At what price? The effects of a pricing rule change on outcomes in a PES auction†

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Abstract

Applications of auctions in Payment for Ecosystem Service (PES) schemes almost universally adopt a "pay-as-bid" (PaB) pricing rule in which successful participants are paid the amount they stipulate in their bid(s). Alternative pricing rules exist, and have been applied to good effect in other economic arenas. This paper focuses on agri-environment schemes, a near ubiquitous PES application, and argues that auctions in that context may be better served by a "uniform price" (UP) rule in which successful bids receive the same per unit payment, determined by the marginal bid. That conjecture is tested through a field experiment where the pricing rule applied in such an auction was experimentally switched from PaB to UP. Our regression discontinuity results are clear: the switch led to a reduction in mean bids of 40% and mean payments by a similar amount. Moreover, the UP format reduces the incidence of costly bidding behaviours: bid-updating reduced by over a half, sniping by ˜30%. Our results are corroborated by a differences-in-differences (DiD) design, supporting our postulation that the identifying variation we exploit is exogenous, and that our results are not the consequence of confounding effects.

1 Introduction

A primary concern for the designers of agri-environment schemes - by far the highest value and most prevalent of PES schemes (Salzman et al., 2018)[1] - is that they achieve value-for-money; that is to say, that they maximise the total ecosystem service provision that can be procured from the funder's limited resources. Moreover, being repeated, such value-for-money must be delivered throughout the scheme's lifetime; it cannot simply realise good value-for-money early on at the expense of later iterations. To achieve that goal, there has been increasing interest in the use of auctions as a means of determining the

[1]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.

prices at which agri-environment contracts are allocated (Latacz-Lohmann and Schilizzi, 2005; Ferraro, 2008; Cramton et al., 2021). While there are numerous different rules through which auction prices can be determined, PES applications have tended to focus on just one. This paper describes the outcome of a field experiment in which the pricing rule used in an agri-environment auction was switched from that established rule to an alternative widely used in other economic settings. We present evidence that shows how the alternative rule not only delivers greater value-for-money but also reduces problematic bidding behaviours that might threaten the long-term success of the scheme.

Perhaps the central economic challenge to designing a scheme that offers value-for-money arises from the inherent information asymmetry of the PES exchange institution. As in other principal-agent problems, farmers (agents) know their costs much more accurately than do scheme funders (principals). Reverse auctions act as a mechanism for price discovery, by creating incentives which encourage farmers to reveal their costs. The funder sets a budget (or quantity) limit and multiple farmers bid to deliver the targeted service on their (potentially) multiple parcels of land. The lowest cost bids are then successful in attracting funding. The price paid to these successful bids is determined by the so-called "pricing rule" used in the particular auction. Indeed, carefully selecting the pricing rule so that the principal achieves the greatest value-for-money is a key challenge of auction design, (Ferraro, 2008). In other areas of economic activity[2], two different auction pricing rules have come to dominate. In one, the "Pay-as-Bid" (PaB) pricing rule, all successful bids are fulfilled at the amount specified in the bid. The other widespread pricing rule is the "Uniform Price" (UP) rule in which all successful bids are fulfilled at the amount specified in the marginal (either last winning or first losing) bid. The central question addressed by this paper is which pricing rule best delivers value-for-money over successive agri-environment auctions.

[2]Auctions are currently used as a pricing mechanism for the exchange of: government debt (Umlauf, 1993; Simon, 1994; Nyborg and Sundaresan, 1996; Nyborg et al., 2002; Kang and Puller, 2008; Brenner et al., 2009; Marszalec, 2017; Barbosa et al., 2019), foreign exchange (Tenorio, 1993), timber (Athey and Levin, 2001; Athey et al., 2011; Hansen, 1985, 1986; Préget and Waelbroeck, 2012; Baldwin et al., 1997), electricity supply (Wolfram, 1998), road building (Krasnokutskaya and Seim, 2011), radio spectrum (Cramton, 1995), and trading cards (Lucking-Reiley, 1999; Engelbrecht-Wiggans et al., 2006; List and Lucking-Reiley, 2000; Reiley, 2005).

Our current understanding of the the impact of pricing rules on auction outcomes is underpinned by the seminal works of Vickrey (1961) and Myerson (1981). They developed the "Revenue Equivalence Theorem" in the context of auctions for the exchange of one, indivisible, good; concluding that under risk-neutral bidding, the Nash-equilibria of UP and PaB auctions generate the same value-for-money for the auctioneer[3]. This theorem, however, does not hold when an individual seller could sell multiple units of a good to an auctioneer who similarly has demand for many goods (Ausubel et al., 2014). Rather, there continues to be much debate over which auction format is, in general, better suited to this so called "multi-unit" setting (see, for example, Friedman, 1960, and Binmore and Swierzbinski, 2000); even within the same economic context, different auctioneers choose different pricing rules (Brenner et al., 2009). At the crux of the matter is that the multi-unit nature changes the incentives that agents face in UP auctions: they may improve their profits by bidding above cost for their higher cost units (Back and Zender, 1993; Lengwiler, 1999; Back and Zender, 2001; McAdams, 2007).

Alongside the theoretical literature, there is growing empirical evidence on outcomes under different pricing rules, garnered from both laboratory experiments[4], and econometric inference from real-world data. Across data sources, the evidence is inconclusive with regards to which pricing rule outperforms on measures of value-for-money and economic efficiency (achieving an outcome at least cost to agents rather than at least spend by the principal). In induced-value laboratory experiments, Smith (1967) find that the UP offers greater value-for-money to the auctioneer; while Engelmann and Grimm (2009) find in favour of the PaB. Outside of the laboratory, evidence from real-world markets is similarly mixed. Structural modelling approaches - which impose particular assumptions concerning the bidding strategies to recover bidders' value distributions from bids - tend to find in favour of the PaB (Kang and Puller, 2008;

[3]This is because, in UP auctions, everyone has an incentive to bid at cost as the bid amount only affects whether the bid is successful, not the amount paid if successful. While in PaB (reverse) auctions bidders are expected to shade up their bids (overstate costs). Indeed, according to theory, the optimal degree of shading up would lead to the winning bidder receiving the same payment as the winning bidder under UP pricing.

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

Marszalec, 2017). Papers that use a similar econometric approach to us - relying on discontinuities in the auction rule used by auctioneers in repeated auctions to causally identify pricing rule effects - have produced mixed results in the context of auctions for the right to extract timber, and for government debt (Mead et al., 1981; Hansen, 1985, 1986; Tenorio, 1993; Umlauf, 1993; Simon, 1994; Nyborg and Sundaresan, 1996). Moreover, such studies have sometimes been undermined by confounding effects; for example Hansen (1985, 1986) highlights that the Mead et al. (1981) study fails to account for the fact that the auctioneer is more likely to use UP pricing rule when they believe bidders to have low values. This selection bias limits one's ability to causally interpret the results on pricing rules. The only randomised control trial to date, in the context of auctions for treasury debt in China, detects no impact of pricing rule on revenue (Barbosa et al., 2019). Taken together, the literature offers little insight as to which pricing rule is likely to offer greatest value-for-money in agri-environment PES schemes over successive iterations. Perhaps the key message emerging from this body of literature is echoed as a conclusion of Klemperer (2002): that to perform well an auction must be designed with its specific context and objectives in mind.

The earliest PES schemes to adopt auctions as a mechanism for price discovery (e.g. the Conservation Reserve Program (Shoemaker, 1989; Cramton et al., 2021) and BushTender (Stoneham et al., 2003)) used PaB pricing. Indeed, a thorough review of the literature reveals that auctions in real-world PES schemes rely solely upon the PaB pricing rule[5].

Yet, UP pricing may actually be better suited to the specific context and objectives of PES auctions, and agri-environment schemes in particular. As discussed, *a priori*

[5]Both PaB and UP pricing rules are used for other auctions in an environmental context, for: fishing boat retirement (Schilizzi and Latacz-Lohmann, 2012), extraction rights for fish (Lynham, 2012; Marszalec et al., 2020) and water (Hartwell and Aylward, 2007), air pollution permits (Lopomo et al., 2011) and to lower car ownership (Chen and Zhao, 2013). In a true PES context, UP auctions have only been used in small-scale trials rather than actual real-world schemes. Moreover, these trails either aim to understand individual bidder's behaviour (Jack, 2013; van Soest et al., 2018), or to establish prices for take-it-or-leave-it offers (Jack et al., 2009; Brown et al., 2011; Pant, 2015). Narloch et al. (2013) compares 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.

we cannot predict which auction pricing rule is likely to offer better value-for-money in a one-off auction. However, agri-environment auctions are repeated and PaB pricing encourages low-cost bidders to increase their bids to the marginal bid, distorting the revealed cost curve and increasing the costs of later scheme iterations to the funder (as occurred in the Conservation Reserve Program, Shoemaker (1989)). On-going participation is also likely key to maintaining value-for-money over successive iterations; indeed auctions "often fail because of insufficient interest by bidders" (Milgrom, 2004, p. 209). As bidders livelihoods are not primarily determined by their participation in a PES agri-environment scheme - they are foremost farmers running complex businesses - each auction tends to be open to receive bids over an extended period of time, the bidding window, which is typically a few weeks, and during which feedback is offered on the provisionally successful bids. Under PaB pricing, bidders therefore have an incentive to play the auction - update their bids throughout in response to feedback, and potentially bid in the last few hours, so called sniping, in an effort to pip less attentive bidders to the few contracts available. Neither bid updating, nor sniping, is expected to be prevalent in UP auctions in which bidders should (to a first approximation) bid at cost, and hence gain no strategic advantage from such actions. Moreover, updating and sniping are thought to be costly to bidders, and hence in reducing the need for such behaviours, we may expect that UP pricing can better sustain value-for-money through multiple iterations. Furthermore, these schemes take part in tight-knit communities, with rival bidders commonly interacting in other settings. Repeated participation may therefore hinge, in part, upon a sense of fairness, and again, the UP rule, which eliminates antagonistic sniping bids and in which every successful bid is paid the same amount, may be perceived as fairer.

This paper is the first to explore whether these insights on the potential advantages of UP pricing hold in real-world agri-environment PES auctions, and whether UP auctions may, therefore, be better suited to such a context. We do so using data on an exogenously imposed discontinuity in the pricing rule used in a series of agri-environment auctions. The programme funds the planting of cover crops, on land that would otherwise be bare over winter, to reduce nitrogen run-off in the Poole Harbour catchment in the UK. These auctions are funded by the regional water company, Wessex Water, who have a regulated obligation to reduce nitrogen loads in the Poole Harbour watershed. EnTrade - a market operator whose parent company is Wessex Water - facilitate this, and various other, agri-environment PES auctions within the UK; acting as an auction house. Following chance discussions between EnTrade and the research team, EnTrade agreed to run an experimental test of the UP pricing rule in the Poole Harbour auctions, while maintaining the PaB in the auctions they manage in other catchments. This paper uses the data from one of these other schemes, in addition to the data from Poole Harbour. Owing to the commercially sensitive nature of the data from this second catchment, we are not privy to its identity, and therefore henceforth refer to it as the control catchment. To be very clear, treatment was *not* randomly assigned across catchments. Rather, the control catchment is funded by a different water company, and so Poole Harbour was chosen as the scheme in which a field experiment could be conducted because the downside risks of experimentation (e.g. that value-for-money declined relative to previous years) fell on Wessex Water, rather than a third party water company, and these risks were therefore easier to justify. There was nothing particular about Poole Harbour as a catchment or scheme more broadly.

