the degree of sniping is much reduced. Conditional on an action occurring, the probability that it would fall in the last day for a PaB auction is roughly half; for the UP it is about a third. These results are also largely robust to excluding the data from the 2016 auction, as can be seen in Appendix Table A3. To reiterate, we are unable to distinguish whether it was the switch to the UP pricing rule – or the concurrent changes in the way bid updates occurred and the change in the constraint – which led to the reduction in sniping and updating. Nonetheless, these results are in line with our expectations regarding the impact of UP pricing on bidding behaviours.

One might interpret bid updating and sniping as a signal of active participation, and a decline in these measures as suggesting a decrease in bidder interest and engagement. Yet, we know that formulating revised bids is time consuming and therefore costly.

[29] It could also be to do with the concurrent switch in the constraint. With a target constraint, from the point of view of a farmer, lower bids necessarily displace other bids. With a budget constraint this is not the case – lower bids mean more bids are successful. Thus in a budget constrained auction, bids solely affect the distribution of payments, where in a target constrained one, they also affect total spend.

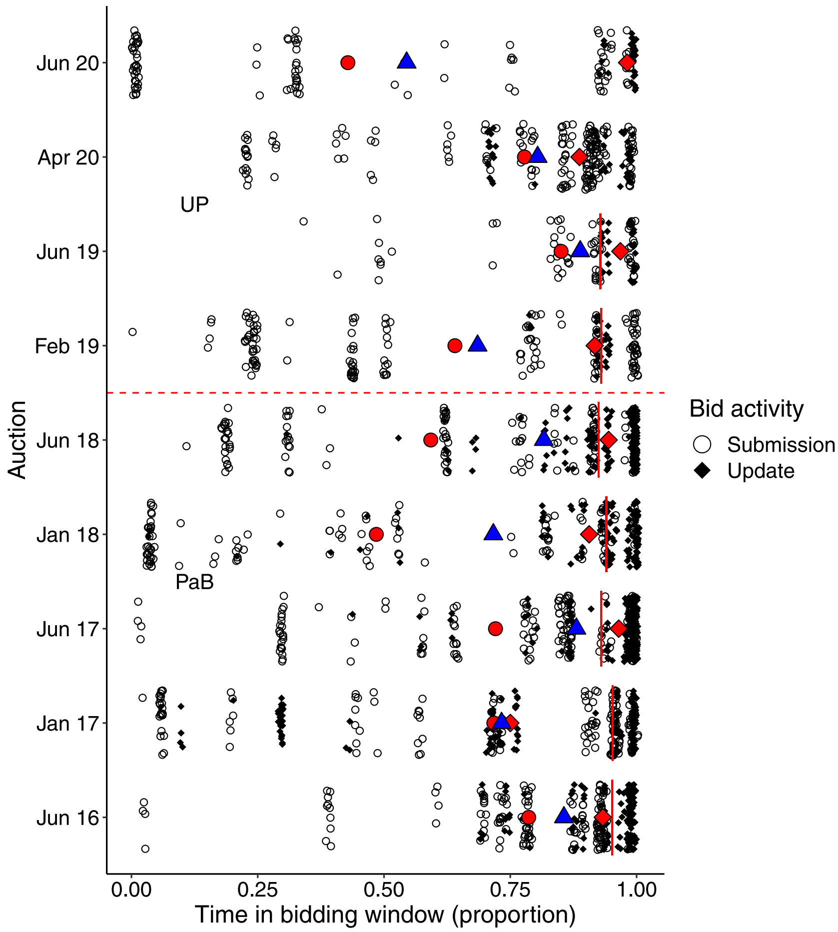


Fig. 7. Bidding behaviour in auctions: updating illustrated by solid diamonds (rather than bid submissions which are hollow circles), sniping by the number of points which fall in the last day.
Notes: Red vertical lines in each auction represent the point at which the last 24 h period starts (i.e. activity to the right is considered sniping). The horizontal red dashed line indicates the switch between PaB (below); and UP (above). The red circles and diamonds represent the mean proportion of the way through at which point a bid is submitted, and updated, respectively. The blue triangles are the mean proportion of the way through for any type of action. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 8
The effect of pricing rule on the probability a particular activity is bid updating (columns 1 and 2) and sniping (columns 3 and 4).

