Behavioral Responses to Price and Quantity Instruments: Theory and Evidence from a Laboratory Experiment*

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Abstract

Standard economic theory predicts that, when regulating environmental externalities, quantity instruments such as tradable permits and price instruments such as taxes will produce identical outcomes when transaction costs are negligible and marginal abatement costs are known with certainty by the regulator, even when marginal damages are uncertain from the perspective of the regulator. In practice, however, behavioral responses on the part of market participants may cause price and quantity instruments to lead to different outcomes. These behavioral responses include endowment effects, fairness concerns, attitudes towards risk deviating from the expected utility framework, and cognitive costs. We develop a theory model to compare the equilibria under price and quantity instruments with and without behavioral responses. We then conduct a laboratory experiment to evaluate the equivalence of price and quantity instruments. According to our results, in terms of aggregate emissions, the quantity-equivalence of quantity and price instruments cannot be rejected when marginal damages are known with certainty. When marginal damages are uncertain, however, the implementation of an optimal tax can lead to more emissions compared to those achieved with a tradable permit system capped at the optimal amount of emissions. The results from our experiment provide evidence for behavioral responses, possibly from endowment effects, fairness concerns, and/or attitudes towards risk deviating from the expected utility framework, that cause price and quantity instruments to lead to different outcomes. We do not find evidence for cognitive costs that make deviations from the optimal decision more likely under a quantity instrument than under a price instrument. Our results therefore suggest that when marginal damages are uncertain, a tradable permit system capped at the optimal amount of emissions may be preferable to an optimal tax.

Keywords: damage uncertainty, experimental economics, externalities, price and quantity instruments, tradable permit systems, behavioral response
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1 Introduction

For several decades, economists have debated whether quantity instruments such as tradable permits or price instruments such as taxes are the more appropriate policy instrument for regulating environmental externalities. Standard economic theory predicts that, when regulating externalities, quantity and price instruments will produce identical outcomes when transaction costs are negligible and marginal abatement costs are known with certainty by the regulator (Adar and Griffin 1976; Stavins 1995; Weitzman 1974). Uncertainties regarding marginal abatement costs generate different policy prescriptions depending on the relative slopes of the marginal damage and marginal abatement cost curves; a relatively flat marginal damage curve would make a price instrument relatively more attractive and vice versa (Adar and Griffin 1976; Weitzman 1974).

While uncertainties regarding marginal abatement costs may matter, the literature largely agrees that uncertainty over marginal damages alone has no impact on the equivalence of price and quantity instruments: according to standard economic theory, even in the presence of uncertainty over marginal damages, both price instruments and quantity instruments perform equally in terms of their ex post efficiency. Marginal damage uncertainty is a feature of many environmental externalities; a stark example of an environmental externality with uncertain marginal damages is global climate change (Weitzman 2014; Auffhammer et al. 2016; Rudik 2019). Stavins (1996) finds that uncertainties in marginal damages only matter if uncertainties in marginal damages and uncertainties in marginal abatement costs are simultaneous and correlated with each other.

The standard economic theory regarding the equivalence of price and quantity instruments may no longer hold, however, when there are behavioral responses, or what Shogren and Taylor (2008) call 'behavioral failures'.[1] Behavioral responses such as endowment effects (Tversky and Kahneman 1991), fairness considerations (Fehr and Schmidt 1999), and cognitive costs (Kahneman 2003) may cause price and quantity instruments to lead to different outcomes in practice, even in the absence of uncertainty about either marginal abatement costs or marginal damages. In addition, behavioral responses such as attitudes towards risk deviating from the expected utility framework (Kahneman and Tversky 1979) may cause price and quantity instruments to lead to different outcomes when marginal damages are uncertain, despite the standard economic theory that uncertainty over marginal damages should not matter. Thus, owing to behavioral responses, and in contrast with standard economic theory, price instruments and quantity instruments may lead to different outcomes even when transaction costs are negligible and marginal abatement costs are known with certainty by the regulator.

In this paper we examine how and whether behavioral responses affect the outcomes of price and quantity instruments. We first develop a theory model to compare the equilibria under price and quantity instruments with and

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[1] For an excellent discussion of behavioral economics, see Thaler (2016), who argues that rather than a paradigm-shifting revolution within economics, behavioral economics is more accurately characterized as a return of economic thinking to the open-minded, intuitively motivated way it began with Adam Smith.

without behavioral responses. The behavioral responses we consider are endowment effects, fairness concerns, attitudes towards risk deviating from the expected utility framework, and cognitive costs. We then conduct a laboratory experiment to evaluate how and whether behavioral responses affect the outcomes of price and quantity instruments when marginal abatement costs are known with certainty.

Our theory predicts that under a quantity instrument, permit prices would be higher in the presence of either endowment effects or fairness concerns than they would be in the absence of behavioral responses. Under a price instrument, our theory predicts that emissions would be lower in the presence of endowment effects but possibly higher in the presence of fairness concerns. Owing to cognitive costs, our theory predicts that individuals may be more likely to make sub-optimal decisions under a quantity control than under a price control.

Market participants whose attitudes towards risk deviate from the expected utility framework and are instead better explained by prospect theory may overweight high damage events and/or seek risks to avoid losses (Kahneman and Tversky 1979). Our theory predicts that, on its own, the overweighting of high damage events would increase perceived marginal damages, and thus reduce the quantity produced under a price control but have no effect on permit prices under a quantity control. On its own, risk seeking to avoid losses would reduce permit prices under a tradable permits policy and reduce production under a price control. The combined effect of both overweighting high damage events and risk seeking to avoid losses on permit prices under a quantity control and on the quantity produced under a price control are ambiguous.

Results of our experiment indicate that in terms of aggregate emissions, the quantity-equivalence of quantity and price instruments cannot be rejected when marginal damages are known with certainty. When marginal damages are uncertain, however, the implementation of an optimal tax can lead to more emissions compared to those achieved with a tradable permit system capped at the optimal amount of emissions. The results from our experiment provide evidence for behavioral responses, possibly from endowment effects, fairness concerns, and/or attitudes towards risk deviating from the expected utility framework, that cause price and quantity instruments to lead to different outcomes. We do not find evidence for cognitive costs that make deviations from the optimal decision more likely under a quantity instrument than under a price instrument.

Our results have important implications for the design of policy. If price and quantity instruments are no longer equivalent when marginal damages are uncertain because of behavioral responses, policy-makers should consider the possibility of behavioral responses in the design of policy and in their choice of whether to use a price or quantity instrument. In particular, our results suggest that when marginal damages are uncertain, a tradable permit system capped at the optimal amount of emissions may be preferable to an optimal tax, since behavioral responses may cause the latter to lead to more emissions.