In examining this field data, we first employ a regression-discontinuity approach, similar to that used in other studies (e.g. (Mead et al., 1981; Tenorio, 1993; Umlauf, 1993; Simon, 1994; Nyborg and Sundaresan, 1996)), focusing exclusively on bidding within the Poole Harbour catchment. In all cases, we observe behaviour only for those individuals who choose to bid in a given auction. The group of potential bidders is (relatively) fixed throughout our sample period, and hence we seek to identify average treatment effects conditional upon participation. Our identifying assumption is that, once we control for inflation and market conditions, the Poole Harbour auctions before and after the change in auction format only systematically differ in the pricing rule that was used. Compared to the existing literature, our design benefits from the fact that the prior information on costs facing farmers does *not* inform which pricing rule EnTrade use[6].

As expected, switching from PaB to UP pricing resulted in a decrease in mean bids which fall by 40%. In subsequent analyses, we show that this effect does not appear to be 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 accurately update their bidding strategy in response to the incentives they face; substantially reducing the amount of shading included within bids. Moreover, despite paying all successful bids the amount stated in the marginal bid, the mean amount paid per unit of nitrate reduction was ˜50% lower in UP than PaB auctions. In short, UP pricing resulted in far better value-for-money for the funder. Finally, we find preliminary evidence to suggest that the increase in value-for-money offered by the UP auction would be long-lasting: both bid-updating and sniping fall, by 60% and 30%, respectively, as compared with under PaB pricing, suggesting that the costs of participation are lower[7]. Indeed, anecdotal evidence from farmers further suggests that they prefer UP auctions (Peacock, 2021).

Of course, one concern with claiming a causal link between the adoption of a UP format and the shift in auction outcomes is that the change in pricing rule just happened to be coincident with a change in wider market conditions. To mitigate against such confounds, we examine bid data from the almost identical auction series being run in the control catchment. Auctions in both Poole Harbour and the control catchment are run repeatedly for the procurement of cover crop planting the following winter[8]. In Poole Harbour, EnTrade have run auctions twice a year since 2016, and in the control catchment, once a year since 2017. To reiterate, when the pricing rule changed in Poole

[6]This is in contrast to the timber auction setting where Hansen (1985, 1986) provides evidence that the pricing rule chosen by the auctioneer correlates with characteristics of the specific goods for sale, which vary from auction to auction. In those designs, correlation between good characteristics and the selected pricing rule confounds the identification of pricing rule effects.

[7]We cannot identify if the reduced updating and sniping are in response to the reduced incentive to strategically engage with the auction, or because a greater proportion of bids in the UP auction are successful due to the bids being lower.

[8]Similarity between treatment and control is not a pre-requisite of DiD identification, rather, just that pre-intervention, the treated and control groups have parallel trends.

Harbour (for the 2019 auctions onward), the control catchment scheme maintained PaB pricing. The data from Poole Harbour, paired with the control catchment, allows us to use "differences-in-differences" (DiD) estimation. We show that the statistically significant and economically meaningful estimates of reductions in bids are robust; and we are therefore able to exclude stories which suggest that the results are spurious correlation rather than causal impacts[9]. Our research findings provide convincing evidence to support the favouring of UP pricing over PaB pricing in in agri-environment PES auctions.

The remainder of the paper is organised as follows. In the next Section (2) we discuss the specifics of the real-world setting, the institutional arrangements, and the field experiment. In Section 3 we present our theoretically-driven hypotheses as well as open empirical questions to which theory cannot speak. Section 4 formalises the empirical strategy we employ to identify the causal impact of pricing rule on various auction outcomes, and assess our hypotheses. Finally, we present the results (Section 5) and then offer some concluding remarks (Section 6).

2 Institutional setting

2.1 General background

The Poole Harbour catchment is situated on the south coast of the UK, in which the regional water company, Wessex Water, are legally responsible for managing ambient nutrient levels. In 2013 the Environment Agency and Natural England (two regulatory bodies in the UK) published a "Nutrient Management Plan" for Poole Harbour which determined that levels of ambient nitrate needed to be reduced so as to avoid the risk of algal blooms and eutrophication which threatened designated wildlife habitats. Rather than meeting this regulatory requirement through the traditional, but extremely costly,

[9]Of course, like all DiD designs, we are unable to rule out stories in which a shock (concurrent with the switch in pricing rule) occurs in just one catchment, or similarly a universal shock (again concurrent with the switch in pricing rule) to which only farmers in one catchment are susceptible (e.g. because they are actually very different types of farmers who simply happen to have similar changes in average bid in advance of the intervention). Such a shock would also have to lead to long-lasting effects in bidding behaviour. While it may be possible to weave such a story, we are aware of no such real-world events which would undermine the DiD identification.

approach of upgrading waste water treatment works, Wessex Water opted to develop an agri-environment scheme. That scheme sought to pay farmers to reduce nitrate leaching from agricultural land, a source which accounts for >75% of the nitrate load in Poole Harbour. Wessex Water calculated that this would meet their regulatory obligation while offering better value-for-money for their customers.

The Poole Harbour scheme is an almost archetypal agri-environment PES programme. Individual members of a small and relatively tight-knit community, in this case, farmers within the Poole Harbour catchment, are paid to carry out specific actions with predicted ecosystem service benefits for both themselves and wider society. Moreover, as in other PES settings, each individual has the potential to supply multiple units (many fields) and faces some privately-known cost to do so. As is typical, bidders tend to be relatively small-scale operations whose main business focus is *not* the provision of ecosystem services[10].

The key land management change for which Wessex Water offers funding is the planting of cover crops on arable land that would otherwise have been left bare over winter. Cover crops act to convert highly-leachable inorganic nitrogen to organic nitrogen held in the plant, preventing it from entering the watercourse. Moreover, the conversion from inorganic to organic nitrogen makes it accessible to future plants on the land, acting to fertilise the following year's crop. Planting of cover crops, however, is costly: it takes labour, machinery, and seed inputs; and these costs are typically greater than the private benefit from planting, hence unless farmers are paid to plant cover crops they will normally choose not to. How much it costs a farmer to deliver cover crops though is unknown and varies between individuals, who may have different access to machinery, or value their labour or the resultant soil fertility enhancement differently. Funding was available at the individual field level, and to be eligible, the field had to be located relatively close to the watercourse, such that the nitrogen would otherwise have been predicted to enter the waterway within the next five years, as is displayed in Figure 1. Hence only the

[10]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.

280 farmers (in 2020, 318)[11] who were expected to have field(s) that may be eligible for funding could enter a bid in the auction through EnTrade's online bidding platform.

Figure 1: A map of the area in which funding was available in the Poole Harbour Catchment for the planting of cover crops.

The scheme implemented in the control catchment, elsewhere in England, was extremely similar. Funding came from a different water company, but was again driven by a desire to lower the costs of complying with a regulatory obligation (in this case regarding drinking water quality) to lower ambient nitrate. Farmers were able to apply for funding via Entrade's online platform, to plant cover crops over the winter on land that would otherwise be bare, and again were therefore arable farmers close to the water course.

2.2 The Poole Harbour auction

Funding in the Poole Harbour catchment was first made available in June 2016, for the planting of cover crops in the winter of 2016/17, and was allocated through a reverse auction with a PaB pricing rule. Interested farmers could propose the planting of a

[11] Of these, some are expected to be livestock farmers for whom cover crops are unsuitable, and others likely to grow winter wheat which would again rule them out for funding. An individual farmer could have some fields eligible for funding and others not.

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. EnTrade use a hydrological model to translate on-the-ground actions into a predicted reduction in nitrogen leaching, which we refer to as "saved nitrogen". Each interested farmer could offer multiple units (fields) with potentially different bid amounts. Bids were evaluated on a cost per unit of saved nitrogen, accepting cheaper bids first until the "saved nitrogen" target was reached[12].

The auction operated as a sealed-bid auction with continuous feedback. Hence, farmers knew only their own bids and not the supply decisions of other farmers. However, upon submitting a bid an individual farmer got instantaneous feedback on whether their bid was currently a "successful" bid - i.e. whether their bid would be funded if the auction ended at that moment. Farmers were also notified via email if the status of their bid changed, for instance if their bid went from being provisionally successful to provisionally rejected as more bids came in. Farmers could update their bids as frequently as they liked, or withdraw a bid altogether, so long as the auction was open (i.e. during the bidding window).

The reverse auction has continued annually, however, from 2017 there have been two auctions each year - one in spring and the second in the summer, both for cover crops to be planted the following winter[13].

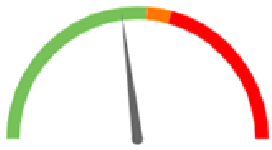
The key discontinuity that we exploit in this paper is the switch in pricing rule which occurred before the 2019 auctions. Up to then, auctions had operated on a PaB basis. The auctions in 2019 and 2020 used the UP pricing rule instead. Under the PaB all successful bids were paid the amount specified in the bid. Under the UP all successful bids were instead paid the amount in the marginal bid in terms of £ per kg of saved

[12]Note verification of successful bids is ascertained through a combination of spot-checks and self-verification through the use of geo-tagged images and a mobile phone application. Funding was only released once projects had been verified. We therefore do not concern ourselves with the potential for moral hazard, in which farmers enter speculative bids in the hope of receiving funding while not implementing the required management practice, impacting bidding behaviour.

[13]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).

nitrogen[14]. This switch happened as a result of chance discussions between EnTrade and the research team. In autumn 2018, EnTrade and the research team were both drafted in as expert advisers on the creation of a new scheme to be run by a third party water company in a separate catchment. In these discussions, the research team explained the different pricing rules available to the third party water company, and upon hearing about the UP rule, EnTrade enquired as to the possibility of running such an auction in their already existing schemes. Hence the timing of the switch in pricing rule is exogenous with respect to market conditions and the goods which could be exchanged; throughout, the same farmers could offer the same fields on which to plant the same kinds of cover crop. Indeed, as we will go on to review, the pricing rule in the array of other EnTrade-facilitated auctions was not changed.

