Designing markets for bundled environmental goods

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June 10, 2025

Abstract

How to efficiently organise the exchange of environmental goods and services between multiple buyers and sellers? The global market for environmental goods is ever growing and already a multi-billion dollar industry. Yet, the mechanisms through which trades currently occur are poorly organised and highly-inefficient. Such inefficiency stems from the package nature of supply and demand for environmental services, which has yet to be recognised by existing market designs. In this paper we propose and test, both in the real world and laboratory, a package market using the Balanced Winners' Contribution rule of Lindsay (2018). Proprietary data from the real world shows that the package market design can facilitate trade where current approaches fail. The experimental results point to this new market design offering substantial efficiency gains relative to the current approaches applied internationally. This suggests that the real world result is likely to generalise, and is underpinned by the package market alleviating exposure risk.

Keywords: market design, biodiversity, water quality, housing
JEL codes: D47, D62, Q21, Q25, Q53
Statements and Declarations: The project was approved by the University of Exeter Business School Ethics Committee.

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1 Introduction

Demand for environmental goods and services is ever increasing. From New Zealand to Colombia, and China to the USA, governments are legislating "no net loss" policies to regulate services as diverse as clean water through to the preservation of endangered species with the aim of halting and reversing the current catastrophic decline in biodiversity and ecosystem function currently engulfing the planet (Madsen et al., 2010). Added to these regulated obligations, the list of companies making similar voluntary pledges, across 133 countries and in sectors as diverse as chocolate manufacturers (e.g. Lindt) to banks (e.g. Deutsche Bank), is also ever growing (Net Zero Tracker, 2023). All such initiatives generate private demand for quantifiable improvements in environmental goods, and already contribute to a market with multi-billion dollar annual transactions (Madsen et al., 2010). However, at present, the solutions currently employed to match supply and demand appear highly inefficient.

Markets for environmental goods and services are not new, but until recently have operated in the context of single-buyer markets, in which all demand is from just one participant. Current market mechanisms range in design from the fixed price offers that are the typical method by which governments allocate their funding (e.g. the European Union's Common Agricultural Policy, McIntosh et al., 2011; and New York State's Catskills water shed programme Landell-Mills et al., 2002) through to reverse auctions, be those pay-as-bid (e.g. Conservation Reserve Programme, Shoemaker, 1989; Cramton et al., 2021; BushTender, Stoneham et al., 2003; and Vittel's scheme for clean water above its bottling plant Barbier et al., 2008) or uniform price (e.g. EnTrade's Poole Harbour auction, EnTrade, 2019). While these mechanisms may be well-suited to the single-buyer markets for which they were designed, they likely perform poorly in the context of multi-buyer demand that is emerging within the market for environmental services.

Both single- and double-sided markets for environmental goods face three constraints. First, they require *sufficient supply*; that is the type and quantity of goods demanded by successful buyers is at least met by the supply offered by successful sellers. Second, they must be *(weakly) budget balancing*; that is the payments made by successful buyers are at least enough to compensate the successful sellers. Third, they require *individual rationality*; that is (at least in expectation) no agent is made worse off by entering the market than they would be by simply not participating. A further, desirable property, is that the mechanism is *strategy proof*; that any individual's best response regardless of the behaviour of other agents is to accurately report one's cost or value. Yet, in double-sided markets it is impossible to have a mechanism which is both budget-balancing and strategy proof Myerson and Satterthwaite, 1983.

The further challenge facing market design is indivisible supply and demand. For example, buyers need a package of environmental services to realise some value (e.g. those with a regulated obligation for "no net loss" policies require, at minimum, their full demand being met), while sellers are able to offer a package of environmental services which cannot be divided (e.g. a field on which they can plant a woodland). This creates a problem of exposure which may be overcome through package bidding, but such bidding has not generally been permitted within environmental markets to date.[1]

While the insights and results presented in this paper are broadly applicable to environmental goods markets, our motivating example comes from the United Kingdom, where we designed markets to overcome these issues for trade in biodiversity and water quality services. Demand for both services stems from regulated obligations which are binding for housing developers. The Conservation of Habitats and Species Regulations (H.M. Government, 2017) requires that developers in at-risk localities have no net-negative impact on water quality (so-called "nutrient neutrality"). Meanwhile, more recent legislation as part of The Environment Act (H.M. Government, 2021) requires all housing developers within England to offset the impacts that they have on biodiversity as measured through Biodiversity Metric 4.0.

These regulations can be most efficiently met by developers paying landowners to establish new habitats which reduce nutrient run-off and offer biodiversity habitat, thereby delivering some combination of water quality and biodiversity credits. The developers can then claim these credits against their obligations in order to obtain planning permission. As such, matching the supply of landowners with the demands of the housing developers perfectly reflects the issues that are commonplace across the nascent double-sided markets for environmental goods.

Globally, the typical market solution proposed for this double-sided problem is the creation of environment or mitigation banks (Morandeau and Vilaysack,

[1] One exception to this is the single-sided RSPB-funded, EnTrade-operated, and Oxford University (Paul Klemperer, Elizabeth Baldwin and Alex Teytelboym) designed, auction for turtle dove habitat in which the auction scoring rule accounts for complementarities in the (single) buyer's objective function (The Economist, 2021).

2012). Such banks (e.g. The Environment Bank; The Environment Bank, 2022) buy up land and establish nature-based solution projects, later selling credits on to buyers. Yet, in so doing, the banks take on exposure risk. It is possible that demand for the credits that they finance does not materialise, or is lower than anticipated. An alternative approach that has been proposed by some policy makers is a model more akin to estate agents. The proposition is that landowners offer potential projects generating a specific combination of credits at a particular price. Buyers then choose whether or not to purchase each project, and may purchase multiple projects and/or sell on excess credits beyond those which they need to meet their own obligations. In such a market, exposure risk persists but simply affects the other side of the market (buyers). As we go on to detail, a stylised fact emerges in the real world: these approaches appear to result in inefficiently low rates of trade.

Previous research has highlighted that in double-sided markets exposure risk can suppress trade (Goeree and Lindsay, 2019). We therefore seek to find a market design capable of fostering more efficient trade by allowing simultaneous trading. Such a market functions as a clearing house. Bids are solicited from buyers stating their value for a particular package of credits. Simultaneously, offers are elicited from sellers stating their cost, and the combination of credits that a particular project generates. The market operator then solves the combinatorial problem so as to generate the maximum surplus (the difference between the stated costs and values of the winners), while accounting for the indivisibility of bids and offers.