Bidding behaviour:	(1)	(2)	(3)	(4)
	Updating		Sniping	
Pricing rule (Uniform price = 1)	−0.342*** (0.024)	−0.455*** (0.045)	−0.143*** (0.028)	−0.225*** (0.048)
Year		0.047*** (0.015)		0.035** (0.016)
Constant	0.565*** (0.015)	0.462*** (0.038)	0.492*** (0.019)	0.417*** (0.043)
Number of observations:	2202			
Number of clusters:	1175			

Notes: A bid activity could be neither updating nor sniping (e.g. a bid submission >24 h before close of the auction), hence there is no requirement for probabilities to sum to 1.
Standard errors clustered at the unique bid level are in parentheses.
* p < 0.1, ** p < 0.05, *** p < 0.01.

Moreover, participation rates, and the number of bids placed in UP auctions relative to PaB auctions does not decline, if anything it seems somewhat higher, suggesting bidders are at least as engaged as under PaB pricing. Indeed, there is tentative evidence that lower participation costs translate into higher rates of participation. Median participation rates in the Monte Carlo simulations of PaB auctions are 14 farmers (95% CI = 9–18) while in the simulated UP auctions it is about 15% higher (median = 16; 95% CI = 10–21). While the effect is not significant, and could be driven by the higher number of eligible farmers in 2020, it is nonetheless consistent with UP pricing lowering participation costs. This underscores that the increase in value-for-money of the UP auctions is likely sustainable.

7. Concluding remarks

This paper presents the results of a natural experiment that allows examination of the impacts of different auction pricing rules on outcomes of an agri-environment PES programme. Our investigation discovers a statistically-significant, and economically-substantial reduction in bids from participants caused by the exogenous change from PaB to UP pricing. In line with theory (e.g. Back and Zender, 1993; Lengwiler, 1999; Ausubel et al., 2014; Pycia and Woodward, 2021), these results are driven by participants bidding close to cost, rather than shading up bids as in the PaB. Moreover, the results are robust, both in significance and magnitude, to a longitudinal fixed effects specification that accounts for the cost of cover crop planting and changes in the reserve price.

Owing to the extremely detailed nature of our dataset, we are able to examine proxies for the cost of participation. The results are striking – sniping and bid updating are much reduced under a UP auction.

From a funder's perspective, value-for-money is key. Our study extends the empirical evidence base to the new and emerging context of auctions for PES contracts. We find that UP pricing substantially increased the value-for-money delivered by the scheme. Holding fixed the quantity of water quality improvements purchased, UP pricing reduced median payments per kg of nitrogen by over 35%. The lower participation costs mean that there is little reason to suspect that the increase in value-for-money offered by UP over PaB auctions will not be sustained in future iterations. Furthermore, switching to UP pricing (combined with a budget constrained auction) meant that more nitrogen was purchased at a cost considerably lower than would have been possible through alternative methods of improving water quality. As such, the improved value-for-money offered by the UP auctions likely coincided with enhanced social welfare.

We speculate that our findings are in part driven by the relatively marginal contribution of PES agri-environment payments to farm profitability and the relatively close social ties that exist in farming communities participating in PES auctions. Such circumstances are very different to those that characterise auctions in other economic settings (e.g. for treasury debt, foreign exchange and spectrum rights) where pricing rules have previously been examined. For instance, the specific environment in which PES auctions occur results in the requirement for extended bidding windows and allowing updating. In the PES context, we conjecture that simplicity in participation and fairness in outcome, rather than profit alone, are key motivators for participants. By eliminating the need to bid strategically, the UP auction offers that simplicity. By paying each farmer the same price per unit of service delivered we infer that the UP auction delivers a fairer, and hence more acceptable, outcome to farming communities. Together, such effects could explain our observed results, and indeed there is anecdotal evidence that participants prefer UP auctions.