The remainder of this paper is structured as follows. Section 2 reviews the previous literature. Section 3 presents our theory model comparing the equilibria under price and quantity instruments with and without behavioral responses.

Our experimental design is described in Section 4. We summarize the predicted effects of behavioral responses according to our theory model in Section 5. The main results from our experiment are presented in Section 6. Section 7 concludes.

2 Literature review

In previous theoretical work on the equivalence of quantity and price controls, regulated agents are assumed to be indifferent to the marginal damages generated by the regulated activity (Adar and Griffin 1976; Stavins 1995; Weitzman 1974). For example, a common implicit assumption in these theory models is that the pollution from regulated firms affects individuals, not the firms themselves.

Similarly, most previous experiments on emissions trading have not analyzed the underlying market for the output that creates the externality. Instead, they analyze the permit market by providing a marginal abatement cost function for emissions reduction (or a marginal benefit function for emissions) and a permit endowment to each participant. For an early review on the subject see Issac and Holt (1999).

One exception is the experiment conducted by Plott (1983), which includes buyers and sellers for a generic good that generates an externality, and which implements an emissions permit market in one treatment. Like Plott (1983), and in contrast to much of the previous theoretical and experimental literature, our paper considers the situation in which regulated agents themselves suffer the damages from their externality generation. In particular, our model is framed as a situation in which agents, which we can think of as countries or governments, obtain individual benefits from the production of an output that also generates a damage that adversely affects all agents, including themselves. By substituting consumption for production, our model also applies to situations in which citizens are regulated, such as personal trading systems.

There are many situations in which the regulated agents themselves suffer from marginal damages from their own externality generation, including pollution problems, such as air pollution and climate change, in which pollution by one agent adversely affects all agents, including the polluter itself; and common-pool resource problems, such as overfished fisheries,[2] groundwater exploitation, and road congestion, in which the use of the common pool resource by one agent adversely affects all agents, including the user himself. Our model is particularly well suited to the case of climate change, in which the welfare of all individuals could be affected by both the benefits of economic activity and the damages from the greenhouse gas emissions resulting from this economic activity.[3] Our theoretical model and experimental design also apply to systems in which countries or regions trade carbon permits, such as those studied by

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[2] For the regulation of fisheries, taxes have seldom been proposed but different systems of tradable fishing quotas have been implemented (Wilen, Cancino, and Uchida 2012).

[3] The debate over the optimal market-based policy for the correction of externalities has been revitalized due to concerns regarding global climate change resulting from anthropogenic greenhouse gas emissions (see Nordhaus (2007), and Stavins (2008) for discussions of policy instrument choice in the context of climate change policy).

Bohm and Carlen (1999), Bohm and Carlen (2002), and Klaasen, Nentjes, and Smith (2005). Importantly, our design accommodates schemes in which individuals participate in so-called personal carbon trading. In a personal carbon trading mechanism, individuals (all of whom are affected by carbon emissions) are endowed with tradable carbon allowances.

In our experimental setting, subjects decide how much to produce of an output that yields individual benefits but also generates an externality that adversely affects all subjects, including themselves. Our experimental design is simpler than that in Plott (1983) in some respects such as the market structure. We build on Plott (1983) by adding uncertainty over marginal damages.[4]

Previous studies have analyzed such features of a personal carbon trading mechanism as design, acceptability, and behavioral impacts (Bristow et al. (2010), Fawcett and Parag (2010), Starkey (2012a), and Starkey (2012b)). Zanni, Bristow, and Wardman (2013) carry out a survey in which respondents state the changes they would make in face of either an hypothetical tax or a personal carbon trading system. Their results show that stated carbon reductions would be similar under the two policy options. Our study, the first to implement experimental economics methods in this context, adds evidence to the body of knowledge regarding behavioral responses that may occur under quantity controls such as a personal carbon trading system.[5]

We also build on the literature on behavioral responses to price controls. Kallbekken, Kroll, and Cherry (2011) find that there is an inherent bias against taxes that causes taxes to be less effective in practice than they are in theory. Lanz et al. (2018) use a field experiment to analyze the behavioral effect of Pigovian regulation. Heutel (2019) finds that the standard Pigouvian prescription to price an externality at expected external costs (or benefits) is modified in the presence of prospect theory. Houde and Aldy (2017) analyze the heterogeneous behavioral responses to an array of energy fiscal policies including taxes and subsidies. Delaney and Jacobson (2016) use lab experiments to study price and non-price measures to address common pool resource overuse. Allcott et al. (2018) analyze optimal commodity taxes and redistribution in the presence of salience effects.

Shogren (2012) provides an excellent review of the implications of the insights from behavioral economics for environmental policy design. Bernheim and Taubinsky (2018) survey work in behavioral public economics, emphasizing the normative implications of non-standard decision making for the design of welfare-improving and/or optimal policies.

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[4] In Plott (1983), an underlying market for a good generating externalities was constructed in addition to the permit market. The structure of the laboratory market implemented for this study is more similar to the designs used in experiments that focus on specific aspects of permit markets (e.g., Cason and Gangadharan (2003); Murphy and Stranlund (2007)).

[5] A standard upstream cap-and-trade system among firms also can be viewed as a price control. Under an upstream cap-and-trade system, the cost of the permits is expected to be passed on through the productive chain to the consumer. Therefore, from the consumer's perspective, a traditional cap-and-trade system in which firms are the regulatees and citizens' participation is limited is not different from a carbon tax. Standard economic theory predicts that a quantity instrument such as a personal carbon trading system would yield the same equilibrium as a price instrument such as an upstream cap-and-trade system. Nevertheless, behavioral responses may cause the outcomes of a personal carbon trading system to differ from those of an upstream cap-and-trade system.

3 Theory Model

We develop a theory model to compare the equilibria under under price and quantity instruments with and without behavioral responses. Our model is framed as a situation in which individual agents, which we can think of as countries or governments, obtain individual benefits from the production of an output that also generates a damage that adversely affects all agents, including themselves.[6]

In our model, there are N agents i. Each agent i decides how much of an externality-generating output q_i to produce. The externality-generating output q_i can represent, for example, emissions.

Profits $\pi_i(q_i)$ for each agent i are increasing in the amount of externality-generating output q_i produced by agent i ($\pi_i'(q_i) > 0$), but at a decreasing rate ($\pi_i''(q_i) < 0$). Specifically, the profit function is of the following form:

$$\pi_i(q_i) = A_i q_i - \frac{\alpha_i q_i^2}{2}, \tag{1}$$

where $\alpha_i > 0$.