Once winning bids and offers have been resolved, the payments (the amounts successful bidders pay, and successful sellers are paid) need to be determined. While competitive prices may provide a clear starting point, such prices might not exist even when trading might be profitable, or may exist but not be unique.[2] Fine et al. (2017) review a mechanism used to trade emissions credits which approximates competitive prices as closely as possible while being budget-balanced and maintaining individual rationality. Instead, Pay-as-Bid pricing circumvents these issues, resulting in unique payments, and always facilitating all welfare enhancing trades based upon *reported* costs (offers) and values (bids). However,

[2]To see this, consider the case where trade involves just one good in addition to money. Suppose there are two buyers and one seller. Buyer 1 values 2 credits at a total of 8, buyer 2 demands 1 credit with a value of 2, and the seller has a cost of 9 for delivering 3 credits. Clearly no one price per credit will allow trade to go ahead despite it being welfare enhancing. Now consider when competitive prices exist but are not unique. This occurs, for instance, in any case where a single buyer has a higher value than a single seller's cost (e.g. a buyer with value 5 for 1 credit and a seller with cost of 1 for 1 credit).

under such pricing, traders are never incentivised to accurately report their values and costs, even in thick markets. Rather, buyers should shade their bids down, and sellers overstate their costs. Such adjustments result in a loss of welfare relative to the optimal allocation. Furthermore, since buyer payments exceed seller receipts, traders have an incentive to trade outside the exchange. Finally, Vickrey-Clarke-Groves rules are strategy proof in private values settings, such that traders are always incentivised to report their true cost and value. Yet, VCG pricing is not budget balancing, with buyer payments potentially falling short of the amount sellers are paid, and therefore requiring outside subsidies. As well as this, sellers' opportunity costs may often have a common-value component.

Given the drawbacks of other pricing rules, or the need for approximations to achieve required properties, the package market that we propose for this context, uses an alternative pricing rule. Specifically, we use the Balanced Winner's Contribution (BWC) of Lindsay (2018). The rule itself is a modification to the Shapley value (Shapley, 1953), allocating the surplus that is generated back to the successful market participants. As we explain somewhat more precisely later, the BWC rule assigns unsuccessful participants no share of the surplus, instead allocating the surplus "fairly" between the winners.

The BWC rule has several advantages compared to the more traditional approaches. Unlike competitive prices, payments determined using the BWC rule will always exist and be unique. Payments are also budget-balanced, unlike under Vickrey-Clarke-Groves and pay-as-bid.

Given the benefit of alleviating exposure risk through a package market, and the desirable properties of BWC-based payments, a BWC package market was pioneered by an industry leader in the UK. We first use this proprietary data to examine the performance of the BWC package market in the real world. Second, we develop a laboratory experiment which captures the essential features of the real-world market setting, and test how the BWC package market compares to the other markets which are currently used (a mitigation bank - "Advance production") and proposed (an estate agent model - "Bilateral on-demand production").

This paper is therefore related to two different literatures. The first examines the developments of markets for the exchange of environmental services (Atkinson and Tietenberg, 1991; Cason and Plott, 1996; Betz et al., 2017; Cramton et al., 2021, e.g.). To now, this literature has focused on the context of single-sided markets in which exposure risk seems unlikely to play a critical role. The second strand of literature examines markets which seek to overcome exposure risk in trades, and design practicable markets for particular contexts. Grether et al. (1981); Rassenti et al. (1982) explored how to allocate landing slots, and Svorenčík (2017) provides a recent review. Similarly, Bykowsky et al. (2000); Milgrom (2000, 2007) inspect how auctions can be designed to account for complementarities in buyer preferences in the context of the single-sided market for spectrum auctions. In contrast to this literature, our work examines overcoming exposure risk through package bidding in the context of double-sided markets.

Our findings are clear. The surpluses and efficiency generated by the BWC package market is substantially and significantly higher than that generated under either of the alternative market mechanisms. Second, and relatedly, traders' profits are substantially and significantly higher in the BWC package market. Indeed, sellers over-enter in the advance production market and such traders make losses in over 20% of periods. Loss making is less common in the bilateral on demand production market, and is incurred by buyers (11.5% of rounds) rather than sellers. The BWC package market meanwhile nearly entirely eliminates loss making, and splits the surplus almost equally between each side of the market.

In sum this paper highlights that the current organisation of emerging double-sided environmental markets leaves significant "cash on the table". Moreover, the efficiency of such markets could be tremendously enhanced through the adoption of mechanisms which explicitly aim to tackle the combinatorial problem and alleviate traders from the risk of exposure. Indeed, as we discuss, such mechanisms are now being implemented in the UK. This could pave the way for their wider adoption, to the benefit of traders and the natural environment.

The rest of the paper is organised as follows. Section 2 explores in greater detail the real-world background and Section 3 describes the use of the BWC package market in the UK context. Sections 4.1, 4.2, and 4.3 explain the experimental environment, the implementation of the different market mechanisms, and specific experimental procedures, respectively. Section 4.4 presents the analysis of the experimental data. Finally, Section 5 offers concluding remarks.

2 Background

2.1 The environmental impact of housing development and present legislation

The UK context that serves as the focus of this paper is founded upon two key recent pieces of legislation regarding the impact that housing developments have on the natural environment. There are a wide range of environmental externalities associated with house building (Ingrao et al., 2018), UK legislation currently addresses two particular problems – water pollution and biodiversity loss.

Housing developments have detrimental effects on water quality owing to the sewage that is generated once people occupy the new houses. In some cases, this sewage can be sufficiently treated by the water treatment works that the houses' sewage network feeds into. However, in other instances the water treatment works does not have spare capacity, and hence the increase in sewage arriving at a plant causes a quantifiable increase in nutrients entering the downstream water course and hence worse water quality. Whether the reduction in water quality has a material effect depends on the current level of ambient water pollution. The worse the starting water quality, the more damage extra nutrients has.

Nutrient-neutrality legislation was adopted in 2017 to improve water quality outcomes by regulating the flow of nitrates and phosphates from new housing developments. Under these rules, if a housing development is to be connected to a water treatment works that is already at capacity, and the discharge will flow into a priority catchment, then the increase in nutrient loading must be offset by the housing developer. These water quality credits must be generated within the same catchment area as the development. Moreover, the developer must ensure that the habitat which offsets the increase in nutrients begins to have its effect prior to the occupation of the houses and lasts for the duration of the house's likely lifespan (80+ years). In practice, this means developers needing credits from arable reversion and cover crop planting in initial years (so-called "bridging credits") before newly established wetlands and woodlands under long-term contracts (again, 80+ years) begin to serve their nutrient sequestering function.

The Biodiversity Net Gain legislation is similar, with slight differences reflecting the different damages that housing development causes, and the different way in which biodiversity generates value for society. Unlike water quality, the damage to biodiversity occurs when development commences, and so credits are required from the point building work starts. It is also difficult to quantify biodiversity, which has resulted in the development of a specific index – Biodiversity Metric 4.0. The biodiversity metric is a multiplicative function which accounts for the area, scarcity, quality and location of habitat. Developers then have to ensure that the habitat they finance generates at least 110% as many units of this metric as the habitat that is damaged for housing development. There is some flexibility in how this is achieved. In contrast to nutrient neutrality, credits can be sourced from other geographic localities, but developers pay a penalty, requiring more credits. Similarly, developers need not offset with the same habitat type, but rather are allowed to offset more common habitats with scarcer ones. Contracts are also shorter, with offsets needing to last for 30 rather than 80+ years. Finally, any time taken by habitat to grow in order to deliver biodiversity gains need not be bridged with short-term credits, but rather requires the developer to buy more credits.