The conclusion of this paper – that the UP auction performs better in the Poole Harbour catchment than does the PaB format on a range of measures – does not mean that this is going to be true in all PES settings. Indeed, PES auctions may often operate in extremely thin markets which could facilitate (perhaps tacit) collusion under UP pricing, as has been observed in other environmental auctions (Marszalec et al., 2020). Moreover, while we believe that our results are most parsimoniously explained as being driven by the pricing rule change, we cannot exclude the possibility that the other changes in auction format contributed to the observed effects. Similarly, our data stem from just two catchments, and errors could be correlated across farmers within catchment which is not accounted for within the clustering used in our DiD regression regarding the change in bids. Nevertheless, this paper begins to shed light on the question of optimal auction design in the PES context. Only by repeatedly testing economic ideas are we able to speak to questions of broader generalisability. That said, it is somewhat surprising that the effects we found in Poole Harbour were as large as they were. First, the market is not particularly thick: while there are 40 farmers who ever bid, in a given auction the maximum is 19. Hence the success of UP pricing in this context mitigates concerns regarding the potential of collusion to undermine UP auctions. Second, given the instant, continuous feedback, combined with the ability to update bids as often as a bidder wanted in all auctions, theory would have predicted that in PaB auctions all successful bids would have already collapsed to the marginally-accepted bid: the amount that defines payments in the UP auction. A reasonable expectation would therefore have been that in this setting the switch to the UP pricing rule would have no effect at all on payments, and yet it does. This suggests that the gains from the use of UP auctions could actually be *greater* in other PES auctions, some of which limit within-auction updating.

The Poole Harbour experience clearly demonstrates that apparently minor changes in auction rules can have large impacts on auction outcomes. While some of these changes (to bidding behaviour and the level of the bid) could have been predicted by theory, others (relating to the payments paid to successful bids) could not have been foreseen. Without natural experiments, theory and laboratory experiments can only advance our understanding so far; they must be complemented with real-world data. Indeed, the power of field trials is clearly shown in the confidence that the findings of this study inspired in the scheme's funders to switch away from their established PaB approach. As a result of the evidence generated by this natural experiment, EnTrade and Wessex Water have continued to use the UP pricing rule in the Poole Harbour catchment, and now view UP pricing as the default as they further expand the number of markets they operate.

More broadly, there is an obvious need for PES schemes to consider, and experiment with, a wider variety of auction designs in the real-world. Scheme designers should look beyond the conventional PaB design that dominates current implementations of auctions in PES settings.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jeem.2023.102889.

References

Athey, S., Levin, J., Seira, E., 2011. Comparing open and sealed bid auctions: Evidence from timber auctions. Q. J. Econ. 126 (1), 207–257. http://dx.doi.org/10.1093/qje/qjq001.

Ausubel, L.M., Cramton, P., Pycia, M., Rostek, M., Weretka, M., 2014. Demand reduction and inefficiency in multi-unit auctions. Rev. Econom. Stud. 81 (4), 1366–1400. http://dx.doi.org/10.1093/restud/rdu023.

Back, K., Zender, J.F., 1993. Auctions of divisible goods: On the rationale for the treasury experiment. Rev. Financ. Stud. 6 (4), 733–764.

Baldwin, L.H., Marshall, R.C., Richard, J.F., 1997. Bidder collusion at forest service timber sales. J. Polit. Econ. 105 (4), 657–699.

Banerjee, S., Kwasnica, A.M., Shortle, J.S., 2015. Information and auction performance: A laboratory study of conservation auctions for spatially contiguous land management. Environ. Resour. Econ. 61 (3), 409–431. http://dx.doi.org/10.1007/s10640-014-9798-4.

Barbosa, K., De Silva, D.G., Yang, L., Yoshimoto, H., 2022. Auction mechanisms and treasury revenue: Evidence from the Chinese experiment. Am. Econ. J. Microecon. 14 (4), 394–419. http://dx.doi.org/10.1257/mic.20200216, URL: https://www.aeaweb.org/articles?id=10.1257/mic.20200216.

Binmore, K., Swierzbinski, J., 2000. Treasury auctions: Uniform or discriminatory? Rev. Econ. Des. 5 (4), 387–410. http://dx.doi.org/10.1007/s100580000026.

Brenner, M., Galai, D., Sade, O., 2009. Sovereign debt auctions: Uniform or discriminatory? J. Monetary Econ. 56 (2), 267–274. http://dx.doi.org/10.1016/j.jmoneco.2008.12.012.

Brown, L.K., Troutt, E., Edwards, C., Gray, B., Hu, W., 2011. A uniform price auction for conservation easements in the Canadian prairies. Environ. Resour. Econ. 50 (1), 49–60. http://dx.doi.org/10.1007/s10640-011-9461-2.

Callaway, B., Sant'Anna, P.H., 2021. Difference-in-differences with multiple time periods. J. Econometrics 225, 200–230. http://dx.doi.org/10.1016/j.jeconom.2020.12.001.

Cameron, A.C., Gelbach, J.B., Miller, D.L., 2008. Bootstrap-based improvements for inference with clustered errors. Rev. Econ. Stat. 90 (3), 414–427, URL: http://www.jstor.org/stable/40043157.