We assume that the damage to each agent i from production by all agents is eQ, where the marginal damages e are constant and the same for every agent, and where $Q = q_i + \sum_{j \neq i} q_j$ is aggregate production. All agents make their production decisions simultaneously.

3.1 Standard model

We first compare the equilibria under under price and quantity instruments in a standard model without behavioral responses. In a standard model without behavioral responses, the utility $U_i(\cdot)$ of each agent i is given by the profits $\pi_i(q_i)$ from its firms minus the monetized damages suffered by its citizens:

$$U_i(q_i; \sum_{j \neq i} q_j) = A_i q_i - \frac{\alpha_i q_i^2}{2} - eQ. \tag{2}$$

3.1.1 Social Optimum

A social planner who applies equal weight to the utility functions of each of the N agents i would maximize the sum of their utilities. The individual quantities $q_{SO,i}$ produced by each agent i in the social optimum (SO) would therefore be given by:

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[6] By substituting consumption for production, our model also applies to situations in which citizens are regulated, such as personal trading systems. The production context is adopted in this section to keep consistency with the experimental design, in which individual benefits are framed in terms of profits from production.

$$q_{SO,i} = \frac{A_i - Ne}{\alpha_i}. \tag{3}$$

At the social optimum, each agent i's marginal profit is equated to the sum of marginal damages on all N agents of a unit of emissions. At the social optimum, each agent internalizes the effects of its emissions not only on itself, but on all the other agents as well.

3.1.2 No Policy

A baseline scenario (BS) with no externality-correcting policy would yield a competitive equilibrium with the following individual production quantities $q_{BS,i}$ for each agent i:

$$q_{BS,i} = \frac{A_i - e}{\alpha_i}. \tag{4}$$

In the absence of policy, each agent will equate its marginal profit to the marginal damage of a unit of emissions on itself, ignoring the effects of its emissions on other agents. As a consequence, in a competitive equilibrium in the absence of policy, agents each produce more of the externality-generating output levels q_i than they would if they internalized the effects of their emissions on all agents, resulting in a larger total quantity of externality-generating output Q than is socially optimal.

3.1.3 Tax

Under a price control scenario (PS), a tax t is charged for each unit of externality-generating output q_i produced. The utility function for each agent i is under a price control is therefore given by:

$$U_{PS,i} = A_i q_i - \frac{\alpha_i q_i^2}{2} - eQ - tq_i. \tag{5}$$

The first-order condition yields the following individual quantities $q_{PS,i}$ for each agent i under a price control:

$$q_{PS,i} = \frac{A_i - e - t}{\alpha_i}, \tag{6}$$

which yields the same outcome as the social optimum when the tax is set at the optimal level $t = e(N-1)$.

3.1.4 Tradable Permits

Under the quantity control scenario (QS), there is no charge for the externality-generating output q_i but there is a cap L on the total quantity that can be produced by the N agents as a group. The cap can be set at any level, but to achieve the social optimum it must be equal to the total quantity under the social optimum (i.e., under the optimal tax policy). Permits are distributed among agents, and agents must hold a permit for each unit they produce. The initial endowment of permits for each agent is denoted by L_i. Permits are tradable, and agents have the option of not using them for production.

The utility function for each agent i is under a quantity control is given by:

$$U_{QS,i} = A_i q_i - \frac{\alpha_i q_i^2}{2} - e q_i - e \sum_{j \neq i} q_j + \tau(l_i^s - l_i^b), \tag{7}$$

where τ is the equilibrium price of each of the permits bought (l_i^b) and sold (l_i^s) by agent i.

Each of the N agents maximizes this utility function subject to the individual permit constraint that their permit holdings must cover their production:

$$L_i + l_i^b - l_i^s - q_i \geq 0, \tag{8}$$

which yields the following individual quantities $q_{QS,i}$ for each agent i under a quantity control:

$$q_{QS,i} = \frac{A_i - \tau}{\alpha_i}. \tag{9}$$

The equilibrium permit price τ is endogenously determined in the market for permits. The price of permits is bounded below by e, which would be the price of permits if the cap were greater than the quantity that would be produced in the absence of any policy and therefore non-binding. Since the cap is binding, it follows that $\sum_i L_i = \sum_i q_{QS,i}$. The last equality allows us to predict the market equilibrium permit price τ. Summing the N functions in (9), and setting total quantity equal to total number of permits $L = \sum_i L_i$, we derive the following expression for the permit price τ:

$$\tau = \frac{\sum_i \frac{A_i}{\alpha_i} - L}{\sum_i \frac{1}{\alpha_i}}. \tag{10}$$

When there is no uncertainty about marginal damages e and no behavioral responses, the market price for permits converges to $\tau = eN$ when the cap is set at the optimal level. This result is obtained by summing the socially optimal quantities $q_{SO,i}$ given by equation (3) across all agents i, yielding the optimal total production $Q_{SO} = \sum_i \frac{A_i}{\alpha_i} - eN \sum_i \frac{1}{\alpha_i}$. Substituting Q_{SO} for L in equation (10) produces an equilibrium permit price $\tau = eN$ when the cap is set optimally.

Note that when the cap is set optimally, the permit price at which each agent is willing to buy or sell incorporates the marginal damage on all agents that results from production, as it is derived from the potential use of the permit by others to produce and therefore generate an externality. In contrast, the optimal tax is equal to the marginal damage of one agent's production on all other agents, since the agent already accounts for the marginal damage of its production on itself. This is the reason why the equilibrium permit price $\tau = eN$ when the cap is set optimally is above the optimal tax rate $t = e(N-1)$. Nevertheless, the quantities produced by each agent under the optimal tradable permits policy would remain as they would be under the optimal tax policy.[7]

3.1.5 Implications of standard model

According to the standard model, the optimal level of emissions can be achieved with a tax of $t = e(N-1)$ or a permit price of $\tau = eN$. When marginal damages e are uncertain and agents are risk neutral, the optimal level of emissions can be achieved with a tax of $t = E[e](N-1)$ or a permit price of $\tau = E[e]N$. Within the context depicted by our model, in which regulatees are also victims of the externality, the instruments are quantity-equivalent but not price-equivalent under both certain and uncertain marginal damages when behavioral responses are absent.

Although the participation of affected parties in the permit market could result in participants holding permits without using them, in the absence of behavioral responses this would not occur as long as all market participants are affected equally by the externality and the cap is binding: $L < \sum_i q_{BS,i}$. Since our model assumes equal marginal damages to all agents and imposes a cap equal to the optimal aggregate production level, all permits will be used in the absence of behavioral responses.