2.2 Current state of markets

As discussed, two market designs have emerged to match supply and demand – environment banks and estate agent models. Yet, a stylised fact emerges: these approaches offer an inadequate solution, resulting in sub-optimal levels of trade. For example, in the UK it is estimated that the building of 100,000 homes is currently delayed by the inability of housing developers to source credits required to meet the nutrient neutrality legislation (Turner, 2022). Indeed, the lack of a well-functioning market renders the legislation so politically unpalatable that the government considered scrapping it (Malnick, 2023).

Similar nutrient-neutrality legislation is also binding in The Netherlands. There, the government proposed buying out nearly 1.5bn€ of agricultural farms for the creation of new habitat (Baazil, 2023). Such a solution was deeply unpopular in the rural community. So unpopular in fact, that at the election which followed shortly after, the government was voted out on the back of a very large swing away in these rural areas (Henley, 2023).

2.3 Package market solution and the Balanced Winners' Contribution rule

Our solution to barely functioning trade was a package market with BWC pricing. Such a market expressly recognises the indivisibility of habitat creation projects and developer needs. A formal definition of the mechanism is provided in Lindsay (2018) but it can be summarised as follows.

Individual sellers submit offers, which detail the quantity of specific commodities that they are able to sell, and the amount of money they would need to receive in order to sell these items. Buyers submit bids, which are similar, but detail the quantity of specific items they need, and the amount they are willing to pay for them. All bidders, should they wish, are able to specify that they would like any given bid to be treated as divisible. Similarly, if they submit multiple bids, they can express "XOR" preferences, such that only a particular subset of their bids may win in any given market resolution.

The market operator then selects the combination of bids and offers which maximises the surplus (total successful amount of money in bids less total successful amount of money in offers), subject to three constraints. First, for every commodity the quantity demanded can be no more than that which is supplied. Second, at most one bid from each group of XOR bids or offers is allowed to be winning. Third, bids and offers are not allowed to be partially winning unless the participant has stated that the specific bid or offer is divisible.

Those steps simply determine the efficient allocation of trade, but do not specify how payments are to be determined. Indeed, Pay-as-Bid and Vickrey-Clarke-Groves pricing rules would use the same algorithm to determine the winners.

BWC payments use an amended version of the Shapley value (Shapley, 1953). Like the Shapley value, BWC pricing allocates the surplus back to participants, not to individual bids or offers, and does so imagining that individuals could have arrived in the coalition in any order. Unlike the Shapley value, BWC payments allocate this surplus back only to the winning participants. Specifically, the BWC rule calculates the share of the surplus to be allocated back to participants in the following way.

First, we assume that all participants with no successful bids or offers are already present in the market. Of course, there is no possible trade between these that could generate a surplus, otherwise those bids and offers would be successful. Second, we imagine that the successful participants arrive in the

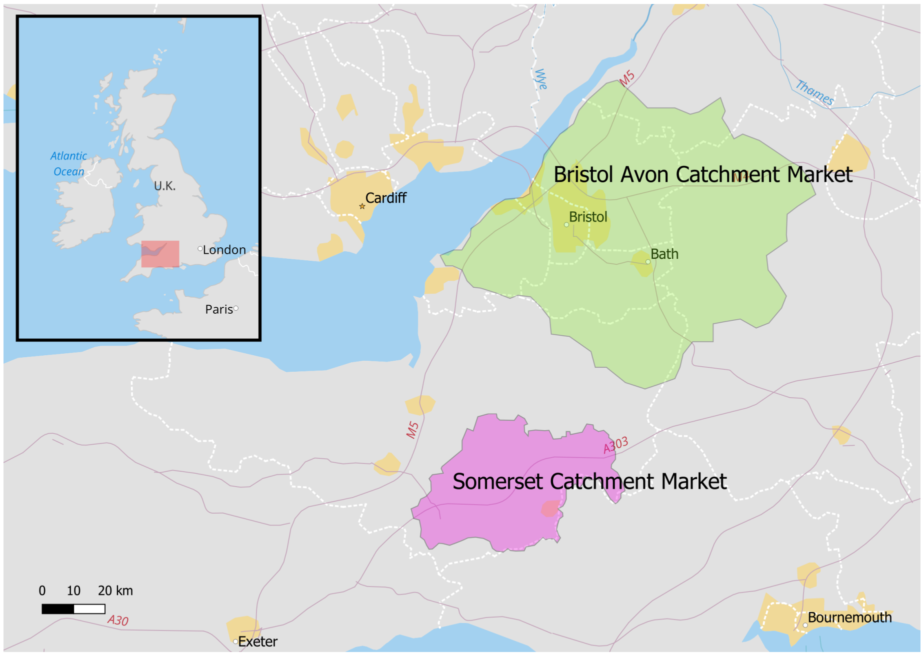

Figure 1: The map shows the areas covered by the two markets.

market, with all of their bids and offers – including their unsuccessful ones – in some random order. Third, we calculate the marginal increase in the surplus which is generated when each participant arrives. Fourth, we repeat this step for all possible random orderings of the successful participants, and take the mean of the marginal contributions they make to the surplus across these orders. Their mean marginal contribution to the surplus is their share of the surplus. Buyers pay the amount specified in their successful bid(s) less their share of the surplus as a discount. Sellers get paid the amount they requested in their successful offer(s) plus their share of the surplus as a bonus.

3 Performance of the BWC package market in the real world

The package market with BWC payments has now been implemented in two different localities in the south-west of the UK shown in Figure 1. In Bristol, the BWC package market was used for Biodiversity Net Gain Credits (Bristol Avon Catchment Market, 2021), and in Somerset for Nutrient Neutrality credits, specifically phosphorus (Somerset Catchment Market, 2021). While it is designed to mitigate the exposure risk that occurs when one side of the market otherwise has to move first, as is clear in Section 2.3 the determination of payments is complex and may be difficult for participants to understand.

Given the complexity of the BWC package market, *a priori* it is unclear how it would perform, and whether it would be able to facilitate trade in settings in which other market designs have failed. The examination of proprietary data from these initial markets make clear the answer is yes: a package market with BWC payments was able to facilitate trades despite its complexity.

In Bristol, biodiversity units with a value to the successful buyers of over £160k were successfully traded. Moreover, this generated a total surplus of £56.6k which was split between the successful traders. In Somerset, where the legislation for nutrient neutrality was already binding at the time the market was run, over £1m worth of phosphorus credits were exchanged, generating a surplus of approximately £338k.

Moreover, the BWC package market was able to adapt to complexities in the real-world application. For both markets, the mechanism was able to ensure that the costs of compliance monitoring and operator fees were covered for the successful trades. In Somerset, the mechanism was able to temporally match supply and demand: through different blends of bridging and long-term habitat projects it ensured that all successful buyers were in compliance with the requirement to have credits generated in advance of house occupation. As such, the BWC package market appears highly flexible and therefore of potential relevance to a wide range of environmental markets.

4 Wind tunnel testing

The success of the BWC package market suggests that it may be appropriate in a wide range of applications, yet understanding whether the optimistic results may generalise requires further investigation. To this end, we designed a laboratory experiment with a stylised market for environmental goods, and investigate the outcomes of trading in double-sided markets with different market mechanisms.