(a) “Linear dial”



(b) “Speedometer”

(c) “Dot”

Figure 2: How bid feedback was offered in auctions

A few other specific auction details also changed between years, as is detailed in Table 1. First, the exact length of bidding window varied between ten days and three weeks. Second, the way in which feedback was given varied somewhat between auctions. In 2016 and 2017, farmers saw a linear dial (Fig. 2a), for 2018 the dial used was more like a speedometer (Fig. 2b), 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. 2c). Third, the way in which updating was allowed changed. In 2019 and 2020 bidders were required to delete and resubmit bids if they wanted to update them, rather

[14] UP auctions can either use the last accepted or first reject bid to set the price. In these auctions, the last (i.e. highest) accepted bid set the price.

than change the amount stated in the bid. Fourth, a reserve price of £2.50/kg of saved nitrogen was introduced in 2017 and maintained in 2018. In 2019 it was lowered to £2.00; and in 2020 first to £1.60 for April and subsequently to £1.40 for June. The reserve was implemented by simply not allowing bidders to bid above the reserve price. Fifth, the constraint changed from a quantity target to a budget limit between the 2018 and 2019 auctions. In most quantity constrained PaB auctions, EnTrade targeted the removal of 18,000 kg of nitrogen. In June 2016 and 2017 it was higher - 35,000 kg and 27,000 kg, respectively - owing to there only being one auction in 2016 and a third party buyer in 2017. In the 2019 and 2020 auctions the budget was calculated to be that required to meet the 18,000 kg target (circa £40,000). In the April 2020 auction extra budget was made available owing to the start of the new Asset Management Plan period in the UK water industry, under which Wessex Water were required to up the amount of saved nitrogen they bought. In all cases, farmers were aware of the constraints of the specific auction. Finally, the number of eligible farmers increased slightly in 2020, to 318 (from 280).

In general, our empirical analysis identifies the combined effects of the several changes in scheme format that took place between 2018 and 2019 in the Poole Harbour catchment. However, there is no theoretical reason to think that changes in the way information was fed-back, or in the way bid revisions were facilitated, should have an impact on bids or payments. Similarly, the small increase in the number of eligible farmers is unlikely to have affected bidding, but in some empirical specifications we exclude the 2020 data to mitigate such concerns. The change in constraint - moving from a quantity target to a budget constraint - should have no impact on bidding by itself. Some change in bidding may exist as the budget constraint was actually more than was needed to purchase 18,000 kg, and hence bids in 2019 and 2020, when the auction was less competitive, would be expected to be higher than if the 18,000kg constraint had remained in place. Throughout, we make the conservative assumption that bids in 2019 and 2020 would have remained unchanged. In one analysis, to understand the impact upon payments, we construct a scenario in which the 18,000 kg target is maintained. Similarly, reserve prices act to preclude the farmers with the highest cost from entering the auction. Hence in some

Auction	Pricing rule	Constraint	Information feedback	Maximum bid (per kg of N)	Updating process	# potential farmers
Jun-16	Pay-as-Bid	Quantity, 35,000kg	Linear dial	No reserve	Revise existing bid	280
Jan-17	Pay-as-Bid	Quantity, 18,000kg	Linear dial	£2.50, publicly known	Revise existing bid	280
Jun-17	Pay-as-Bid	Quantity, 27,000kg	Linear dial	£2.50, publicly known	Revise existing bid	280
Jan-18	Pay-as-Bid	Quantity, 18,000kg	Speedometer	£2.50, publicly known	Revise existing bid	280
Jun-18	Pay-as-Bid	Quantity, 18,000kg	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

Table 1: Details of how each auction was run

analyses we simply exclude bids from 2020, as well as bids in 2017 and 2018 above the £2.00 reserve used in 2019. 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 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. As will become apparent, there is evidence that the initial auction in 2016 had very different outcomes to subsequent auctions, and so this auction is also often dropped from analyses. We therefore expect that by restricting which data to include, any effect we pick up is primarily driven by the switch in pricing rule from the PaB to the UP. Moreover, in all cases, we make assumptions about bidding behaviour which are conservative, in the sense that if the assumptions did not hold, the UP auction would actually result in lower bids than we observe.

It is also worth highlighting that, according to theory, the availability of instantaneous feedback and unlimited updating should result in very similar outcomes under both pricing rules. In the PaB auction all bidders can discover the marginal bid, and, so long as their costs are less than this, bid at that amount. In the UP auction, while bids should better reflect costs, the marginal bid remains unchanged, and so, therefore, would the overall payments. 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 and/or there is less scope for repeated bid updating.

2.3 The control catchment auction

Auctions in the control catchment treatment were broadly similar. These auctions ran once per year in 2017-2020 and throughout used the PaB pricing rule. In all auctions there was a reserve price which was the same in all four auctions in the control catchment. The exact level of the reserve is commercially sensitive, and hence cannot be released, but it was different to that used in any of the Poole Harbour auctions. 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 target in all auctions.

3 Testable expectations

Economic theory is able to shed some light on the expected impact of a pricing rule change on bids and bidding behaviour. In PaB auctions an individual's best bidding strategy is to shade up their bid - that is, overstate their costs - on all of the items (fields) they could sell. Indeed, the degree to which they should shade up is determined by the trade-off of the increased profit in the auction if their bid is successful versus the decreased probability of success with a higher bid. The net result is that people should shade up by more on their lower cost units. In contrast, in a UP auction bidders are expected to bid at cost on their low-cost units. If the marginal bid is higher than their costs they would like their bid to be successful (earning a profit of the difference between the marginal bid and their cost) and if the marginal bid is below their cost they are best if the item is unsuccessful. In multi-unit UP auctions, there is an additional incentive for bidders to exert market power: overstating their costs on higher cost items may increase the marginal bid, and hence increase the profits they accrue on their lower cost items Lengwiler (1999)[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. Therefore there is a very clear ranking of expected bids:

Hypothesis 1: *Bids are lower in the UP than in the PaB*

While bids may be lower in the PaB auction than under a UP pricing rule, recall that 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, as Ausubel et al. (2014) neatly show, it is an empirical question as to whether the mean *payment* is higher or lower in the UP or PaB

[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 are may actually be incentivised to *overstate* their supply at prices they think could be marginal does not apply.

auction, critically depending on the unobserved cost distribution and the risk preferences of bidders. Indeed:

Open empirical question 1: *How do payments compare under PaB and UP pricing rules?*

As well as considering outcomes which directly impact on the overall cost of an individual auction, the repeated nature of agri-environment PES schemes requires continued participation by bidders for success in later iterations. We are therefore interested too in the impact of the switch in pricing rule on the cost to bidders in taking part in the auction. How are transaction costs associated with bidding affected by the switch?

We cannot directly answer this question, but rather seek to understand two proxies for the cost of bidding: the number of times a farmer chooses to update their bids, and the degree of sniping involved in the auction. We regard these as costs of participation for slightly different reasons. Clearly, updating bids involves some time cost. Farmers must logon to the website and formulate a revised offer. Contrary to the assumptions running through large swathes of the auction literature, such actions are not cost-less. Rather, farmers manage complex business operations, and therefore face a high opportunity cost of time. The prevalence of sniping would hint at further transaction costs as farmers would face an extra incentive to be active at a specific period in the auction, when they are unlikely to be facing their lowest time cost[16]. Second, sniping is part of a sophisticated bidding strategy, and suggests that such bidders must therefore have engaged in complex reasoning; again, this is costly. Third, sniping is likely to result in provisionally-winning bids being relegated, not because they are relatively high-cost, but rather because the provisionally-successful bidder was not active during the last moments of the bidding window. Individuals who get displaced late on may feel some degree of dissatisfaction with the auction process, a cost to their utility as compared with lower rates of sniping.

[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.

Moreover, the efficiency of the auction may suffer[17].

The different pricing rules are expected to impact these two manifestations of transaction costs through a similar channel. Specifically, in EnTrade's UP auctions, all farmers are incentivised to bid at cost on their lowest cost units and to only bid above cost on their more costly units to the extent they think it will increase the final price paid. On the other hand, in the PaB auction, farmers are incentivised to bid as high above cost as possible while still being accepted. This large difference in the optimal strategy means one would expect the PaB auction to be much more involved. There is a far greater incentive to update bids (in which the gap between cost and bid is predicted to be far larger), and a larger incentive to try and "pip" competitors at the last. Indeed, one would expect:

Hypothesis 2: *Bids are updated less frequently in the UP auction*

And that:

Hypothesis 3: *A lower proportion of bidding activity (bid submission and bid updating) occurs in the last 24 hours 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, like the reduced strategic incentives, decrease the need for bidders to update bids. We are not able to identify whether this mechanism, 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 on these problematic bidding behaviours.

4 Empirical strategy

The data provided to us by EnTrade is exceptionally rich recording details of each and every bidding event in both the Poole Harbour and control catchment auction series.

[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.

Those details include the level of bid, the type of cover crop proposed, the time and date of bidding, the anonymised identity of the bidder, and the anonymised identity of the field parcel for which that bid is placed. Accordingly, not only can we track individual bidders through time, we can also identify bids for specific fields through and across auctions. We exploit this fine-grain detail in order to understand bidding patterns and timings, as well as controlling for pseudo-replication between observations in the regression specifications.

Our analyses focus on two different forms of data arising from each auction series. The first is the level of each final standing bid, including whether it was successful and, if so, how much it was paid. In all cases, these bids and payment amounts are expressed in £2016 per kg of saved nitrogen, having been converted into 2016 prices using the CPI[18]. The second concerns the history of all bid submissions and updates (either a bid revision or deletion and resubmission) through each auction.

Throughout, our aim is causal identification seeking estimates of average treatment effects conditional upon participation.

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 participation decision, denoted d_{it} which takes a value 1 when farmer i chooses to enter a bid for at least one field in auction t, and 0 otherwise. Similarly, we indicate whether a farmer enters a particular field in an auction by d_{ijt}, which again takes a value 1 if field j of farmer i is entered into auction t, and 0 otherwise. We use superscript p to indicate an auction in Poole Harbour and superscript c to indicate an auction in the control catchment. Likewise we use superscript b to indicate any auction that ran before the date of the pricing rule switch (the treatment) in Poole Harbour and superscript a to identify any auction running after that date. With that notation, the set of auctions which happen in the Poole Harbour catchment before the switch in the pricing rule is denoted by $A^{p,b}$, and those in the Poole Harbour catchment

[18] We use estimates for yearly inflation from the Office for National Statistics' "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.

after the switch by $A^{p,a}$. Similarly, the set of auctions in the control catchment before the switch in the pricing rule used in *Poole Harbour* are referred to as $A^{c,b}$, and after as $A^{c,a}$.

To assess Hypothesis 1 we begin with a series of analyses relying on regression discontinuity designs to identify the effect of pricing rule on bid amount. To do so, we use data from all bids across all Poole Harbour auctions. The amount requested in a bid by farmer i for field j in auction t, conditional upon their participation (denoted $Bid_{ijt}|(d_{ijt} = 1)$), is modelled as a function of an indicator variable for the pricing rule used in that auction ($Pricing\, rule_t$), taking a value of 0 for PaB, and 1 for UP, auctions. We control for an estimate of the cost of seed and machinery inputs for the planting of a cover crop at the time of the auction, which is captured as an index relative to 2016 costs ($Cost\ controls_t$)[19]. Thus the estimating equation is:

$$\begin{aligned} Bid_{ijt}|(d_{ijt} = 1) = \beta_0 + \beta_1 Pricing\, rule_t + \beta_2 Cost\ controls_t + \epsilon_{ijt} \\ \forall t \in A^{p,b} \cup A^{p,a} \end{aligned} \tag{1}$$

Our interest is in the estimate for β_1, which is the effect of the pricing rule change on bids. As is the case in implementing all regressions regarding bids and payments in this paper (Equations 1-12), ϵ_{ijt} is estimated using cluster robust standard errors, clustering at the farmer level.