3.2 Behavioral Responses

We now extend the standard model to allow for behavioral responses, and compare the equilibria under price and quantity instruments with and without behavioral responses.

3.2.1 Endowment effects

The first behavioral response we examine are endowment effects. An endowment effect is an aversion to the loss of something with which an individual is endowed (Tversky and Kahneman 1991). Endowment effects may cause price and quantity instruments to lead to different outcomes even in the absence of uncertainty about either marginal abatement costs or marginal damages.

The existing literature provides mixed results regarding the presence and persistence of endowment effects in large markets. While an endowment effect in the form of reluctance to sell may be absent in “routine commercial transactions, in which goods held for sale have the status of tokens for money” (Tversky and Kahneman 1991, p.1055), endowment effects may arise for “property rights acquired by historic accident or fortuitous circumstances, such as government licenses, landing rights, or transferable pollution permits”(Kahneman, Knetsch, and Thaler 1990, p.1345). Endowment effects could also be more widespread in a tradable permits system among consumers or countries who would not necessarily perceive permits as “tokens for money". Even when they do arise, however, findings in Baldur-

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[7] The equilibrium permit price would be greater (smaller) than eN when the cap is below (above) the optimal quantity.

son and Sturluson (2011), Kujal and Smith (2008b), List (2004), and Plott and Zeiler (2005) suggest that endowment effects may only be a temporary phenomenon in markets.

Let us first consider endowment effects under the quantity control scenario (QS). When permits are allocated freely rather than via an auction, the initial permit allocation is a form of endowment that may be subject to endowment effects. In particular, endowment effects may lead individual agents to be reluctant to sell their endowed permits even if they do not use their permits for their own production. Thus, endowment effects can increase the value of each permit compared to the case in which the value of the permit is only linked to the benefits that can be obtained by generating the externality. This can ultimately reduce the externality because the holder of a permit might not find it attractive to use the permit or to sell it at the prevailing market price. Endowment effects may therefore cause the outcome of a tradable permits policy to be different from that under a tax policy.

Incorporating $\delta_i \geq 0$ as the marginal disutility from selling a permit into equation (7) for an agent's utility under a quantity control yields:

$$U_{QS,i}^{EE} = A_i q_i - \frac{\alpha_i q_i^2}{2} - e q_i - e \sum_{j \neq i} q_j + \tau(l_i^s - l_i^b) - \delta_i l_i^s. \tag{11}$$

Maximizing (11) with respect to q subject to (8) yields the following expression for the individual quantities $q_{QS,i}^{EE}$ for each agent i in the presence of endowment effects:

$$q_{QS,i}^{EE} = \frac{A_i - \tau + \delta_i}{\alpha_i}. \tag{12}$$

Equation (12) for the individual quantity $q_{QS,i}^{EE}$ for agent i in the presence of endowment effects reduces to equation (9) for the individual quantity $q_{QS,i}$ in the absence of behavioral responses if agent i's marginal disutility δ_i from selling a permit is zero in a sale or if agent i is buying.

If all permits are used ($\sum_i L_i = \sum_i q_i$),[8] we can solve for the equilibrium permit price τ. Summing up the N individual quantities in (12), setting the resulting total quantity equal to the total number of permits $L = \sum_i L_i$, substituting the socially optimal total production $Q_{SO} = \sum_i \frac{A_i}{\alpha_i} - eN \sum_i \frac{1}{\alpha_i}$ for L, and solving for τ yields the following equilibrium permit price:

$$\tau = eN + \frac{\sum_i \frac{\delta_i}{\alpha_i}}{\sum_i \frac{1}{\alpha_i}}. \tag{13}$$

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[8] Unlike in the standard model, in the presence of endowment effects it is possible that some permits are left unused. We explore the case in which some permits are left unused in Appendix A.

We can see from equation (13) that, whether or not marginal damages e are uncertain, the equilibrium price of permits would be higher compared to the standard case in which $\tau = eN$ in the case of certainty, or $\tau = E[e]N$ under uncertainty, as long as at least one agent experiences endowment effects (i.e., $\delta_i > 0$ for at least one agent i).

When all permits are used, the aggregate quantity in the presence of endowment effects would be the same as that under the standard case in the absence of fairness concerns, but the final allocation of permits across individual agents may differ. Substituting (13) back into (12), we obtain the following solution for the individual quantities $q^{EE}_{QS,i}$ for each agent i in the presence of endowment effects:

$$q^{EE}_{QS,i} = \frac{A_i - eN - \frac{\sum_i \frac{\delta_i}{\alpha_i}}{\sum_i \frac{1}{\alpha_i}} + \delta_i}{\alpha_i}. \tag{14}$$

Comparing the individual quantities $q^{EE}_{QS,i}$ in the presence of endowment effects to the individual quantities $q_{QS,i} = \frac{A_i - eN}{\alpha_i}$ from the standard case, we find that, whether or not marginal damages e are uncertain, the quantity $q^{EE}_{QS,i}$ agent i produces in the presence of endowment effects may be greater than, equal to, or less than the quantity $q_{QS,i} = \frac{A_i - eN}{\alpha_i}$ agent i produces in the absence of endowment effects, depending on the relative values of agent i's parameters and those of others.

We see from equation (14) that if every agent has the same marginal disutility from selling a permit δ, the final allocation is not different from the standard case. Likewise, if no agent has a marginal disutility from selling a permit $\delta_i > 0$, the final allocation is not different from the standard case. Any other final allocation may be observed given differences in the marginal disutility from selling a permit δ_i. For any agent j, the difference between the quantity $q^{EE}_{QS,i}$ in the presence of endowment effects and the quantity $q_{QS,i}$ in the standard case would be given by $\frac{1}{\alpha_j}(\delta_j - \frac{\sum_i \frac{\delta_i}{\alpha_i}}{\sum_i \frac{1}{\alpha_i}})$.

For instance, consider the special case in which only one agent j has a marginal disutility from selling a permit $\delta_j > 0$: in other words, only one agent j exhibits an endowment effect. The difference in quantity q_j in the presence of endowment effects from that in the standard case can be written as $\frac{\delta_j}{\alpha_j}(1 - \frac{\frac{1}{\alpha_i}}{\sum_i \frac{1}{\alpha_i}})$. Since the α_i's are all positive, the second term inside the parentheses is smaller than 1, yielding a higher quantity q_j in the presence of endowment effects compared to the standard case with no endowment effects, for that one agent j with an endowment effect. In this scenario, all other agents k would have a lower quantity compared to the standard case, with the difference in quantity compared to the standard case given by $\frac{\delta_j}{\alpha_k}(-\frac{\frac{1}{\alpha_j}}{\sum_i \frac{1}{\alpha_i}})$.