4.1 Environment

Agents are assumed to have quasi-linear utility. Trading groups consist of 4 individuals: 2 agents assigned the role of buyers, and 2 agents assigned the role of sellers. Trade occurs in two goods, which to aid participant understanding we referred to in the experiment as "apples" and "bananas", and we use such terms here too. Each buyer is assigned a "target combination" which consists of a number of fruit drawn *iid* from a uniform distribution on integers in the range [1..5]. Given the total fruit requirement, each possible combination of fruit is equally likely (e.g. if the total fruit were 2, requiring 2 apples and 0 bananas occurred with probability one third, as did each of 1 apple and 1 banana, and 0 apples and 2 bananas) . Each buyer is also assigned a value for their target combination which is *iid* from a uniform distribution on integers in the range [0..100], and which they realise at the end of trading if and only if they hold at least as many apples, and at least as many bananas, as in their target combination. Buyers gain no value for holding a portion of their target combination.

Buyers and sellers are symmetric. Hence, sellers are assigned an "output combination" consisting of a number of fruit drawn *iid* from a uniform distribution on integers in the range [1..5]. Given the total size of the output combination, each possible fruit combination was equally likely. Each seller is also assigned a cost associated with their output combination, which is also *iid* from a uniform distribution on integers in the range [0..100]. This cost is only realised if the seller produces their output combination. Production is binary such that the seller is unable to ration the proportion of their output combination that they produce, and they may only produce their output combination, at most, once per trading period. Each individual starts each period with 100 cash and no fruit. Their earnings each period are the initial cash endowment plus any profit or loss that they make from their producing and trading decisions. As is detailed for each treatment, participants cannot, by construction, make an overall loss in any period. At the end of the experiment, they are paid conditional on their total earnings across these 10 periods.

In this environment, the optimal allocation is the solution which maximises the buyers' realised values less the sellers' realised costs. When seller costs are high relative to buyer values, or seller output combinations cannot meet buyer target combination demands, then no trade is optimal. There are also a broad range of instances in which some trade may be optimal, but individual traders are not involved (one seller sells to one buyer; two sellers sell to one buyer; or one seller sells to two buyers). As such, in many instances it is optimal for sellers to *not* produce and *not* bear their production cost.

4.2 Alternative market designs

The experiment is specifically designed to compare the market mechanisms being used and proposed for the emerging double-sided environmental markets. We therefore consider three such formats in the experiment: 1) Advance production; 2) Bilateral production on demand; and 3) a Package market with BWC pricing.

4.2.1 Advance production

The advance production market is designed to mimic how environmental banks function. Sellers first observe their output combination and cost. They then make a choice as to whether they wish to pay their cost to produce their output combination and enter the market. In the market phase, sellers who produced their output combination can then list their individual fruit for sale at any integer price between 1 and 100. The prices can be different for each individual fruit (e.g. 1 apple could be priced at 20 and another at 25) and sellers can only list as many fruit for sale as they hold. Sellers are also able to update their prices by removing any unsold fruit from sale and relisting with a revised price. Buyers, so long as they have sufficient cash at the time, can select which fruit (if any) they would like to purchase, and in so doing the fruit transfers from the seller to the buyer for the price that the seller listed it at. Buyers who hold fruit are then also able to sell them on in a similar fashion to sellers, listing them with a price. However, only buyers are able to buy fruit.

4.2.2 Bilateral production on demand

The market with bilateral production on demand resembles the estate agent model. It operates in a similar fashion to the second (market) phase of the advance production treatment. Rather than list individual fruit for sale, sellers can list their output combination, for an integer price between 1 and 100, so long as their output combination is not already listed for sale or already sold. Sellers can again update the price at which they list their output combination by removing it from sale and relisting it with a revised price. Trades then proceed as before: buyers with sufficient cash can select and purchase any output combination that they like, taking ownership of the fruit within that output combination, and paying the stated price to the seller. Only if an output combination is bought by a buyer does the seller pay their output combination cost.

Buyers who hold fruit can again sell them on. As in the advance production treatment, buyers are able to sell individual fruit, again listing them with a price. As before, only buyers are able to buy items.

4.2.3 Package market with BWC pricing

The package market with BWC pricing is analogous to that used in the real world. It operates through sealed bidding. Sellers submit offers stating the minimum that they are prepared to accept to produce their output combination, and buyers state the maximum they are willing to pay to receive their target combination. These bids and offers then enter an algorithm which determines successful bids and offers by selecting those which generate the largest difference between realised bid and offer amounts, while ensuring that any successful buyer receives their complete target combination from the successful sellers. In the case that the bids, offers, and target and output combinations are such that no profitable trade is possible, no trades occur. Payments are then determined using the BWC rule, which, as described before, broadly redistributes the surplus back to the successful traders by employing a modification to the Shapley value. As with the bilateral production on demand market, sellers only realise their output combination costs if their offer is successful.

4.3 Experimental design and procedures

A total of 240 subjects participated in the experiment, which was conducted in the FEELE lab at the University of Exeter. Subjects were students and no subject participated in more than one session. The experimental software was developed in python using the oTree framework (Chen et al., 2016). Screenshots can be found in Appendix A. Printed instructions were provided to the participants, and included annotated screenshots to familiarise the subjects with the experimental interface.

A between-subject design was used and there was one treatment for each of the three market mechanisms described in Section 4.2 and using the environment described in Section 4.1. Each treatment had 20 groups (80 subjects) per treatment. There were 10 periods with each group of traders, and a trader's role, fixed throughout. However, each trader's output or target combination and their associated cost or value was re-drawn at the start of each period. The random draw was initiated using a seed dependent on the group number in treatment, such that in each period participant i in group j in period p had the same output or target combination and cost or value regardless of which treatment they were in.

Participants additionally completed four unpaid practice periods: two as seller, and then two as buyer, or vice versa. Their role in the initial two practice rounds was then the role they participated in during the paid periods. After the practice, participants completed a comprehension quiz which the experimenter checked, and had the opportunity to ask the experimenter questions, before starting the 10 paid periods.

Across the advance production and bilateral production treatments, there was a 3 minute time limit on the market phase. This was replicated in the package market treatment with a 3 minute time limit on entering bids. In the advance production market, sellers had up to 1 minute to decide whether or not to produce their output combination. Across treatments, traders had up to 1 minute to review the results of each market period. After completing the experiment, participants completed a debrief survey and then were paid by Wise bank transfer. The payment was £1 for every 50 points of earnings. Sessions typically lasted around 1.5 hours, and subjects earned approximately £21 on average.

4.4 Experimental results

Performance of the different market mechanisms will be broadly evaluated along two dimensions. The first dimension relates to the group-level gains from trade, or the surplus, that is realised. The second relates to individual trader outcomes.

To explore the surplus delivered by each market mechanism, we shall construct two metrics: 1) realised surplus – the realised value of buyers less the realised cost of sellers; and 2) relative efficiency – the realised surplus divided by surplus generated under the optimal allocation. Realised surplus is calculated for each trading group for each period, while relative efficiency is calculated for each trading group across periods to avoid instances of zero values for the denominator (as would occur calculating this on a per period basis).