Canay, I.A., Santos, A., Shaikh, A.M., 2021. The wild bootstrap with a "small" number of "large" clusters. Rev. Econ. Stat. 103 (2), 346–363. http://dx.doi.org/10.1162/rest_a_00887, arXiv:https://direct.mit.edu/rest/article-pdf/103/2/346/1915882/rest_a_00887.pdf.

Channa, H., Chen, A.Z., Pina, P., Ricker-Gilbert, J., Stein, D., 2019. What drives smallholder farmers' willingness to pay for a new farm technology? Evidence from an experimental auction in Kenya. Food Policy 85, 64–71. http://dx.doi.org/10.1016/j.foodpol.2019.03.005.

Chen, X., Zhao, J., 2013. Bidding to drive: Car license auction policy in shanghai and its public acceptance. Transp. Policy 27, 39–52. http://dx.doi.org/10.1016/j.tranpol.2012.11.016.

Cramton, P.C., 1995. Money out of thin air: The nationwide narrowband PCS auction. J. Econ. Manag. Strategy 4, 267–343.

Cramton, P., Hellerstein, D., Higgins, N., Iovanna, R., López-Vargas, K., Wallander, S., 2021. Improving the cost-effectiveness of the conservation reserve program: A laboratory study. J. Environ. Econ. Manag. 108, 1–37. http://dx.doi.org/10.1016/j.jeem.2021.102439.

de Chaisemartin, C., D'Haultfœuille, X., 2020. Two-way fixed effects estimators with heterogeneous treatment effects. Amer. Econ. Rev. 110, 2964–2996. http://dx.doi.org/10.1257/aer.20181169.

de Chaisemartin, C., D'Haultfœuille, X., 2022. Two-way Fixed Effects and Differences-in-Differences Estimators with Several Treatments. Working Paper 30564. Working Paper Series, National Bureau of Economic Research, Cambridge, MA, URL: http://www.nber.org/papers/w30564.

de Chaisemartin, C., D'Haultfœuille, X., 2022a. Two-way fixed effects and differences-in-differences with heterogeneous treatment effects: a survey. Econom. J. http://dx.doi.org/10.1093/ectj/utac017.

de Chaisemartin, C., D'Haultfoeuille, X., 2022c. Difference-in-Differences Estimators of Intertemporal Treatment Effects. Working Paper 2007.04267v10, URL: http://arxiv.org/abs/2007.04267.

Engelmann, D., Grimm, V., 2009. Bidding behaviour in multi-unit auctions - An experimental investigation. Econom. J. 119 (537), 855–882. http://dx.doi.org/10.1111/j.1468-0297.2009.02249.x.

Evans, D., Reeson, A., 2022. The performance of a repeated discriminatory price auction for ecosystem services. Environ. Resour. Econ. 81, 787–806. http://dx.doi.org/10.1007/s10640-022-00651-8.

Ferraro, P.J., 2008. Asymmetric information and contract design for payments for environmental services. Ecol. Econom. 65 (4), 810–821. http://dx.doi.org/10.1016/j.ecolecon.2007.07.029, URL: https://www.sciencedirect.com/science/article/pii/S0921800907004272, Payments for Environmental Services in Developing and Developed Countries.

Ferraro, P.J., Messer, K.D., Shukla, P., Weigel, C., 2022. Behavioral biases among producers: Experimental evidence of anchoring in procurement auctions. Rev. Econ. Stat. http://dx.doi.org/10.1162/rest_a_01215, arXiv:https://direct.mit.edu/rest/article-pdf/doi/10.1162/rest_a_01215/2032366/rest_a_01215.pdf.

Friedman, M., 1960. A Program for Monetary Stability. Fordham University Press, New York.

Hartwell, R., Aylward, B., 2007. Auctions and the Reallocation of Water Rights in Central Oregon. Technical Report, Deschutes River Conservancy River Paper 1.

Hill, M.R.J., McMaster, D.G., Harrison, T., Hershmiller, A., Plews, T., 2011. A reverse auction for wetland restoration in the Assiniboine River Watershed, Saskatchewan. Can. J. Agric. Econ. (Revue canadienne d'agroeconomie) 59 (2), 245–258. http://dx.doi.org/10.1111/j.1744-7976.2010.01215.x.