Despite correcting for inflation, as well as controlling for the costs of inputs in a given year, one might be concerned that bid levels are also subject to some underlying time trend. For example, one could imagine that farmers learn over time about their best bidding strategy. If such a time trend existed it would confound the coefficient on pricing rule (β_1) estimated through Equation 1. If one is willing to assume that any underlying

[19]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.

time trend is linear, then an improved regression specification is given by:

$$Bid_{ijt}|(d_{ijt}=1) = \beta_0 + \beta_1 Pricing\, rule_t + \beta_2 Cost\, controls_t + \beta_3 Year_t + \epsilon_{ijt} \qquad \forall t \in A^{p,b} \cup A^{p,a} \tag{2}$$

In which $Year_t$ denotes the year that a particular auction takes place in.

To recover causal estimates of the effect of the pricing rule switch on bids, these regression discontinuity approaches rely on the assumption of exogenous timing of the pricing rule change with respect to wider market conditions. However, a story in which some long-lasting wider-market shock, coincident with the switch in pricing rule, and affecting the economic conditions faced by farmers (and therefore their bids) and not captured by the direct costs farmers face to plant cover crops, would undermine the assertion that this is a causal effect. For example, one could imagine that the trading conditions faced by the farmers changed in 2019 and that for some reason this affected their costs of participation.

We relax this assumption of exogenous timing by pursuing a DiD startegy. Farmers in the control catchment are arable farmers within England and so likely exposed to the same market pressures, but continue to participate in PaB auctions even after the switch in Poole Harbour. We first ascertain whether there is a statistically significant difference in average annual change in bid amount across catchments prior to the switch in pricing rule[20]:

$$Bid_{ijt}|(d_{ijt}=1) = \beta_0 + \beta_1 Year_t + \beta_2 Catchment_t + \beta_3 Year_t \times Catchment_t + \epsilon_{ijt} \qquad \forall t \in A^{p,b} \cup A^{c,b} \tag{3}$$

Where $Catchment_t$ is an indicator variable for whether the auction took place in Poole Harbour (given a value 1) or in the control catchment (0). This regression tests for the

[20]Note no price controls are included as data limitations mean these are co-linear with the time trend in the DiD estimates and hence cannot be independently identified.

"parallel trends" assumption of the DiD approach, and therefore controls for a common time trend and any constant difference between catchments. Hence our interest is in the estimate of β_3: is there a statistically significant difference in the mean change in bids in these catchments pre-intervention, which would undermine the assumption of the DiD approach. To be clear, there is limited data with which to make this inference because the two catchments only use PaB auctions at the same time in two years. We go on to find no significant difference between catchments - and hence cannot reject that the rate of change in bids is the same across them.

To understand the impact of the pricing rule change in the Poole Harbour catchment, we build on the basic insight that bids in the control catchment are a relatively good proxy for expected bids in Poole Harbour, albeit with a step change in the bid amounts. There are relatively few data points with which to parameterise the model examining the effect of the switch in pricing rule on bids, owing to the few number of times that the auctions in the two catchments both ran with PaB pricing (2017 and 2018). Hence, we build up to a fully flexible model relaxing particular assumptions present in our initial models. However, our preferred specification is also the simplest. While it imposes additional assumptions on the data generating process, it affords the greatest power to identify any impact of the switch in pricing rule. That preferred specification is:

$$\begin{aligned} Bid_{ijt}|(d_{ijt}=1) = \beta_0 + \beta_1 Catchment_t + \beta_2 After\ intervention_t + \\ \beta_3 After\ intervention_t \times Catchment_t + \epsilon_{ijt} \\ \forall t \in A^{p,b} \cup A^{p,a} \cup A^{c,b} \cup A^{c,a} \end{aligned} \tag{4}$$

In which the variable "After $\text{intervention}_\text{t}$" is an indicator variable which takes a value of 1 for auctions that occur in 2019 and 2020 (i.e. after intervention in the Poole Harbour catchment) *regardless* of which catchment the auction took place in. This model excludes (by assumption) any change in bids as a result of a time trend, and further excludes the possibility that the switch in the pricing rule in Poole Harbour affected a time trend. Rather, it simply estimates mean bids in each catchment before and after the intervention in Poole Harbour.

A more flexible model allows for a linear time trend, but restricts this to be the same for both catchments regardless of whether this is before or after the switch in the Poole Harbour catchment:

$$\begin{aligned} Bid_{ijt}|(d_{ijt}=1) = \beta_0 + \beta_1 Year_t + \beta_2 Catchment_t + \beta_3 After\ intervention_t + \\ \beta_4 After\ intervention_t \times Catchment_t + \epsilon_{ijt} \\ \forall t \in A^{p,b} \cup A^{p,a} \cup A^{c,b} \cup A^{c,a} \end{aligned} \tag{5}$$

Greater flexibility in the time trends is incorporated by first allowing the linear time trend to be different in different catchments, but fixed through time:

$$\begin{aligned} Bid_{ijt}|(d_{ijt}=1) = \beta_0 + \beta_1 Year_t + \beta_2 Catchment_t + \beta_3 Year_t \times Catchment_t + \\ \beta_4 After\ intervention_t + \beta_5 After\ intervention_t \times Catchment_t + \epsilon_{ijt} \\ \forall t \in A^{p,b} \cup A^{p,a} \cup A^{c,b} \cup A^{c,a} \end{aligned} \tag{6}$$

And second by re-imposing the assumption any time trend is fixed across catchments; instead allowing the time trend to vary before and after intervention:

$$\begin{aligned} Bid_{ijt}|(d_{ijt}=1) = \beta_0 + \beta_1 Year_t + \beta_2 Catchment_t + \beta_3 After\ intervention_t + \\ \beta_4 After\ intervention_t \times Year\ minus\ year\ of\ intervention_t + \\ \beta_5 After\ intervention_t \times Catchment_t + \epsilon_{ijt} \\ \forall t \in A^{p,b} \cup A^{p,a} \cup A^{c,b} \cup A^{c,a} \end{aligned} \tag{7}$$

Here, "Year minus year of intervention$_t$" is a continuous variable reflecting the number of years between the year of intervention and the year the auction takes place regardless of catchment. Hence, this takes a value of 1 in 2019 and a value of 2 in 2020. The most flexible model relaxes both assumptions about the time trend simultaneously - allowing the time trend to vary both by catchment (β_3), and after intervention (β_5). Moreover, the effect of the UP rule on bids in Poole Harbour is additionally permitted to result in a shift in mean bids (β_6) and an additional divergence in the slope of the catchment-specific time trend (β_7):

$$\begin{aligned} Bid_{ijt}|(d_{ijt}=1) = \beta_0 + \beta_1 Year_t + \beta_2 Catchment_t + \beta_3 Year_t \times Catchment_t + \\ \beta_4 After\ intervention_t + \beta_5 After\ intervention_t \times Year\ minus\ year\ of\ intervention_t + \\ \beta_6 After\ intervention_t \times Catchment_t + \\ \beta_7 After\ intervention_t \times Year\ minus\ year\ of\ intervention_t \times Catchment_t + \epsilon_{ijt} \\ \forall t \in A^{p,b} \cup A^{p,a} \cup A^{c,b} \cup A^{c,a} \end{aligned} \tag{8}$$

Our primary research interest is in establishing the overall causal change in bids driven by the switch in pricing rule. However, given that we find such a change exists, and owing to the extremely fine-grain detail at which we observe individual bids in our sample, we further 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) which change the costs of saving nitrogen; or 4) the farmers simply respond to the incentives they face and hence reduce the shading included in their bids. We investigate this question by adding fixed effects for farmer, field and cover crop choice, in turn, to Equation 2.

As highlighted in Open Empirical Question 1, the amount stated in a bid is in part of interest because of its impact on payments. Hence we additionally investigate the effect of pricing rule on payments in Poole Harbour. Restricting the analysis to bids which are successful, and hence paid (recall, the amount paid is independent of the bid in the UP but not the PaB), we specify another estimating equation. In this case, we model the amount paid to a successful bid ($Payment_{ijt}|(f_{ijt}=1)$) as a function of the pricing rule:

$$Payment_{ijt}|(f_{ijt}=1) = \beta_0 + \beta_1 Pricing\ rule_t + \epsilon_{ijt} \qquad \forall t \in A^{p,b} \cup A^{p,a} \tag{9}$$

Subsequently we parameterise a model which corrects for any underlying linear time trend:

$$Payment_{ijt}|(f_{ijt}=1) = \beta_0 + \beta_1 Pricing\ rule_t + \beta_2 Year_t \epsilon_{ijt} \qquad \forall t \in A^{p,b} \cup A^{p,a} \tag{10}$$

Using data from all Poole Harbour auctions obviously confounds the effect of changing the auction pricing rule with any effect that might have also arisen from the simultaneous change in the auction constraint rule which switched from a budget constraint to a quantity constraint. Changing the constraint on the auction could have the effect of purchasing nitrogen reduction from (on average) a potentially more or less costly part of the cost distribution of farmers irrespective of any change in pricing rule if the budget imposed over- or under-estimates the amount of money required to buy the same quantity as before[21]. To circumvent this issue, we take bids as given and instead assume that EnTrade had maintained a constraint of 18,000kgs across all auctions, assessing winners on this basis. The assumption of bids remaining constant is obviously a best approximation. In both the PaB auctions with a target over 18,000kgs and all UP auctions (which bought far more than 18,000kgs) the expected impact of a lower target would be lower bids, owing to increased competitive pressures[22]. Our analysis does not account for this effect. But only two of the five PaB auctions are affected (one of which is the 2016 auction

[21] There is no reason to think that switching between a budget or quantity constraint in itself has any effect on bids. If these represented merely the vertical and horizontal coordinates of the same point on the supply curve it would not matter how such a point was identified. Rather, the problem for our analysis arises in that different auctions accept bids from more or less of the overall supply curve, and hence the successful bids have different underlying cost distributions.