Individual trader outcomes are explored through 1) profits – the difference between the number of points each participant has, and the starting endowment of 100; and 2) loss making – a binary variable for whether an individual's profits are negative. Both are evaluated for each individual trader for each period.

To begin considering the results of the experiment, Table 1 shows the mean group level outcomes and Figure 2 shows the outcomes of each group in each

Market mechanism	n	Surplus	Efficiency (%)	Loss making (%)
Package market	20	18.96	88.17	0.50
Advance production	20	1.57***	-42.30***	37.50***
Bilateral production	20	13.80**	48.17**	13.00***

Table 1: Summary group level outcomes by mechanism.

Notes: Surplus is the mean group surplus per round. Efficiency is the percentage of the potential gains from trade realised by a group over the ten periods. Loss making is the percentage of periods where the surplus realised by the group is less than zero. Two-sided sign tests are used to test the null hypothesis that the median outcome of the package market is equal to the median for each of the other mechanisms. * p<0.05, ** p<0.01, *** p<0.001

market round.

Both Figure 2 and Table 1 highlight that the surplus generated in the advance production market is considerably lower than that realised in the two other market mechanisms. Moreover, the package market delivers by far the highest overall surplus. Similarly, loss making is relatively common in the advance production treatment (in a given round, 37.5% of groups made an overall loss). Loss making is rarer in bilateral production (13% of groups) and almost non-existent in the package market (0.5% of groups).

To summarise, we find that group-level surplus is substantially and significantly higher in the package market than in the other two mechanisms. A similar pattern is true for efficiency. And the reverse pattern holds for loss making.

Individual level outcomes are shown in Table 2. Buyer and seller profits are substantially and significantly lower under advance production compared to the package market ($p < 0.001$ and $p < 0.05$). Comparing the package market and bilateral production, the effects appear mixed. Buyer profits are higher under the package market whereas seller profits are higher profits under bilateral production. Neither of these differences is statistically significant at the 5 percent level.

There are stark differences in loss making between treatments. In the package market, loss making is rare for both buyers and sellers. In contrast, under advance production, both buyers and sellers regularly make losses (14.0% and 21.7% of periods). Whereas, under bilateral production, buyers regularly make losses (11% of periods) but sellers do not.

It is interesting to consider to what extent our results may be driven by the role of information and the risks of exposure being realised. Under advance

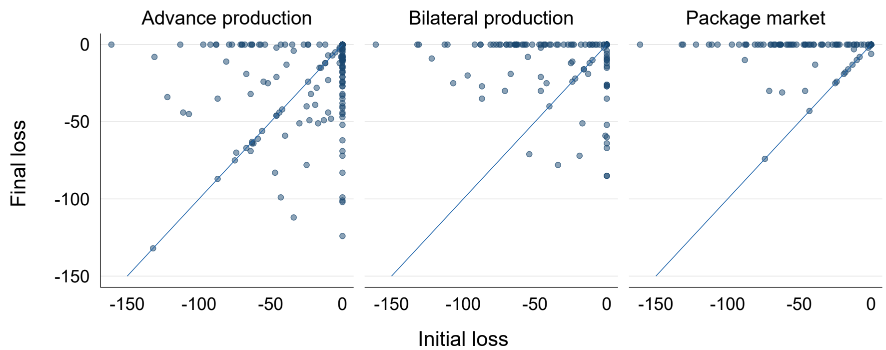

Figure 2: There is one observation per group per round. Loss is defined as the actual social surplus minus the optimal social surplus.

Market mechanism	**Type**	**Profit**	**Loss making (%)**
Package market	Seller	3.89	0.75
	Buyer	5.59	0.50
Advance production	Seller	-1.92***	21.75***
	Buyer	2.71*	14.00***
Bilateral production	Seller	5.86	0.00
	Buyer	1.04	11.50***

Table 2: Summary statistics of individual outcomes by type for each mechanism.

Notes: Profit is the mean per period. Loss making is the percentage of periods where the trader made a loss. Two-sided sign tests are used to test the null hypothesis that the median outcome of the package market is equal to the median for each of the other mechanisms. * $p<0.05$, ** $p<0.01$, *** $p<0.001$

production it is the sellers who must decide to produce, with no information regarding buyer values. Under bilateral production it is the buyers who must decide to purchase an output combination, unsure of whether it will be sufficient to meet their demand. These buyers, however, do have some information regarding seller costs, given that they can observe the output combinations for sale before making their purchase decisions. In the package market, exposure risk is completely eliminated. Table 2 decomposes profits that participants accrue, and the rate of loss making, by whether the participant is a buyer or seller. What is striking is that sellers in the advance production treatment make far lower profits, indeed on average making losses, than their buyer counterparts. Under bilateral production on demand, while average profits are higher and loss making lower than in advance production, this is driven by sellers. Indeed, sellers in the bilateral production treatment enjoy the (joint) highest profits of all participants and make losses relatively infrequently. In contrast, buyers in bilateral production make losses rather frequently and average very low profits. Under the package market, loss making is extremely rare for both sides of the market, and almost non-existent for sellers, and profits relatively high and split nearly equally across the two sides. Indeed, these patterns of profits and loss making are in line with how exposure risk affects these markets differently.

5 Discussion

This paper proposed the use of a package market with BWC payments to facilitate trade in the double-sided markets which are beginning to emerge for environmental services. Unlike existing solutions, we report data which shows that the package market can lead to successful trading in the real world. Moreover, our laboratory experiment provides clear evidence that the inefficiencies of current market institutions are likely the cause of limited trade. It is no surprise that trades are extremely rare when the surplus that the current markets are likely to facilitate are so low, and so many participants likely to make a loss. In contrast, the evidence shows that nearly 90% of the possible gains from trade are realised using the package market approach, and as such it appears highly applicable for other environmental markets.

Taking a step back, while efficiently operating markets are not sufficient to halt the loss of biodiversity and wider environmental degradation, they certainly are necessary. This paper shows such market mechanisms, much like Lewis

Carroll's Red Queen and the evolutionary dynamics underpinning the nature we seek to preserve (Van Valen, 1973), must keep pushing for better designs just to keep pace with the developments that are changing the face of environmental market conditions.