Under the price control scenario (QS), endowment effects may lead individual agents to be reluctant to use their initial financial (cash) endowment to pay the tax, leading them to produce less than they would in the absence of endowment effects.

3.2.2 Fairness concerns

A second behavioral response we examine are fairness concerns (Fehr and Schmidt 1999), which may cause price and quantity instruments to lead to different outcomes even in the absence of uncertainty about either marginal abatement costs or marginal damages. Fairness concerns may arise from agents experiencing disutility when their equilibrium externality generation is less than the average equilibrium externality generation of other agents, since this inequity in externality generation would mean that others are contributing more on average to the externality than they are.[9]

Concerns about fairness and equity have been observed in experimental economics (Roth 1995) and have formed the bases for arguments in international environmental negotiations, including those regarding long-range transboundary air pollution and greenhouse gas emissions (Lange and Vogt 2003). Similar to previous work on endowment effects, however, the evidence regarding the impact of fairness concerns in markets is not conclusive. On the one hand, Fehr and Schmidt (1999, p.834) argue that in some instances it is "...the impossibility of preventing inequitable outcomes by individual players that renders inequity aversion unimportant in equilibrium." On the other hand, Franciosi et al. (1995) admits that fairness concerns can result in deviations from competitive equilibrium predictions in bilateral trading situations but not in large multilateral trading markets where gains from exchange are reduced by fair behavior. Kachelmeier, Limberg, and Schadewald (1991) and Kujal and Smith (2008a) consider that in large markets, fairness concerns, like endowment effects, may only affect the competitive equilibrium temporarily.

Under the quantity control scenario (QS), market participants exhibiting fairness concerns can affect the amount of externality generated by others through their decisions in the permit market by incurring costs to achieve outcomes that appear more fair to them. Individual agents could do so by holding more permits than their optimal level of externality generation, and possibly leaving some of the additional permits unused, thus precluding others from using the permits at the cost of foregone income from further permit sales. Studies such as Fehr and Gachter (2000) have found that individual agents incur costs to punish agents who make unfair decisions.

Following Fehr and Schmidt (1999), we introduce inequity linearly into the utility function. We assume that agents can observe the total number of permits, and can therefore infer the average permit holdings of other agents.[10] We furthermore assume that advantageous inequity does not have an impact on the utility of agent i. Let γ_i represent the disutility agent i receives from inequity when agent i's equilibrium permit holdings (after trading) H_i are less than the average equilibrium permit holdings of other agents. The utility of agent i under a quantity control is then given by:

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[9] We focus on fairness concerns as arising from inequities in externality generation, rather than from inequities in utility, for several reasons. First, as we are examining situations in which there are externalities that may need to be addressed with either price or quantity controls, it is possible that individual agents may be particularly concerned about inequities in externality generation. Second, in our experiment, subjects observe the number of permits held by other subjects, which is correlated with the externality generated by others, but do not observe the utility or marginal benefit type of other subjects. As explained below, in our experimental design the total number of permits is among the information that is provided to subjects on their computer screen. As a consequence, we model fairness concerns as arising from inequities in permit holdings, which are related to inequities in externality generation, rather than from inequities in utility.

[10] As explained below, in our experimental design the total number of permits is among the information that is provided to subjects on their computer screen.

$$U_{QS,i}^{FC} = A_i q_i - \frac{\alpha_i q_i^2}{2} - e q_i - e \sum_{j \neq i} q_j + \tau(l_i^s - l_i^b) - \gamma_i \left(max \left\{ \frac{L - NH_i}{N-1}, 0 \right\} \right). \tag{15}$$

Maximizing (15) with respect to q subject to (8) yields the following individual quantities $q_{QS,i}^{FC}$ for each agent i in the presence of fairness concerns:

$$q_{QS,i}^{FC} = \frac{A_i - \tau + \gamma_i \frac{N}{N-1}}{\alpha_i}. \tag{16}$$

If all permits are used ($\sum_i L_i = \sum_i q_i$),[11] we can solve for the equilibrium permit price τ. Summing up the N individual quantities in (16), setting the resulting total quantity equal to the total number of permits $L = \sum_i L_i$, substituting the socially optimal total production Q_{SO} for L,and solving for τ yields the following equilibrium permit price:

$$\tau = eN + \frac{\frac{N}{N-1} \sum_i \frac{\gamma_i}{\alpha_i}}{\sum_i \frac{1}{\alpha_i}}. \tag{17}$$

We can see from equation (17) that, whether or not marginal damages e are uncertain, the equilibrium price of permits in the presence of fairness concerns would be higher compared to the standard case in which $\tau = eN$ in the case of certainty, or $\tau = E[e]N$ under uncertainty.

When all permits are used and the cap is set optimally, the aggregate quantity in the presence of fairness concerns would be the same as that under the standard case in the absence of fairness concerns, but the final allocation of permits across individual agents may differ. Substituting (17) back into (16), we obtain the following solution for the individual quantities $q_{QS,i}^{FC}$ for each agent i in the presence of fairness concerns:

$$q_{QS,i}^{FC} = \frac{A_i - eN - \frac{\frac{N}{N-1} \sum_i \frac{\gamma_i}{\alpha_i}}{\sum_i \frac{1}{\alpha_i}} + \gamma_i \frac{N}{N-1}}{\alpha_i}. \tag{18}$$

Comparing the individual quantities $q_{QS,i}^{FC}$ in the presence of fairness concerns to the individual quantities $q_{QS,i} = \frac{A_i - eN}{\alpha_i}$ from the standard case, we find that, whether or not marginal damages e are uncertain, the quantity $q_{QS,i}^{FC}$ agent i produces in the presence of fairness concerns may be greater than, equal to, or less than the quantity $q_{QS,i} = \frac{A_i - eN}{\alpha_i}$ agent i produces in the absence of fairness concerns, depending on the relative values of agent i's parameters and those of others.