[22] Indeed, the penultimate column of Table 2 makes very clear that change in constraint led to less competitive auctions: a far greater % of all bids are accepted.

which is also dropped in most specifications), rather than all four of the UP auctions. Moreover, the much higher target in UP auctions increases the percentage of bids which are accepted in UP auctions by more than in PaB auctions (as can be seen in Table 2) thus the reduced competitive effect is much stronger in the UP than PaB auctions. Therefore, our view is that suggesting bids remain unchanged if the constraint were maintained represents a comparison which, if anything, would over-estimate payments in the UP. We therefore construct a new indicator variable h_{ijt} which indicates whether a bid would, hypothetically, have been accepted had the auction used an 18,000kg target. We evaluate the impact of the change in pricing rule on payments to hypothetically successful bids (denoted $Payment_{ijt}|(h_{ijt} = 1)$) first without, and then with, a linear time trend:

$$\begin{aligned} Payment_{ijt}|(h_{ijt} = 1) = \beta_0 + \beta_1 Pricing\, rule_t + \epsilon_{ijt} \\ \forall t \in A^{p,b} \cup A^{p,a} \end{aligned} \tag{11}$$

$$\begin{aligned} Payment_{ijt}|(h_{ijt} = 1) = \beta_0 + \beta_1 Pricing\, rule_t + \beta_2 Year_t + \epsilon_{ijt} \\ \forall t \in A^{p,b} \cup A^{p,a} \end{aligned} \tag{12}$$

To mitigate against any affects of the changing reserve price and eligible number of farmers between years, as well as any learning that occured following the initial auction in 2016, we do not always employ the full data set in estimation. For the regression discontinuity designs without a time trend (Equations: 1, 9, and 11) we initially use the full dataset before excluding first just 2016 data, and subsequently also exclude bids in 2020 and any bid above £2.00 in 2017 or 2018[23]. We can only parameterise the regression discontinuity designs which include a time trend (Equations 2, 10, and 12) with the full data set, and with the data excluding 2016. Attempting to parameterise these equations using the smallest data set - which excludes bids in 2020 - fails as we are then unable to independently identify the time trend and the effect of the cost controls, and hence

[23]Note that the £2.00 here refers to 2017 and 2018 prices, respectively.

one coefficient is undefined owing to collinearity. For the DiD designs (Equations 3 to 8) we focus exclusively on the data set which excludes the 2016 data from Poole Harbour catchment as no auction occurred in the control catchment that year. Note that our treatment of the reserve price is likely to bias assessment in favour of the PaB auction: bids between £2.00 and £2.50 are typically excluded, yet in reality had the bidder faced a £2.00 reserve price they may well have chosen to bid a little below it if their costs were below this lower reserve [24].

We are interested too in the behaviour of individual participants in the Poole Harbour auction, and the costs that they face. To answer Hypothesis 2 we model the probability that any given action (bid submission or updating) is an update to a bid conditional upon participation ($P(update|action)_{ijt}|(d_{ijt} = 1)$) as a function of the pricing rule in the auction. Hence:

$$\begin{aligned} P(update|action)_{ijt}|(d_{ijt} = 1) &= \beta_0 + \beta_1 Pricing\,rule_t + \epsilon_{ijt} \\ &\forall t \in A^{p,b} \cup A^{p,a} \end{aligned} \tag{13}$$

We identify the effect on sniping in a similar manner to provide insight on Hypothesis 3. We define "sniping" as any action (either an initial submission or an update) which occurs in the last 24 hours of an auction window, and therefore 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:

$$\begin{aligned} P(snipe|action)_{ijt}|(d_{ijt} = 1) &= \beta_0 + \beta_1 Pricing\,rule_t + \epsilon_{ijt} \\ &\forall t \in A^{p,b} \cup A^{p,a} \end{aligned} \tag{14}$$

In Equations 13 and 14 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

[24] A lower reserve price could additionally act as an anchor (as in Gao et al., 2019 and Li et al., 2019) hence ignoring this effect by simply assuming other bids remain unchanged could result in a slight over-estimate of bids in the years 2017 and 2018 had a lower reserve been used.

be updated through the auction. We again run these analyses with and without the data for 2016 to mitigate against any effect being driven by learning. To reiterate, we identify the total effect of UP pricing on bid updating, (potentially) resulting from both the lower strategic incentives to update the degree of shading included within a bid and by more bids being accepted because bids are lower.

5 Results

5.1 Auction summary statistics

We first consider overall auction outcomes. As is clear in Table 2 while the auctions are always open to a large number of 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 6 newly-eligible bidders participate. Moreover, we also see relatively high turnover in bidders between auctions. Across all auctions, 43 different bidders ever participate, despite the maximum in any one auction of 19. The difference is of course explained by the fact that the benefit of winning a contract to a particular bidder may change through time and be 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.

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

Table 2: Summary statistics of auction outcomes

Table 2 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 (a notable exception being January 2017 when just two-fifths 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, and just a 1.6% rejection rate in June 2019. Second, and potentially in part 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 (˜18,000kg)[25]. This itself is in part driven by the budget in UP auctions being more than was actually required to meet the 18,000kg target.

5.2 Effects on bids

The bids that are placed for measures on individual fields are displayed in Figure 3, with the bid amount displayed 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. 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. Hence, one might have expected that bids in each auction collapse to one bid as participants learn the marginally winning bid[26]. The range of placed bids is greatest in 2016, while in later auctions this range

[25] As explained previously, 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.

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 (illustrated, in £2016, by the horizontal red lines). It is worth highlighting, that while the reserve prices may influence the highest bids, the maximum bids in June 2019 are much 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 as defined horizontal "lines" of bids in Figure 3. Rather than reflecting that bids are submitted at the marginally accepted price at the time of submission, these lines simply show individual farmers submitting multiple fields at the same price. Interestingly, these lines often happen at 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 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, Figure 3 identifies a noticeable step down in bids moving from the PaB auctions to the UP auctions, a finding consistent with theory. Table 3 presents a formal analysis of the mean change in bids identified using the regression discontinuity approach specified in Equations 1 and 2. Across regression specifications, bids tend to be significantly lower in the UP auctions than in the PaB auctions. The lone, non-significant result is for the smallest dataset and hence associated with a very large error in estimation, and still shows a substantial reduction in bids. Not only are most of the estimated pricing rule effects statistically significant, they are all economically meaningful. Across our four preferred specifications, the effect of UP pricing is to lower bids by between 68 and 83 pence per kilogram of saved nitrogen. this compares to a mean bid of £1.79 in the PaB auctions, and is therefore equivalent to a ˜40% reduction in bids.

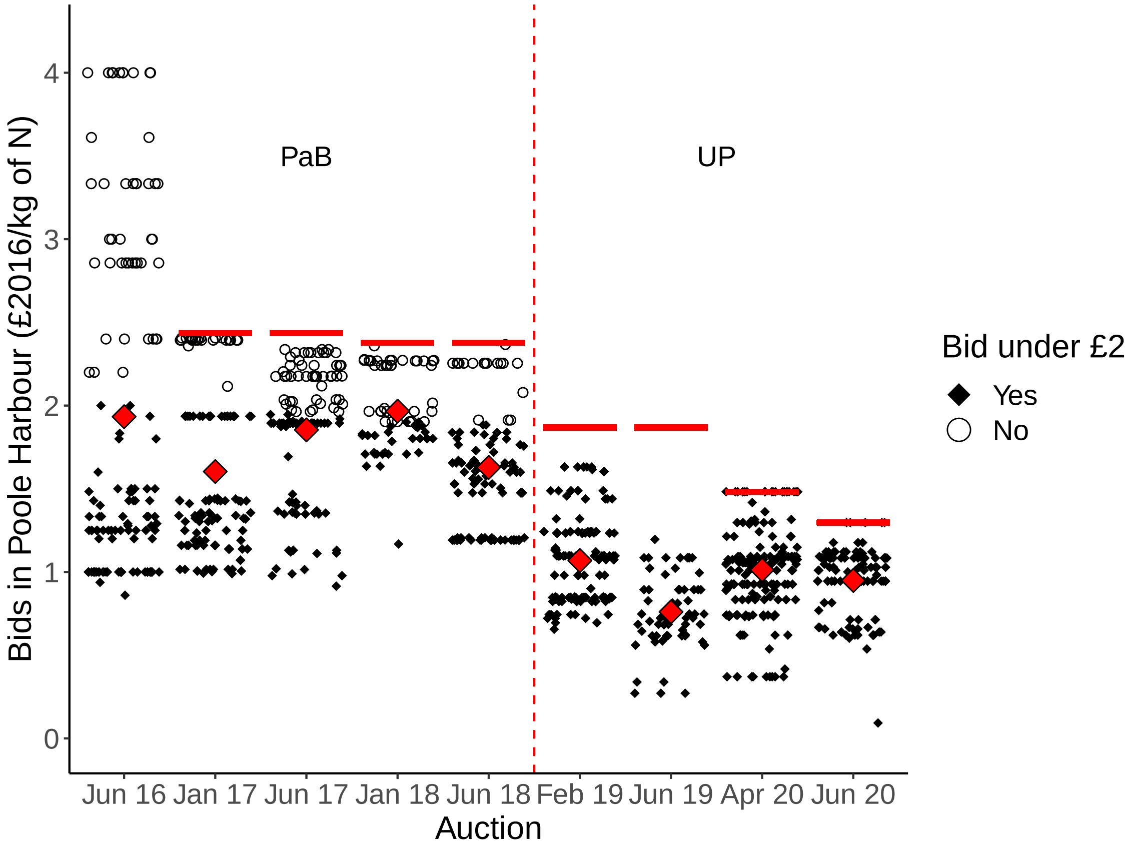


Figure 3: Final bids in each auction.

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).

	(1)	(2)	(3)	(4)	(5)
Sample:	Full sample		Excl. '16		Additionally excl. '20 & bids > £2.00
Pricing Rule	-0.736***	-0.686***	-0.778***	-0.829***	-0.360
(Uniform price = 1)	(0.074)	(0.187)	(0.093)	(0.139)	(0.482)
Cost controls:	Yes	Yes	Yes	Yes	Yes
Linear time trend:	No	Yes	No	Yes	No
Number of observations:	987	987	861	861	456
Number of clusters:	43	43	42	42	29

Table 3: The effect of pricing rule on bids in Poole Harbour in 2016 prices (£/kg of N).

Notes: Clustered standard errors in parentheses.

* p<0.1, ** p<0.05, *** p<0.01

Our regression discontinuity specifications provide a clear indication of significant and substantial effects of the impact of the change in pricing rule on bids. However, one may be concerned that a long-lasting change in wider market conditions, concurrent with the switch to UP pricing in Poole Harbour auctions, drives results such that the effects reported in Table 3 are spurious correlation rather than causal impacts. To mitigate against such an eroneous conclusion, we use data from the control catchment (which maintained a PaB pricing rule throughout) to ascertain the causal effect through a DiD identification strategy. Mean bids in each year (excluding the 2016 data from Poole Harbour) are displayed in Figure 4 for each catchment. Note that to maintain confidentially 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. Indeed, results of the regression analysis using Equation 3 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 = 0.241).

Turning to the impact of the pricing rule intervention, Table 4 reports estimates from the DiD regressions from Equations 4 to 8 (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).

Column (1) 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 after intervention. The results are notable for two reasons. First, it shows clear evidence of a highly significant and substantial reduction in mean bids. Second, our DiD results are strikingly similar to the results from our regression discontinuity analyses, reported in Table 3. The core finding, of substantially and significantly lower bids is robust to different econometric specifications. 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. We are reticent to over-interpret those results: with only two years' worth of data before and after intervention in each catchment, we have very little power with which to precisely identify many of the effects. Nonetheless, in all specifications, the clear result is that bids are substantially reduced, and this is always significant to at least $p < 0.1$.

Of course, none of these results would be robust to a story which suggests that the change in Poole Harbour bids was driven by a long-lasting change which happened to affect Poole Harbour farmers, but not similar arable farmers in a different English catchment. We are unable to rule such a story out, however, we are not aware of any real-world events which would support such a theory. Accordingly, we believe that our regression discontinuity and DiD analyses provide strong and consistent support for a statistically and economically significant reduction in bid levels under a UP pricing rule in comparison to those under PaB pricing.