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Appendix A Screenshots

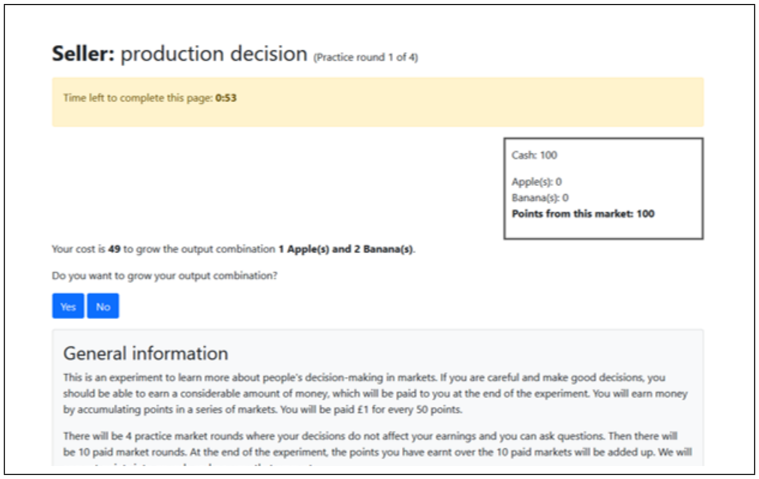

Figure 3: Treatment: advance production - seller production decision

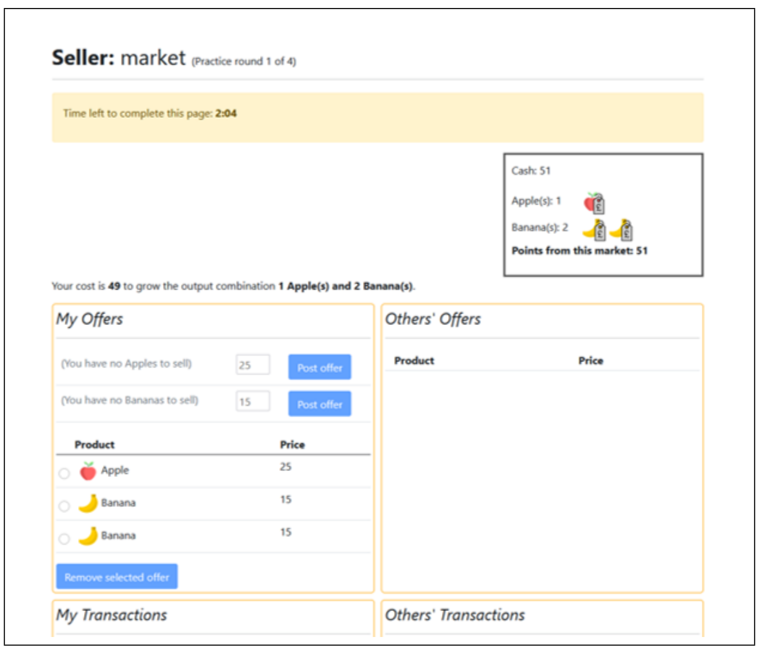

Figure 4: Treatment: advance production - seller ongoing market

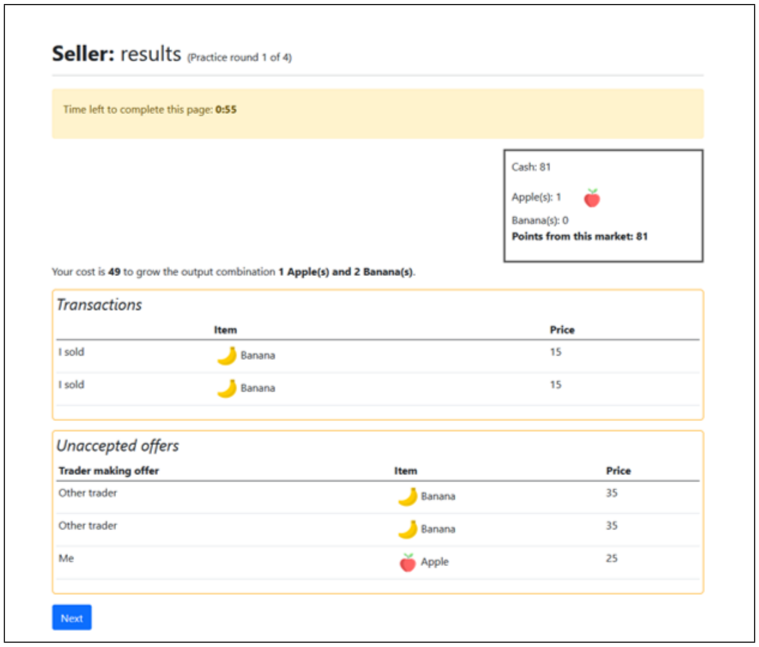

Figure 5: Treatment: advance production - seller results

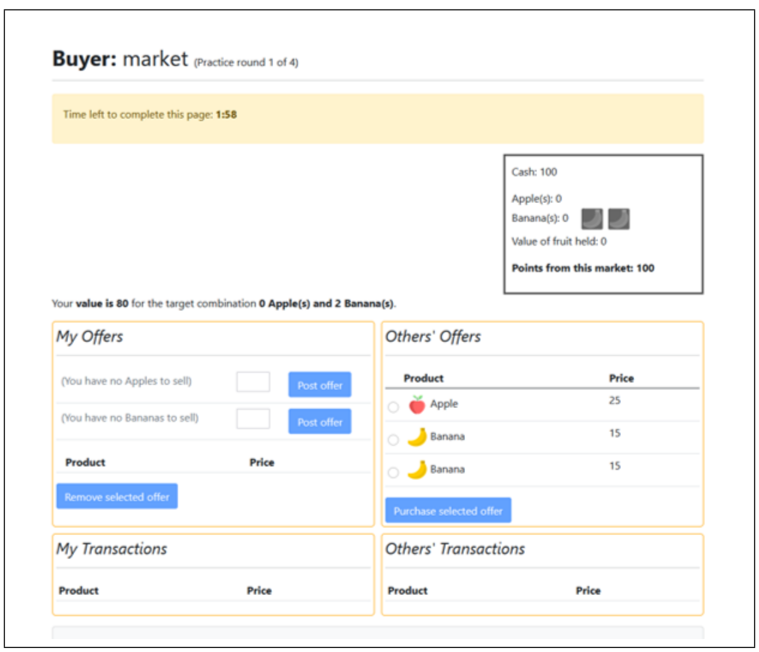

Figure 6: Treatment: advance production - buyer ongoing market