From equation (18), we see that if every agent has the same disutility from equity γ_i, the final allocation is not different from the standard case. Likewise, if no agent has a disutility from inequity $\gamma_i > 0$, the final allocation is not different from the standard case. Any other final allocation may be observed given differences in the disutility from inequity γ_i. The sign of the difference between the quantity $q_{QS,i}^{FC}$ for agent i in the case incorporating fairness concerns and the quantity $q_{QS,i}$ for agent i in the standard case is given by:

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[11] Unlike in the standard model, in the presence of fairness concerns it is possible that some permits are left unused. We explore the case in which some permits are left unused in Appendix A.

$$\text{sign}(q^{FC}_{QS,i} - q_{QS,i}) = \text{sign}\left(\sum_{j \neq i} \frac{1}{\alpha_j}(\gamma_i - \gamma_j)\right), \tag{19}$$

which is the weighted sum of the differences between agent i's disutility from inequity γ_i and the disutility from inequity γ_j of every other agent j, the weights given by the inverse of the corresponding α_j. The sign of the difference between the quantity $q^{FC}_{QS,i}$ for agent i in the case incorporating fairness concerns and the quantity $q_{QS,i}$ for agent i in the standard case thus depends on the both the weights and the magnitudes of the differences between one's own disutility from inequity γ_i and everyone else's diutility from inequity γ_j, and would be unambiguously positive (negative) if $\gamma_i > \gamma_j$ ($\gamma_i < \gamma_j$) for all j. In other words, if agent i's disutility from inequity is higher (lower) than those of all other agents j, then agent i's quantity in the presence of fairness concerns would be higher (lower) than her quantity in the standard case with no behavioral responses.

Thus, those with a lower permit endowment may have a relatively large disutility from inequity γ_i and therefore potentially produce more than predicted in the standard case. The opposite would be true for those subjects with a large permit endowment.

Under a price control scenario (PS), fairness concerns that arise from agents experiencing disutility when their equilibrium externality generation is less than the average equilibrium externality generation of other agents have less of an effect on the market behavior of individual agents, since under a price instrument an individual agent is unable to affect the amount of externality generated by others. Under a price instrument, individual agents can only affect inequities in different market participants' contributions to the externality by increasing their own emissions contribution, which they may perceive to have little impact on the behavior of others and which has the adverse effect of increasing the overall externality. Thus, fairness concerns will likely have only a small effect, if any, on equilibrium quantity under a price control.

3.2.3 Prospect theory

The third behavioral response we consider are attitudes towards risk deviating from the expected utility framework. Unlike the other behavioral responses we consider (endowment effects, fairness concerns, and cognitive costs), attitudes towards risk that deviate from the expected utility framework can only arise when there is uncertainty, and therefore can only cause price and quantity instruments to lead to different outcomes when there is uncertainty.

Under marginal damage uncertainty, decisions from regulatees who are also victims of the externality can alternatively be explained by principles from prospect theory (Kahneman and Tversky 1979) instead of those from the standard expected utility theory. Under prospect theory, market participants may exhibit loss aversion and/or weigh events by magnitudes that differ from their respective probabilities of occurrence, thus leading to different decisions under uncertainty. In particular, a loss averse market participant would overweight negative consequences when marginal damages are uncertain, and therefore overstate the negative impact of the externality.[12]

Under the expected utility framework, the outcome would be the same for risk-neutral decision-makers whether or not there is uncertainty in the level of marginal damages $\tilde{e}$ as long as the mean of the uncertain marginal damages $\tilde{e}$ when marginal damages are uncertain is equal to the certain marginal damages e when marginal damages are certain:

$$E[\tilde{e}] = pe^h + (1-p)e^l = e, \tag{20}$$

where e^h and e^l respectively represent scenarios with high and low damages that occur with probabilities p and $(1-p)$, respectively.

We consider two dimensions along which attitudes towards risk may deviate from the expected utility framework, both of which are features of prospect theory.

The first feature of prospect theory we consider is what we term the 'overweighting of high damage events'. Under the 'overweighting of high damage events', individual agents assign their own perceived weights to high and low damage events, instead of basing their decisions on the actual probabilities of high and low damage events, and end up overweighting high damage events for behavioral reasons. In particular, the perceived marginal damages e_i, which vary across subjects i, are given by:

$$e_i = w_i(p)e^h + w_i(1-p)e^l, \tag{21}$$

where the weights associated with the high and low damage events are respectively $w_i(p) > p$ and $w_i(1-p) < (1-p)$, where $w_i(p) + w_i(1-p) = 1$, such that the high damage event e^h is given a higher weight than its probability p of occurrence, and the low damage event e^l given a lower weight than its probability $(1-p)$ of occurrence. Owing to the overweighting of high damage events, the perceived marginal damages e_i are higher than the expected value of the marginal damage $E[\tilde{e}] = e$.[13]

The second feature of prospect theory we consider is what we term 'risk seeking to avoid losses'. Under 'risk seeking to avoid losses', attitudes towards risk deviate from the expected utility framework because individual agents are loss aversion and therefore are more willing to take risks to avoid a loss than they are to achieve an equivalent amount of gain. In particular, the utility of agents can be represented through the following value function W_i which separates the gains $x \geq 0$ from the losses $y \leq 0$:

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[12] As Tversky and Kahneman (1991, p.1057) argue: "Because of this asymmetry [between pain and pleasure] a decision maker who seeks to maximize the experienced utility of outcomes is well advised to assign greater weight to negative than to positive consequences."

[13] For instance, take the prospect (ηx,p;x,1-p) where $\eta > 1$. The expected value of this prospect is $E = p\eta x + (1-p)x$. Now, assume that instead of probabilities, weights (w_p and w_{1-p}, $w_p + w_{1-p} = 1$) are assigned such that the prospect takes the following form: $V = w_p \eta x + w_{1-p} x$. The difference $V - E = (w_p - p)(\eta x - x)$ is positive because $w_p > p$ and $\eta > 1$.

$$W_i = U_i(x) + V_i(y), \tag{22}$$

where $U_i(\cdot)$ is the concave utility from gains and $V_i(\cdot)$ is the convex utility from losses, with $U_i(\cdot) \geq 0$, $U_i'(\cdot) > 0$, $U_i''(\cdot) < 0$; $V_i(\cdot) \leq 0$, $V_i'(\cdot) > 0$, $V_i''(\cdot) > 0$; and $U_i(0) = V_i(0) = 0$. Furthermore, the utility from gaining an amount $x > 0$ is less than the disutility from losing that same amount x: $U_i(x) < -V_i(-x)$ for any $x > 0$.

Figure 1 depicts a value function W that exhibits loss aversion in that the function is steeper in the negative domain than in the positive domain; losses loom larger than corresponding gains, and this divergence is more pronounced in the value function shown in red over the losses domain. Moreover, both the marginal utility of gains and the marginal utility of losses decrease with their size. These properties give rise to an asymmetric S-shaped value function, concave above the origin and convex below it (Tversky and Kahneman 1991). When the utility $V(\cdot)$ from losses is convex, individual agents may be more willing to take risks to avoid a loss. We call the convex nature of the utility $V(\cdot)$ from losses 'risk seeking to avoid losses'.