Iftekhar, M.S., Latacz-Lohmann, U., 2017. How well do conservation auctions perform in achieving landscape-level outcomes? A comparison of auction formats and bid selection criteria. Aust. J. Agric. Resour. Econ. 61 (4), 557–575. http://dx.doi.org/10.1111/1467-8489.12226.

Jack, K.B., 2013. Private information and the allocation of land use subsidies in Malawi. Am. Econ. J. Appl. Econ. 5 (3), 113–135. http://dx.doi.org/10.1257/app.5.3.113.

Jack, B.K., Leimona, B., Ferraro, P.J., 2009. A revealed preference approach to estimating supply curves for ecosystem services: Use of auctions to set payments for soil erosion control in Indonesia. Conserv. Biol. 23 (2), 359–367. http://dx.doi.org/10.1111/j.1523-1739.2008.01086.x.

Kastl, J., 2011. Discrete bids and empirical inference in divisible good auctions. Rev. Econom. Stud. 78 (3), 974–1014. http://dx.doi.org/10.1093/restud/rdq024.

Krasnokutskaya, E., Seim, K., 2011. Bid preference programs and participation in highway procurement auctions. Am. Econ. Rev. 101 (6), 2653–2686.

Latacz-Lohmann, U., Schilizzi, S., 2005. Auctions for Conservation Contracts: A Review of the Theoretical and Empirical Literature. Technical Report, Scottish Executive Environment and Rural Affairs Department.

Lengwiler, Y., 1999. The multiple unit auction with variable supply. Econom. Theory 14 (2), 373–392. http://dx.doi.org/10.1007/s001990050299.

List, J.A., Lucking-Reiley, D.H., 2000. Demand reduction in multiunit auctions: Evidence from a sportscard field experiment. Amer. Econ. Rev. 90 (4), 961–972. http://dx.doi.org/10.1257/0002828053828437.

Loft, L., Gehrig, S., Salk, C., Rommel, J., 2020. Fair payments for effective environmental conservation. Proc. Natl. Acad. Sci. 117 (25), 14094–14101. http://dx.doi.org/10.1073/pnas.1919783117, arXiv:https://www.pnas.org/doi/pdf/10.1073/pnas.1919783117, URL: https://www.pnas.org/doi/abs/10.1073/pnas.1919783117.