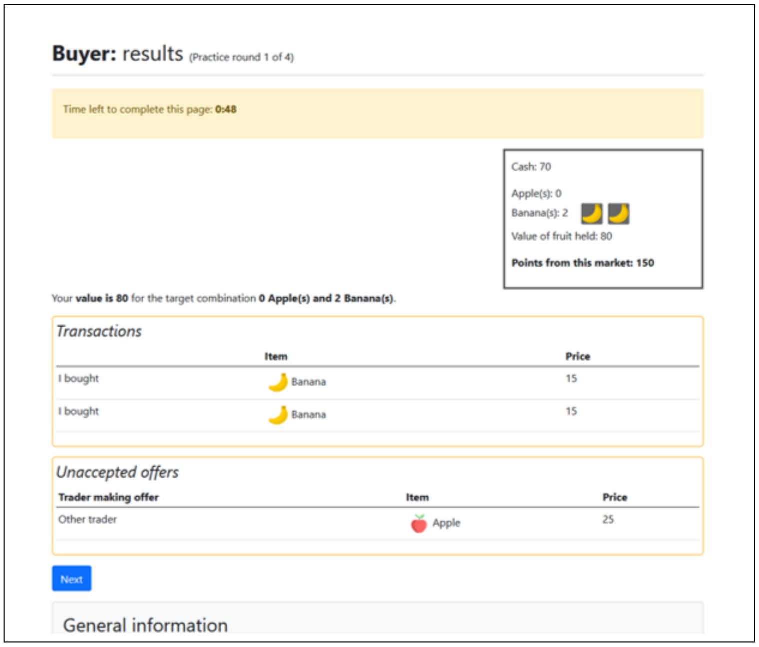

Figure 7: Treatment: advance production - buyer results

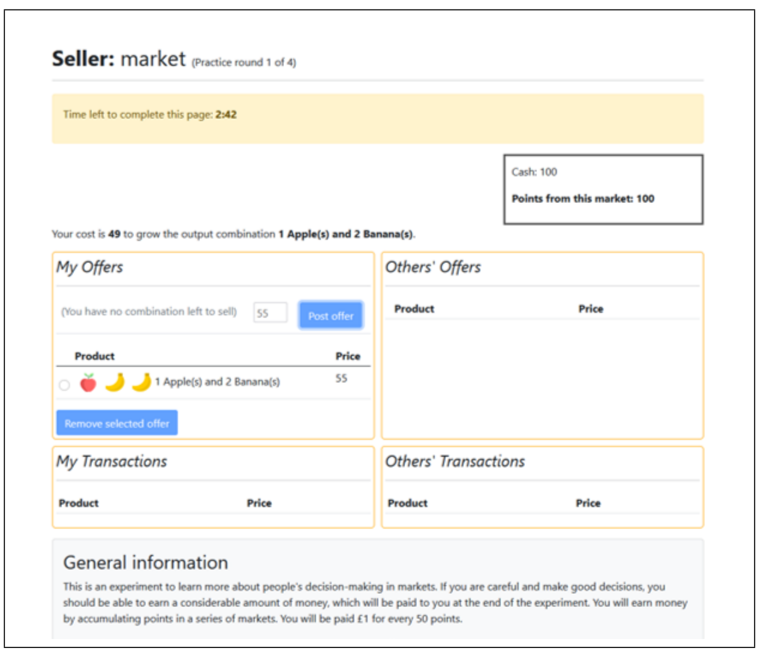

Figure 8: Treatment: bilateral production on demand - seller ongoing market

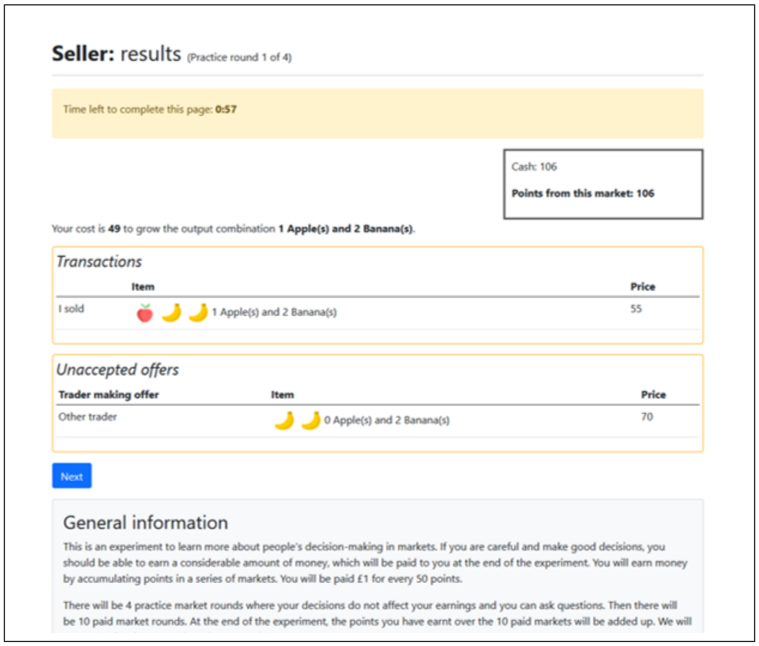

Figure 9: Treatment: bilateral production on demand - seller results

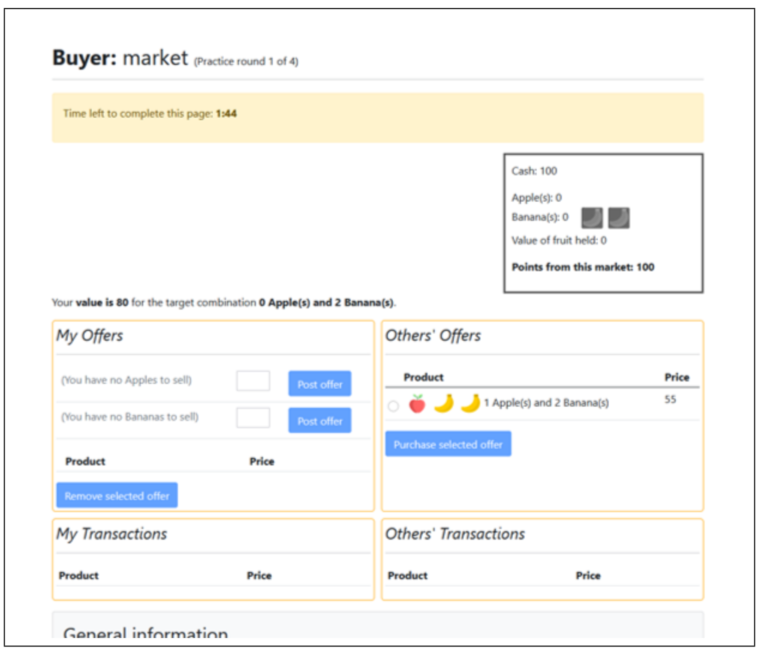

Figure 10: Treatment: bilateral production on demand - buyer ongoing market

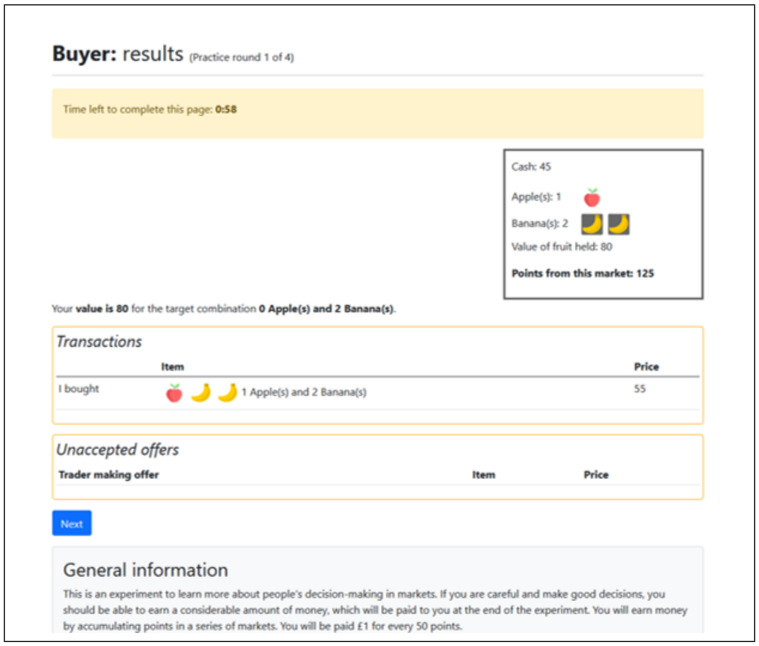