Let us first examine the outcome of the quantity control scenario (QS) under these two features of prospect theory. When allowing for 'overweighting of high damage events' but not 'risk seeking to avoid losses', the utility function for each agent i under a quantity control would be given by the same utility function in equation 7 as in the standard model in the absence of behavioral responses, except that the pollution damages that enter the utility function would be evaluated using the perceived marginal damages e_i in equation 21 rather than the actual marginal damages e. As a consequence, under the 'overweighting of high damage events' but not 'risk seeking to avoid losses', the individual quantity $q_{QS,i}^{PT}$ for agent i would be given by equation (9) for the individual quantity $q_{QS,i}$ in the absence of behavioral responses; and the equilibrium price of permits would similarly equal that in the standard case in which $\tau = eN$. Thus, on its own, the overweighting of high damage events would have no effect on permit prices P.

When allowing for 'risk seeking to avoid losses', the utility of agents under the quantity control can be represented through the following value function:

$$W_{QS,i} = U_i(A_i q_i - \frac{\alpha_i q_i^2}{2} + \tau l_i^s) + V_i(-e_i q_i - e\sum_{j \neq i} q_j - \tau l_i^b), \tag{23}$$

where the gains are from production profits and the sale of permits, and the losses are from pollution damages and the purchase of permits. If there is 'overweighting of high damage events' in addition, then the pollution damages that enter the utility from losses $V_i(\cdot)$ is evaluated using the perceived marginal damages e_i in equation 21 rather than the actual marginal damages e.

Maximizing (23) with respect to q subject to $L_i + l_i^b - l_i^s - q_i \geq 0$, and assuming $\pi_i(q_i) = A_i q_i - \frac{\alpha_i q_i^2}{2}$, we obtain the following expression for individual quantities $q_{QS,i}^{PT}$ for each agent i under prospect theory:

$$q_{QS,i}^{PT} = \frac{A_i - \frac{V_i'}{U_i'}\tau}{\alpha_i}, \tag{24}$$

where, if there is 'overweighting of high damage events' in addition, the marginal utility from losses V_i' is evaluated using the perceived marginal damages e_i in equation 21 rather than the actual marginal damages e. Equation (24) for the individual quantity $q_{QS,i}^{PT}$ for agent i under prospect theory reduces to equation (9) for the individual quantity $q_{QS,i}$ in the absence of behavioral responses if agent i's marginal utilities over gains and losses are equal ($V_i' = U_i'$) in a purchase or if agent i is selling.

If all permits are used ($\sum_i L_i = \sum_i q_i$),[14] we can obtain an equation for the equilibrium permit price τ. Summing up the N individual quantities in (24), setting the resulting total quantity equal to the total number of permits $L = \sum_i L_i$, substituting the socially optimal total production Q_{SO} for L, and solving for τ yields the following equilibrium permit price under the two features of prospect theory:

$$\tau = eN\frac{\sum_i \frac{1}{\alpha_i}}{\sum_i \frac{V_i'/U_i'}{\alpha_i}}. \tag{25}$$

We can see from equation (25) that whether the equilibrium permit price under 'risk seeking to avoid losses' is equal to, larger than, or smaller than the equilibrium permit price $\tau = eN$ in the standard case depends on the ratios V_i'/U_i' of the marginal utilities of losses and gains for all agents i. The equilibrium price of permits under prospect theory would equal that in the standard case in which $\tau = eN$ if $\sum_i \frac{V_i'/U_i'}{\alpha_i} = \sum_i \frac{1}{\alpha_i}$.

Under 'risk seeking to avoid losses' but not the 'overweighting of high damage events', owing to the convexity of the utility $V(\cdot)$ from losses, when losses are small enough and gains are large enough, the ratios V_i'/U_i' of the marginal utilities of losses and gains can be greater than one, resulting in an equilibrium permit price under prospect theory that is lower than that in the standard case. Thus, on its own, risk seeking to avoid losses would reduce permit prices P under a tradable permits policy.

The combined effect of both overweighting bad events and risk seeking to avoid losses is less straightforward, however. When both overweighting of high damage events and risk seeking over losses are combined, the expected loss is amplified for those subjects who overweight high damage events, thus lowering their marginal utility from losses V_i' and therefore lowering their ratios V_i'/U_i' of their marginal utilities of losses and gains. The ratios V_i'/U_i' of the marginal utilities of losses and gains can therefore be greater than, equal to, or less than one under the combined

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[14] Unlike in the standard model, under prospect theory it is possible that some permits are left unused. We explore the case in which some permits are left unused in Appendix A.

effect of both features of prospect theory, resulting in an equilibrium permit price under prospect theory that can be lower than, equal to, or greater than that in the standard case, respectively. As a consequence, the combined effect of both features from prospect theory on permit prices under a quantity control is ambiguous.

When all permits are used, the aggregate quantity under prospect theory would be the same as that under the standard case, but the final allocation of permits across individual agents may differ. Substituting equation (25) back into equation (24) we obtain the following expression for individual quantities $q_{QS,i}^{PT}$ for each agent i under prospect theory:

$$q_{QS,i}^{PT} = \frac{A_i - \frac{V_i'}{U_i'} eN \frac{\sum_i \frac{1}{\alpha_i}}{\sum_i \frac{V_i'/U_i'}{\alpha_i}}}{\alpha_i}. \tag{26}$$

Comparing the individual quantities $q_{QS,i}^{PT}$ under prospect theory to the individual quantities $q_{QS,i} = \frac{A_i - eN}{\alpha_i}$ from the standard case, the quantity $q_{QS,i}^{PT}$ agent i produces under prospect theory may be greater than, equal to, or less than the quantity $q_{QS,i} = \frac{A_i - eN}{\alpha_i}$ agent i produces in the absence of prospect theory, depending on the relative values of agent i's parameters and those of others. In general, the sign of the difference in quantity $q_{QS,i}^{PT}$ under prospect theory and the quantity $q_{QS,i}$ in the standard case is given by the following expression:

$$\text{sign}(q_{QS,i}^{PT} - q_{QS,i}) = \text{sign}\left(1 - \frac{V_i'}{U_i'} \frac{\sum_i \frac{1}{\alpha_i}}{\sum_i \frac{V_i'/U_i'}{\alpha_i}}\right). \tag{27}$$

The second element in the last expression can be rewritten as:

$$\frac{\sum_j \frac{V_i'/U_i'}{\alpha_j}}{\sum_i \frac{V_i'/U_i'}{\alpha_i}}. \tag{28}$$