Lopomo, G., Marx, L.M., McAdams, D., Murray, B., 2011. Carbon allowance auction design: An assessment of options for the United States. Rev. Environ. Econ. Policy 5 (1), 25–43. http://dx.doi.org/10.1093/reep/req024.
Lucking-Reiley, D., 1999. Using field experiments to test equivalence between auction formats: Magic on the internet. Am. Econ. Rev. 89 (5), 1063–1080.
Lybbert, T.J., Magnan, N., Bhargava, A.K., Gulati, K., Spielman, D.J., 2013. Farmers' heterogeneous valuation of laser land leveling in eastern Uttar Pradesh: An experimental auction to inform segmentation and subsidy strategies. Am. J. Agric. Econ. 95, 339–345. http://dx.doi.org/10.1093/ajae/aas045.
Lynham, J., 2012. How Have Catch Shares Been Allocated? Working Paper No. 12-19. Working Paper Series, Department of Economics, University of Hawai'i.
Marszalec, D., Teytelboym, A., Laksá, S., 2020. EPIC Fail: How Below-Bid Pricing Backfires in Multiunit Auctions. Working Paper CIRJE-F-1096. CIRJE Discussion Papers, Tokyo, pp. 1–48.
Monostori, Z., 2014. Discriminatory Versus Uniform-Price Auctions. Working Paper 111. MNB Occasional Papers, Magyar Nemzeti Bank, Budapest.
Munday, V., 2018. NaturEtrade NFM natural flood management: FAQ. URL: https://nfmea.sylva.org.uk/faq.
Narloch, U., Pascual, U., Drucker, A.G., 2013. How to achieve fairness in payments for ecosystem services? Insights from agrobiodiversity conservation auctions. Land Use Policy 35, 107–118. http://dx.doi.org/10.1016/j.landusepol.2013.05.002.
Nyborg, K.G., Rydqvist, K., Sundaresan, S.M., Journal, S., April, N., Nyborg, K.G., Sundaresan, S.M., 2002. Bidder behavior in multiunit auctions: Evidence from Swedish treasury auctions. J. Polit. Econ. 110 (2), 394–424.
Ong, A., Cuttle, C., 2021. Outcome Based Environmental Regulation: Enabling the Water Sector to Make Its Contribution to the 25 Year Environment Plan. Technical Report, Frontier Economics Ltd.
Pant, K.P., 2015. Uniform-price reverse auction for estimating the costs of reducing open-field burning of rice residue in Nepal. Environ. Resour. Econ. 62 (3), 567–581. http://dx.doi.org/10.1007/s10640-014-9830-8.
Pycia, M., Woodward, K., 2021. Auctions of homogeneous goods: A case for pay-as-bid. SSRN Electron. J. (October), 1–91. http://dx.doi.org/10.2139/ssrn.3865760.
Reichelderfer, K., Boggess, W.G., 1988. Government decision making and program performance: The case of the conservation reserve program. Am. J. Agric. Econ. 70 (1), 1–11. http://dx.doi.org/10.2307/1241970.
Rico-Straffon, J., Wang, Z., Panlasigui, S., Loucks, C.J., Swenson, J., Pfaff, A., 2023. Forest concessions and eco-certifications in the Peruvian Amazon: Deforestation impacts of logging rights and logging restrictions. J. Environ. Econ. Manag. 118, http://dx.doi.org/10.1016/j.jeem.2022.102780.
Rolfe, J., Whitten, S., Windle, J., 2017. The Australian experience in using tenders for conservation. Land Use Policy 63, 611–620. http://dx.doi.org/10.1016/j.landusepol.2015.01.037, URL: https://www.sciencedirect.com/science/article/pii/S026483771500126X.
Rolfe, J., Windle, J., McCosker, J., 2009. Testing and implementing the use of multiple bidding rounds in conservation auctions: A case study application. Can. J. Agric. Econ. (Revue canadienne d'agroeconomie) 57 (3), 287–303. http://dx.doi.org/10.1111/j.1744-7976.2009.01152.x, URL: https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1744-7976.2009.01152.x.
Roth, J., Sant'Anna, P.H., Bilinski, A., Poe, J., 2023. What's trending in difference-in-differences? A synthesis of the recent econometrics literature. J. Econometrics http://dx.doi.org/10.1016/j.jeconom.2023.03.008, URL: https://www.sciencedirect.com/science/article/pii/S0304407623001318.
Salzman, J., Bennett, G., Carroll, N., Goldstein, A., Jenkins, M., 2018. The global status and trends of payments for ecosystem services. Nat. Sustain. 1 (3), 136–144. http://dx.doi.org/10.1038/s41893-018-0033-0.
Schilizzi, S.G., 2017. An overview of laboratory research on conservation auctions. Land Use Policy 63, 572–583. http://dx.doi.org/10.1016/j.landusepol.2015.06.035.
Schilizzi, S., Latacz-Lohmann, U., 2012. Evaluating conservation auctions with unknown bidder costs: The scottish fishing vessel decommissioning program. Land Econom. 88 (4), 658–673. http://dx.doi.org/10.3368/le.88.4.658.
Shoemaker, R., 1989. Agricultural land values and rents under the conservation reserve program. Land Econom. 65 (2), 131–137.
Smith, V.L., 1967. Experimental studies of discrimination versus competition in sealed-bid auction markets. J. Bus. 40 (1), 56–84.
Stoneham, G., Chaudhri, V., Ha, A., Strappazzon, L., 2003. Auctions for conservation contracts: An empirical examination of victoria's BushTender trial. Aust. J. Agric. Resour. Econ. 47 (4), 477–500. http://dx.doi.org/10.1111/j.1467-8489.2003.t01-1-00224.x.
Sun, L., Abraham, S., 2021. Estimating dynamic treatment effects in event studies with heterogeneous treatment effects. J. Econometrics 225, 175–199. http://dx.doi.org/10.1016/j.jeconom.2020.09.006.
Tenorio, R., 1993. Revenue equivalence and bidding behavior in a multi-unit auction market: An empirical analysis. Rev. Econ. Stat. 75 (2), 302–314.
Thompson, G., 2021. Personal communication.
van Soest, D., Turley, T., Christian, P., van der Heijden, E., Kitessa, R., 2018. Can Uniform Price Auctions Inform the Design of Payments for Ecosystem Services Schemes? Evidence from the Lab and Field. Working Paper, The World Bank.
Vickrey, W., 1961. Counterspeculation, auctions, and competitive sealed tenders. J. Finance 16 (1), 8–37.
Woodland Carbon Code, 2023. Woodland carbon guarantee. URL: https://woodlandcarboncode.org.uk/woodland-carbon-guarantee.