Figure 11: Treatment: bilateral production on demand - buyer results

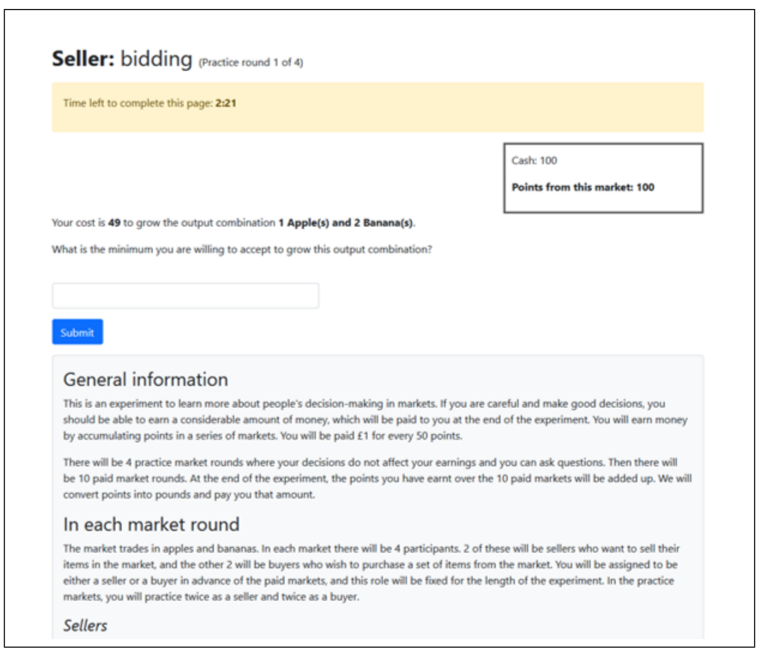

Figure 12: Treatment: package market with BWC payments - seller bidding

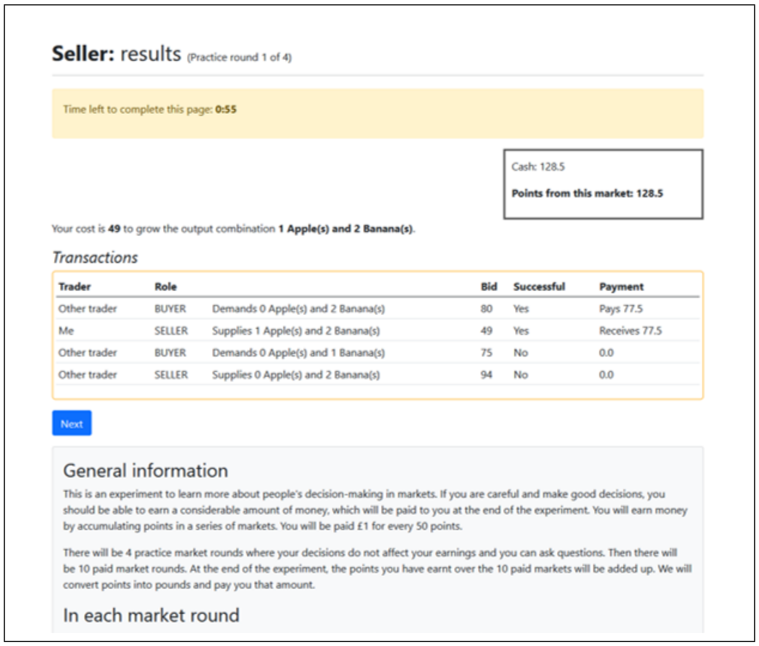

Figure 13: Treatment: package market with BWC payments - seller results

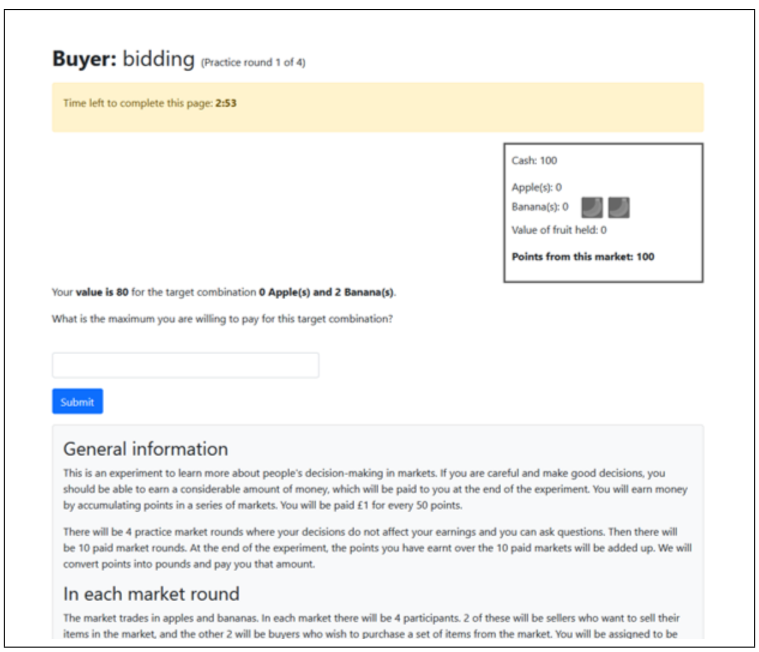

Figure 14: Treatment: package market with BWC payments - buyer bidding

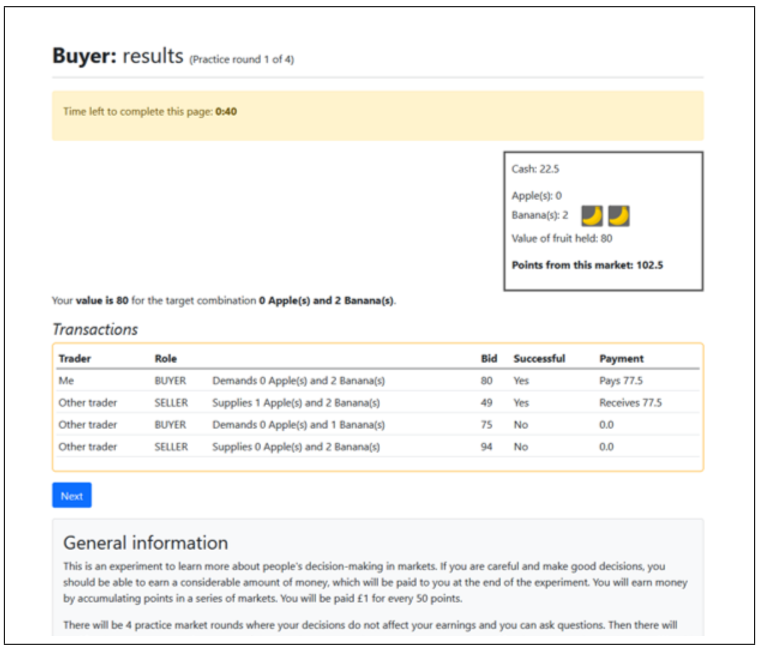

Figure 15: Treatment: package market with BWC payments - buyer results