	(1)	(2)	(3)	(4)	(5)
	Effect size (std. err.)				
After intervention × Catchment (Poole Harbour = 1)	-0.764*** (0.107)	-0.783*** (0.097)	-0.510* (0.292)	-0.783*** (0.098)	-0.567* (0.315)
After intervention × Year minus year of intervention × Catchment (Poole Harbour = 1)	-	-	-	-	0.112 (0.207)
	Absolute t-values				
Year	-	0.83	1.72*	0.55	2.86***
Catchment	9.53***	9.79***	1.56	9.70***	0.91
Year × Catchment	-	-	1.15	-	1.20
After intervention	0.02	0.62	1.26	0.55	0.88
After intervention × Year minus year of intervention	-	-	-	0.25	1.15
Number of observations:			1,027		
Number of clusters:			61		

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

Notes: The results reported in Columns (1) to (5) are parameterised using Equations 4 to 8, respectively, and 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 so as 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

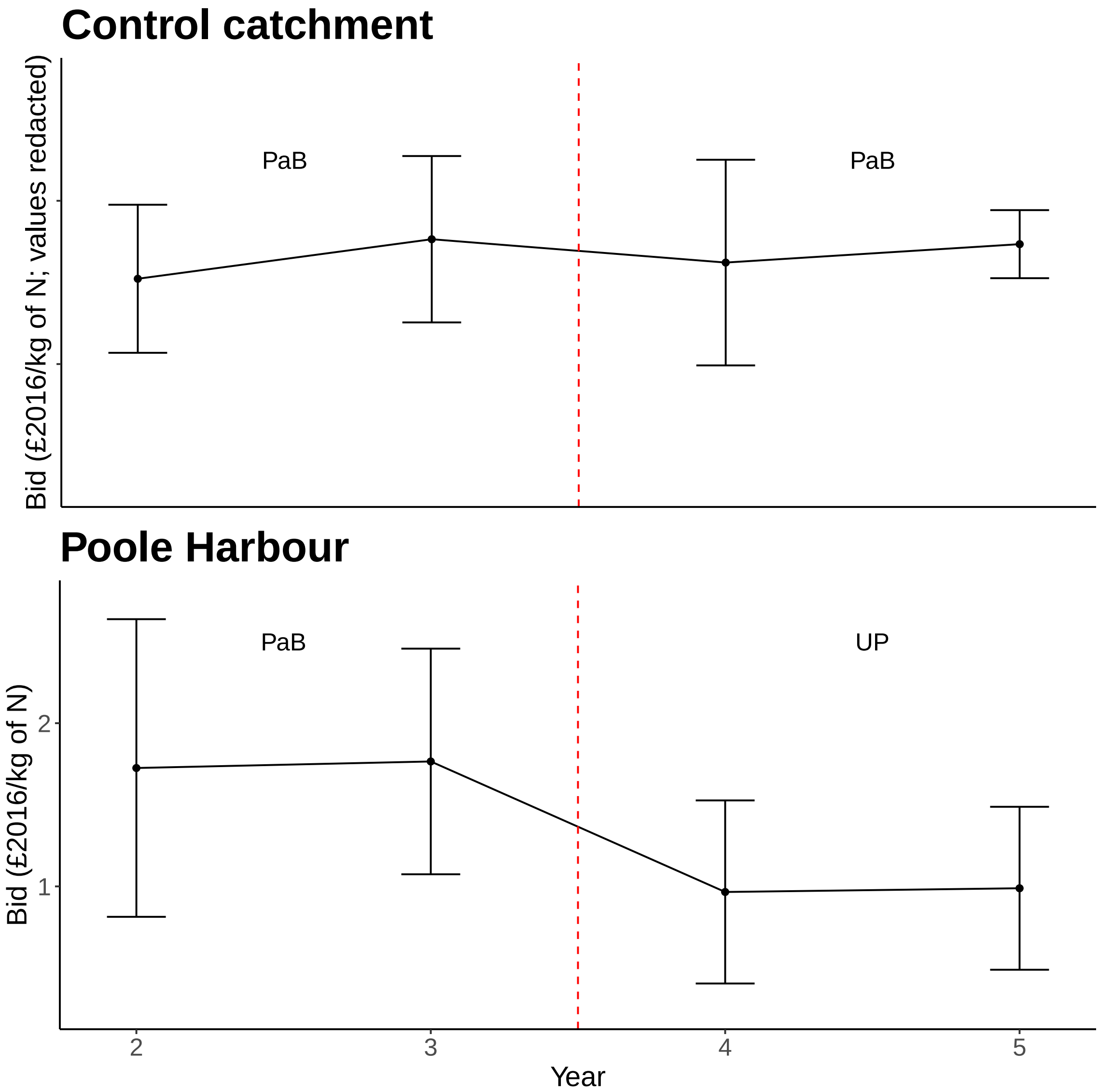


Figure 4: Bidding trends in the Poole Harbour and control catchment auctions.

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 $mean \pm 1.96 \times std.dev.$. 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.

5.3 Possible mechanisms underlying changes in bids

Our analysis confirms that the switch to the UP pricing rule 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 can be found in the changing incentive properties of the two pricing rules; bids are lower under a UP pricing rule because farmers no longer have an incentive to overstate their costs in bids on low-cost fields; rather bidding at cost on such fields is their best strategy. However, there are rival explanations. First, it is possible that farmer preferences over auction institutions play a role, and for some reasons farmers facing lower costs are more likely to enter UP auctions. Two further explanations are that the UP auction encourages farmers to submit bids on lower cost fields, or for lower cost cover crop species. Note that these run counter to economic reasoning which would expect that farmers in the PaB auctions are already bidding in ways to minimise the costs they face.

Table 5 presents mean bids for farmers (5a) and fields (5b) based upon whether they participated in the auctions run in 2018 and 2019 - either side of the change in pricing rule. Observe that the change in mean bid is similar for farmers (and fields) who participated in both 2018 and 2019 auctions as compared to the change in bids of those only participating in one or other year. This suggests that the causal changes in bids observed in both the regression discontinuity and DiD approaches are not driven by lower-cost farmers, or fields, being more likely to participate in UP auctions.

Moreover, Table 6 reports regression results from Equation 2. In columns 2-4 we additionally include fixed effects to control for farmer participation, field selection and cover crop choice. By doing so we can ascertain the effect of UP pricing on bids *conditional* upon three hypothesised mechanisms[27]. If any such mechanism were driving the impact of UP pricing, we would expect a substantial difference 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

[27]We are unable to control for all three mechanism 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.

	Mean bid in 2018	Mean bid in 2019
Farmers in 2018 and 2019	1.74	0.98
Farmers in 2018 only	1.89	-
Farmers in 2019 only	-	0.89

(a) Mean bids (£2016/kg of N) for different farmers

	Mean bid in 2018	Mean bid in 2019
Fields in 2018 and 2019	1.72	0.98
Fields in 2018 only	1.80	-
Fields in 2019 only	-	0.96

(b) Mean bids (£2016/kg of N) for different fields

Table 5: Average bids for individual farmers (5a) and fields (5b) split by whether they bid in the 2018, 2019 or both, auctions.

extremely close to that reported in the regression which does not include any fixed effects for mechanism (Column 1). Taken together, there is clear evidence that bidders are simply reducing the degree of shading included within their bids, appropriately responding to the incentives of the UP pricing rule.

	(1)	(2)	(3)	(4)
Mechanism controlled for:	None	Farmer participation	Field selection	Cover crop choice
Pricing Rule	-0.829***	-0.765***	-0.810**	-0.832***
(Uniform price = 1)	(0.139)	(0.143)	(0.312)	(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	861	861	861
Number of clusters:	42	42	42	42

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).
Notes: Clustered standard errors in parentheses.
* p<0.1, ** p<0.05, *** p<0.01

5.4 Changes in payments

While funders who care about efficiency are likely to want bids to be a more accurate reflection of costs, they are more typically concerned with achieving value-for-money. That is, ensuring that they spend as little as possible in achieving a particular quantity target, or generate the greatest environmental change for a fixed budget. Accordingly, we also explore what happens to the amount that successful bids are *paid* across auction pricing rules. Recall, that the PaB auction pays bids the amount specified in the bid, while in the UP auction all bids receive the amount specified in the marginally-accepted bid. Hence, there is no *a priori* reason to expect that payment amount would move in the same direction as bid amount, as is made clear in Open empirical question 1.

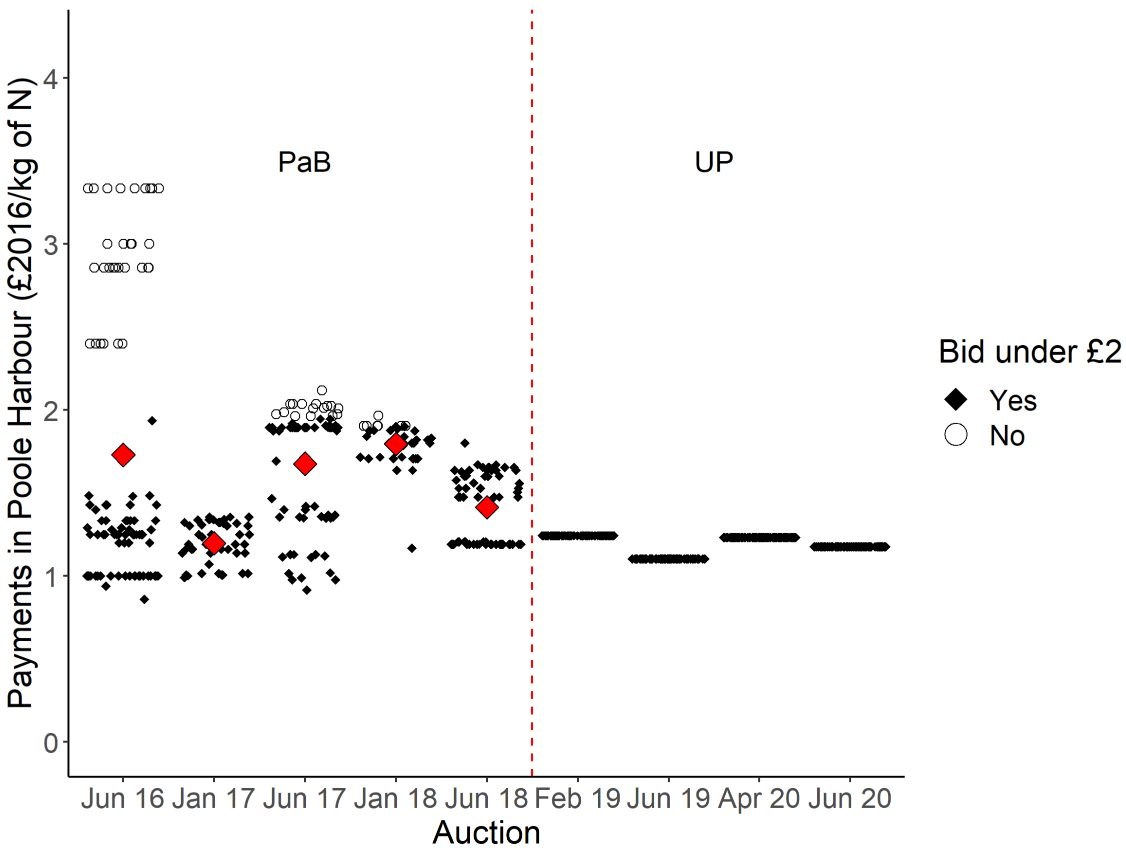


Figure 5: Actual payments paid to successful bids.

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.

Figure 5 displays the amount paid to each successful bid, and mean payment, in each Poole Harbour auction. The impact of the pricing rule change is perhaps most obvious in the reduction in spread of payments. While in the 2016-2018 auctions there is a great deal of variation in the amount which successful bids are paid, in 2019 and 2020 UP auctions all winning bids are paid the same amount, and hence no variation remains. The mean amount paid in each auction varies; payments made in the UP auctions appear generally lower than those made in the PaB auctions. Indeed, as Table 7 makes clear, the direction of the effect is negative - payments in the UP auction are, on average, lower, and this tends to be statistically significant. Moreover, the effects tend to be economically meaningful; mean payments were close to £1.60 before the pricing rule switch, and hence the estimated effects typically account for a reduction in mean payment of between 16 and 25%.

	(1)	(2)	(3)	(4)	(5)
Sample:	Full sample		Excl. '16		Additionally excl. '20 & bids > £2.00
Pricing Rule	-0.310***	-0.252	-0.331***	-0.401**	-0.054
(Uniform price = 1)	(0.059)	(0.192)	(0.062)	(0.161)	(0.399)
Cost controls:	Yes	Yes	Yes	Yes	Yes
Linear time trend:	No	Yes	No	Yes	No
Number of observations:	724	724	627	627	369
Number of clusters:	39	39	39	39	28

Table 7: The effect of pricing rule on actual, inflation adjusted, payments (£).
Notes: Clustered standard errors in parentheses.
* p<0.1, ** p<0.05, *** p<0.01

As discussed earlier, any effect of pricing rule in this analysis could be masked by the effect of the simultaneous changes in the auction constraint. 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 result would be significantly under-estimating how much UP pricing reduced payments by relative to PaB in the results presented in Table 7.

To identify only the effect of the pricing rule change on auction outcomes, we consider the impact that might have been realised had the same constraint - buying up to 18,000kg of N - been maintained (as explained in Section 4 regarding Equations 11 and 12). The hypothesised payments under such an approach are presented in Figure 6. There appears a much more pronounced reduction in payments in the UP auction compared to the PaB auctions once the constraint is held fixed.

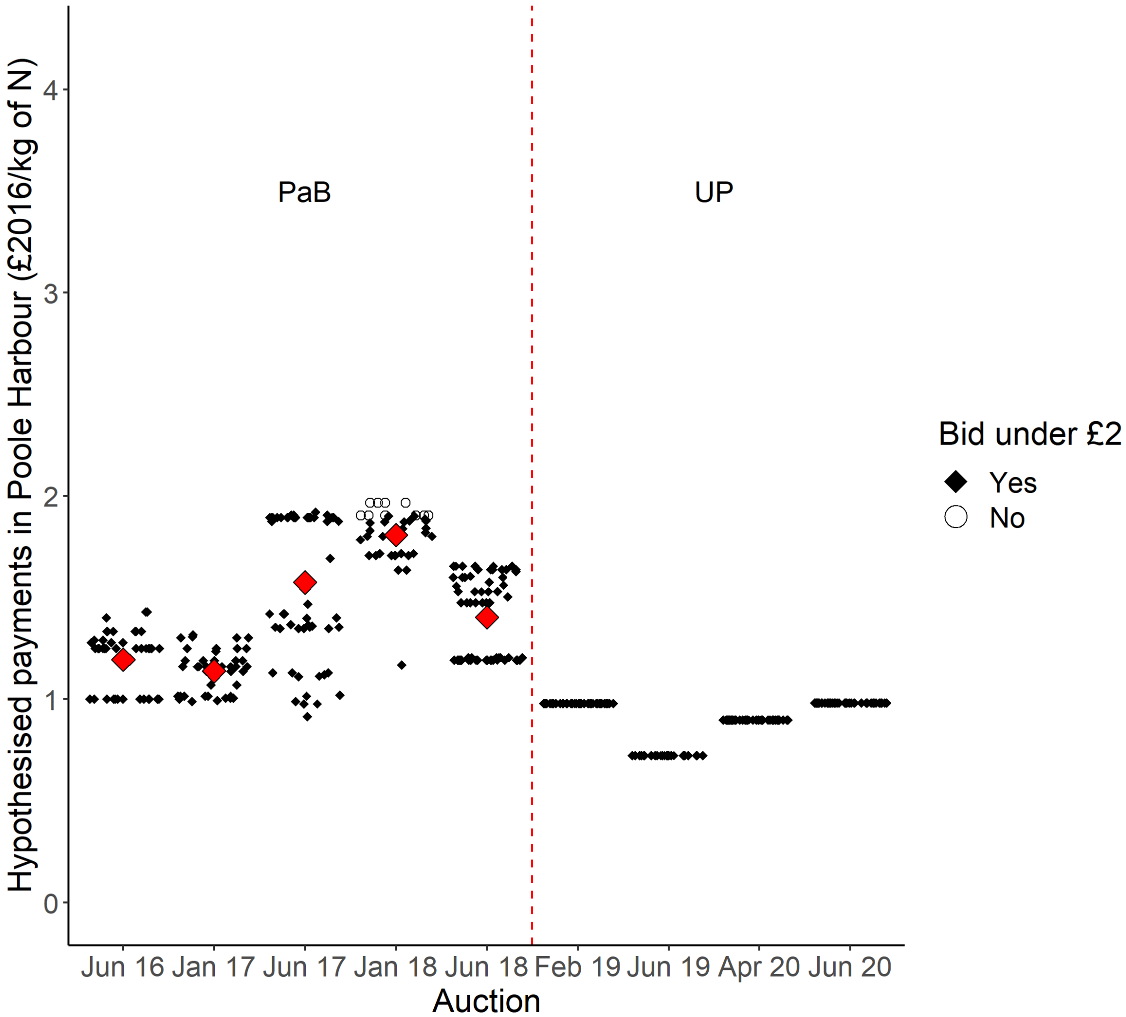


Figure 6: Hypothesised payments paid to successful bids if the 18,000kg of N constraint was maintained.
Notes: To the left of the red dashed line auction operate as PaB; to the right as UP. The red diamond is the mean hypothesised payment, included for the PaB auctions only as in the UP auctions all successful bids are paid the same amount.

Indeed, Table 8 presents regression results which show, that in all but one regression specification the decline in hypothetical payments caused by the switch in pricing rule is statistically significant. What is more, in all specifications the effect is economically meaningful, typically reducing mean hypothesised payments by between 38 and 56% relative to under PaB pricing. Indeed, the lower than anticipated rate of payment ensured that in Poole Harbour, Wessex Water was able to fund far more nitrogen removal measures in UP than PaB auctions (as can be seen in the last column of Table 2).

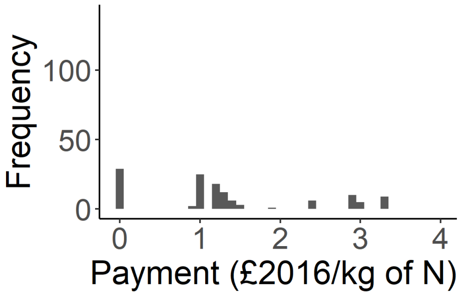
	(1)	(2)	(3)	(4)	(5)
Sample:	Full sample		Excl. '16		Additionally excl. '20 & bids > £2.00
Pricing Rule	-0.624***	-0.833***	-0.568***	-0.774***	-0.289
(Uniform price = 1)	(0.107)	(0.131)	(0.097)	(0.197)	(0.430)
Cost controls:	Yes	Yes	Yes	Yes	Yes
Linear time trend:	No	Yes	No	Yes	No
Number of observations:	431	431	389	389	281
Number of clusters:	29	29	29	29	25

Table 8: The effect of pricing rule on hypothesised, inflation adjusted, payments (£).
Notes: Clustered standard errors in parentheses.
* p<0.1, ** p<0.05, *** p<0.01

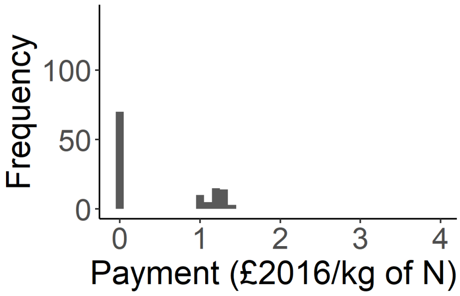
While the data clearly identify that payments per kg of saved nitrogen received by successful bidders are lower in the UP auctions, an interesting counterpoint is that Poole Harbour farmers report to EnTrade a general preferences for the UP pricing rule over the PaB rule (Peacock, 2021). Of course, this could be because of lower costs associated with bidding (which are investigated in the next Subsection, 5.5). However, a further possibility concerns the perceived fairness of UP auctions[28]. To explore this, Figure 7 shows the frequency of different payments made to all fields entered in each auction (as £ per kg of N amounts, in 2016 prices). The difference as compared with the previous analyses on payments, is that here those fields which have unsuccessful bids are included as a mass at a payment of £0.00. In all cases, the auctions are associated with a bi-modal distribution - a peak at £0.00, and then another mass of bids between £1.00 and £2.00. There are two patterns clear in the UP auction payments (7f to 7i) as compared with the payments in PaB auctions (7a to 7e). First, a greater proportion of bids are successful in UP auctions, which is likely driven by a combination of lower bids and a budget which allowed for the purchasing of more nitrate reduction measures. Second, and by construction of the pricing rule, all successful bids are paid the same amount in the UP auctions, whereas the

[28]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.

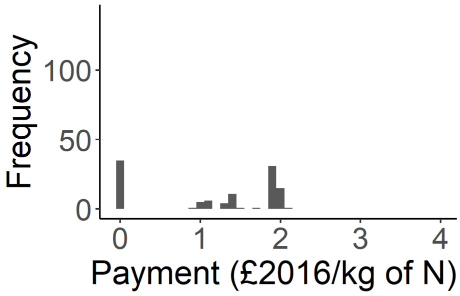
amounts vary, often quite considerably, in the PaB auctions. This may well mean that there is a greater perception of fairness in the UP than PaB auctions, encouraging farmer participation. Accordingly, farmers may prefer the UP auctions because their bids are more likely to be accepted, and they perceive the payments as fairer.



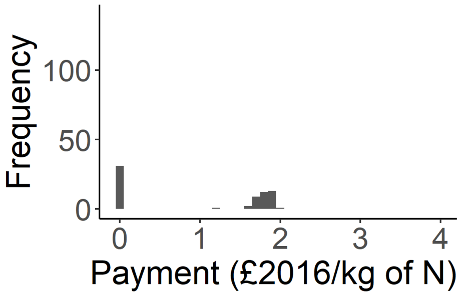
(a) "June 2016"



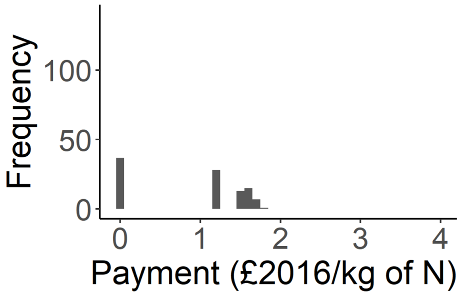
(b) "January 2017"



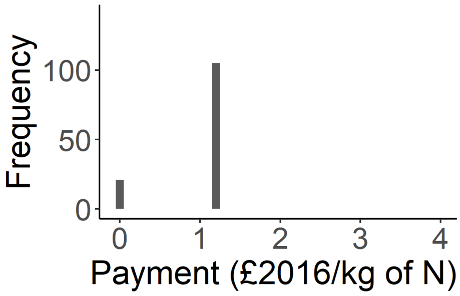
(c) "June 2017"



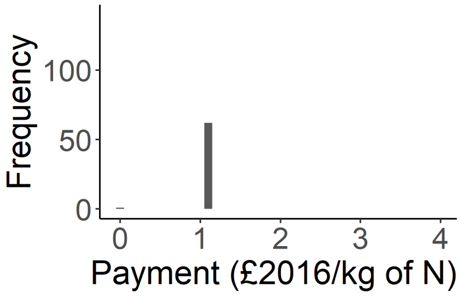
(d) "January 2018"



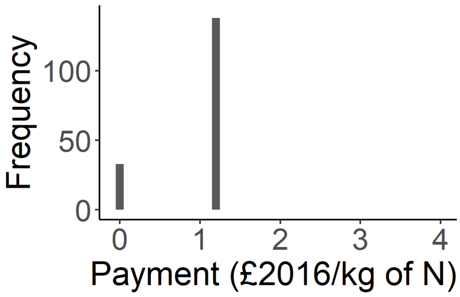
(e) "June 2018"



(f) "February 2019"



(g) "June 2019"



(h) "April 2020"

(i) "June 2020"

Figure 7: Histograms displaying the frequency of different payment amounts in each auction.

5.5 Differences in participation costs

Our analyses examine the impact of pricing rule 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. Figure 8 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.

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. People are choosing to submit and update their bids relatively late into bidding windows. A visual inspection suggests that black diamonds are far more common in PaB auctions (below the red dashed line) than in UP auctions, suggesting updates are more frequent in the PaB setting. This is also illustrated by the proximity of the blue triangles to the red circles in UP auctions, whereas in the PaB auctions they are approximately half way between the red circles and diamonds. Blue triangles are also shifted slightly left in UP than PaB auctions overall - highlighting that actions occur somewhat earlier in UP auctions. Moreover, the density of all points right of the red vertical lines, seems higher in PaB than UP auctions. These results would be in keeping with Hypotheses 2 and 3, respectively.

A formal statistical analysis, presented in Table 9, 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. Furthermore, the degree of sniping has 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[29].

	(1)	(2)	(3)	(4)
Bidding behaviour:	Updating		Sniping	
Sample	Full sample	Excl. '16	Full sample	Excl. '16
Pricing Rule	-0.342***	-0.362***	-0.143***	-0.184***
(Uniform price = 1)	(0.024)	(0.025)	(0.028)	(0.029)
Constant	0.565***	0.585***	0.492***	0.533***
	(0.015)	(0.017)	(0.019)	(0.021)
Number of observations:	2,202	1,920	2,202	1,920
Number of clusters:	1,175	1,027	1,175	1,027

Table 9: The effect of pricing rule on the probability a particular activity is bid updating (columns 1 and 2) and sniping (columns 3 and 4).

Notes: A bid activity could be neither updating nor sniping (e.g. a bid submission >24hrs 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

[29] 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.

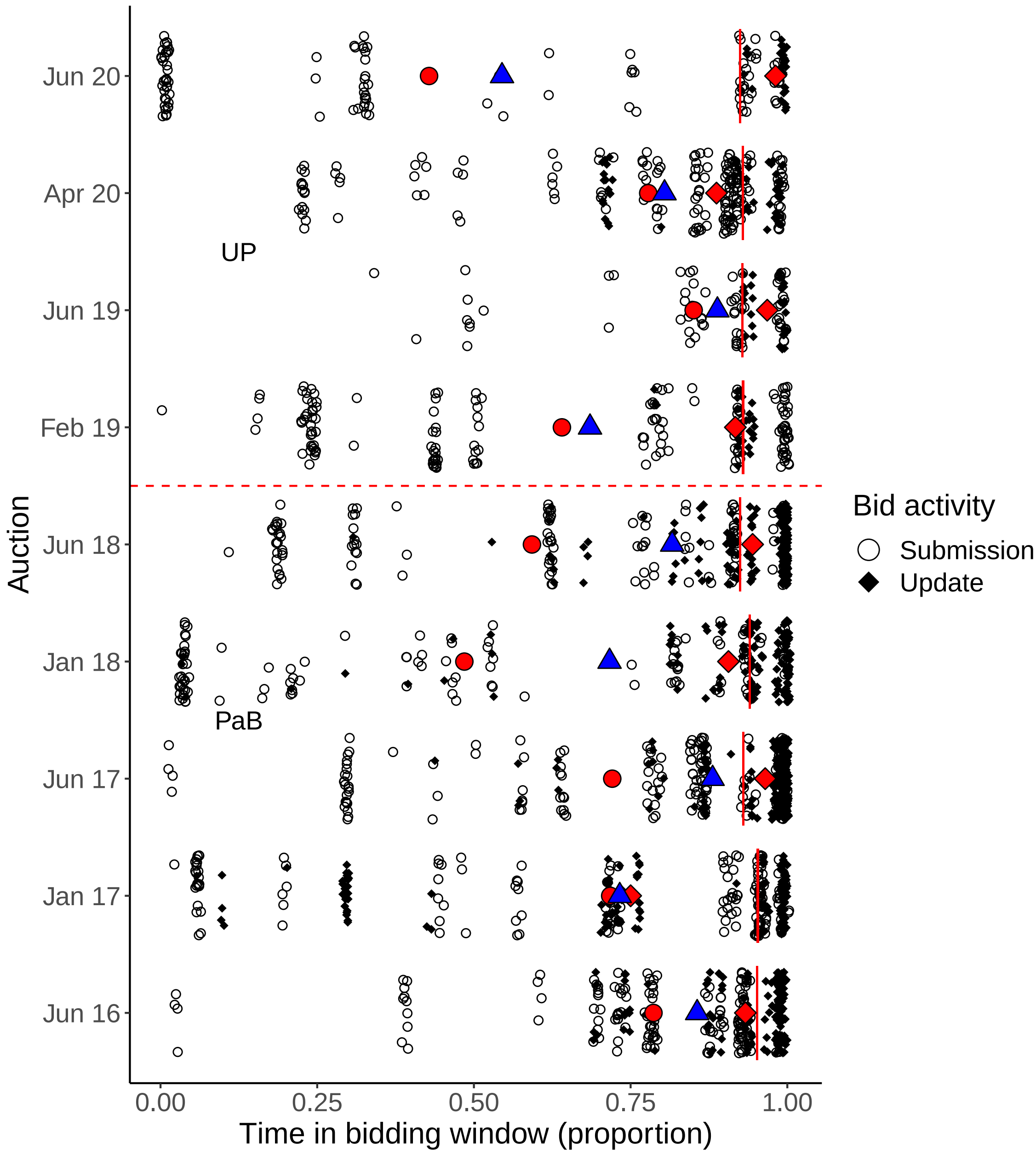


Figure 8: Bidding behaviour in auctions: updating illustrated by solid diamonds (rather than bid submissions which are hollow circles), sniping by the number of points which fall in the last day.

Notes: Red vertical lines in each auction represent the point at which the last 24 hour 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.

6 Concluding remarks

This paper presents the results of the first field experiment comparing the impacts of different auction pricing rules on outcomes of an agri-environment PES programme. The results of our regression discontinuity design find very clear, statistically significant, and economically substantial reductions in bids from participants caused by the exogenous change from PaB to UP pricing. As is predicted by theory (e.g. Back and Zender, 1993; Lengwiler, 1999; Ausubel et al., 2014), we find that these results are driven by participants responding to the incentives at play - bidding at cost rather than including a larger degree of shading-up, as in the PaB. Moreover, the results are strikingly similar when we instead use a DiD approach, underscoring that these results are not driven by some wider change in market conditions.

Of course, while it is anticipated that bids in the UP should be lower, theory is ambiguous on the relative value-for-money of PaB and UP pricing. Hence, second, we extend the results of previous studies on forwards auctions for treasury debt and timber extraction rights, which have sometimes found PaB achieves better value-for-money (Umlauf, 1993; Simon, 1994), at other times the UP (Tenorio, 1993), and in some cases no discernible difference (Hansen, 1986; Nyborg and Sundaresan, 1996; Barbosa et al., 2019), in this new and emerging context: reverse auctions for PES contracts. This is a very significant contribution given the critical role that context plays in auction design and auction outcomes (Klemperer, 2002), particularly as a primary concern for participants in PES auctions, unlike those in timber and treasury debt auctions, is *not* the auction. Rather, they are busy business operators, for whom PES schemes offer relatively marginal returns as compared with more traditional business activities. Our empirical evidence makes clear that in the PES context bids in UP auctions are lower by more than enough to compensate for paying all winning bids the amount stated in the marginal bid, rather than in the bid itself. Thus, in this PES context, the UP pricing rule better achieved the key objective of almost all PES schemes: value-for-money.

Third, owing to the extremely detailed nature of the dataset, we are able to assess proxies for the cost of participation on bidders. The results are striking - sniping and bid updating are much reduced. Moreover, there is anecdotal evidence, supported by our quantitative analysis of payments, that participants prefer UP auctions, owing in part to their perceived fairness, and the relative simplicity of bidding. Such results suggest that the increase in value-for-money offered by UP, rather than PaB, auctions is likely sustainable into future iterations.

Indeed, given the success of this field experiment, EnTrade and Wessex Water have continued to use the UP pricing rule in the Poole Harbour catchment. Moreover, EnTrade now view UP pricing as the default to be used as they further expand the number of markets they operate.

Obviously, the conclusion of this paper - that the UP auction performs better in the Poole Harbour catchment than does the PaB on a range of measures - does not mean this is going to be true in all PES settings. However, it does begin to shed light on the question of optimal auction design in such a 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. Indeed, 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 all successful bids would have already collapsed to the marginally accepted bid, and that the switch to the UP pricing rule would have no effect on mean bids or mean payments. Hence, one might actually anticipate *larger* gains from the use of UP auctions in other PES contexts.

The EnTrade 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 field 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 experiments is clearly shown in the confidence this field experiment gave policy-makers to switch away from the standard approach within PES despite the uncertainties and risk in advance of the experiment. 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. PES auctions must look beyond the simplistic PaB design that currently pre-occupies most policy makers.

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