The sign of the difference in expression (27) depends on the magnitudes of the numerator and denominator in expression (28). The difference in the quantity $q_{QS,i}^{PT}$ under prospect theory and the quantity $q_{QS,i}$ in the standard case would be negative, zero, or positive if expression (28) is greater, equal, or smaller than one, respectively, which translates into the following expression being respectively greater, equal, or smaller than zero:

$$\sum_{j \neq i} \frac{1}{\alpha_j} \left(\frac{V_i'}{U_i'} - \frac{V_j'}{U_j'}\right). \tag{29}$$

From expression (29) it can be inferred that if every agent shares the same constant marginal value on gains and losses, the final allocation under prospect theory is not different from the standard case. When the ratio of an agent $i's$ marginal utilities over losses and gains exceeds (is below) that of every other agent, the quantity produced by this agent would be smaller (greater) compared to the standard case. Larger risk seeking to avoid losses and risk aversion over gains tends to push this ratio up. The slopes also depend on the magnitudes of the losses and the gains. The larger the loss and the larger the gain, the smaller would be the slope of the corresponding function (i.e. V' and U') and vice versa.

It should be noted that subjects who overweight the probability of bad events more would have smaller V'. Thus, overweighting would tend to increase the individual quantity (i.e., by reducing V') while risk seeking to avoid losses would tend to decrease the individual quantity (i.e., by increasing V').

Now let us examine the outcome under the price control scenario (PS). When there is 'risk seeking to avoid losses', the utility of agents under the price control can be represented through the following value function:

$$W_{PS,i} = U_i(A_i q_i - \frac{\alpha_i q_i^2}{2}) + V_i(-e_i Q - t q_i), \tag{30}$$

where the gains are from production profits, and the losses are from pollution damages and the tax payment. If there is 'overweighting of high damage events' in addition, then the pollution damages that enter the utility from losses $V_i(\cdot)$ is evaluated using the perceived marginal damages e_i in equation 21 rather than the actual marginal damages e.

First-order conditions yield the following individual quantities $q^{PT}_{PS,i}$ for each agent i under a price control once both 'risk seeking to avoid losses' and 'overweighting of high damage events' are allowed for:

$$q^{PT}_{PS,i} = \frac{A_i - (e_i + t)\frac{V_i'}{U_i'}}{\alpha_i}. \tag{31}$$

Whether this quantity differ from the quantity $q_{PS,i} = \frac{A_i - e - t}{\alpha_i}$ in the standard case depends on the magnitude by which perceived marginal damages e_i exceeds the expected marginal damage e, and on the relative slopes of the value function over the gains and losses.

On its own, overweighting of high damage events would increase perceived marginal damages e_i, and thus reduce the quantity produced under a price control. On its own, risk seeking to avoid losses tends to reduce production under a price control, since, owing to the convexity of the utility $V(\cdot)$ from losses, the ratio V_i'/U_i' of the marginal utilities of losses and gains can be greater than one when losses are small enough and gains are large enough.

The combined effect of both overweighting high damage events and risk seeking to avoid losses is less straightforward, however. As overweighting gets more severe, the slope V' of the value function in losses will be smaller due to the convexity of the value function in the loss domain, thus pushing production upwards. As a consequence, the combined effect of both features of prospect theory on the quantity produced under a price control is ambiguous.

3.2.4 Cognitive costs

A fourth behavioral response we examine are cognitive costs. The idea behind cognitive costs is that, contrary to classical economic theory, individual agents faced with costly cognition may not make the optimal decision, and may instead exhibit bounded rationality (Lin and Muehlegger 2013).

Simon (1955) observed that "the concept of, ‘economic man’ (and, I might add, of his brother, ‘administrative man’) is in need of fairly drastic revision", and that "the task is to replace the global rationality of economic man with a kind of rational behavior that is compatible with the access to information and the computational capacities that are actually possessed" by human decision-makers.

Gabaix et al. (2006) find evidence that the search activity of individuals seems to more closely follow a myopic model of cognition when information is costly. Luttmer and Shue (2009) find evidence in the 2003 California recall election that is consistent with misvoting relating to cognition costs.

When faced with cognitive costs, subjects do not perform all the calculations necessary to achieve rational outcomes and may instead apply heuristic rules in their decisions. Lin and Muehlegger (2013) examine one such ’heuristic strategy’ and its resulting equilibrium.

It is possible that a tradable permit system may be harder for individual agents to understand than a tax. For example, in a tradable permit system, cognitive costs could result in non-optimal exchanges and, under uncertainty, in miscalculations of expected values (Kahneman 2003). As a consequence, individual agents faced with cognitive costs may be more likely to make sub-optimal decisions under a quantity control than under a price control.

4 Experimental Design

We conduct a laboratory experiment to evaluate how and whether behavioral responses affect the outcomes of price and quantity instruments when marginal abatement costs are known with certainty. Details of our experimental design are presented in Table 1. In our experiment, we expose groups of individuals to different policies and marginal damage (MD) environments, and then compare the prices and quantities between groups. The policies imposed were a baseline scenario with no regulatory intervention (BS), a tax policy scenario (PS), and a tradable permits policy scenario (QS). In addition, some of the participants played games in which the marginal damage was uncertain.

The experiment was programmed and conducted with the experimental software z-Tree (Fischbacher 2007). Experimental subjects received detailed and identical instructions that were read aloud by the experimenter at the beginning of each session and prior to each policy intervention.[15] Experimental subjects anonymously interacted with other

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[15] Detailed instructions and screenshots from the participants’ interface are available from the authors upon request.

subjects within only one group during the whole experimental session through computer terminals. There were twelve independent groups (or experimental markets), each consisting of 8 subjects acting as firms.[16]

Participants were endowed with experimental cash (M_i) every round that, where applicable, could be used to pay for units produced (q) under a price control (PS), to buy permits (l) under a quantity control (QS), or to keep for themselves. They also received a marginal benefit schedule listing the profits they would receive from the production of units of a fictitious good.

Production by each member of the group created negative impacts on all members of the group. As described in Table 1, groups played under different environments regarding the damage function, which we refer to as different marginal damage (MD) environments or treatments. In order to simplify the decision-making, the marginal damage (e) was specified as a constant for each unit produced in the group. Four of the groups were given the certainty treatment (C), in which the marginal damage ($e = 3$) was known with certainty and the value of e was revealed before the production decision was made. In the eight other groups, the marginal damages were uncertain, with a state (e_l) being less adverse than the other (e_h), but with the expected value of e under the uncertainty treatments equal to that from the certainty treatment. Four of these eight groups were given the balanced uncertainty treatment (Ub), in which the two states would occur with equal probabilities. The other four of these eight groups were given the unbalanced uncertainty treatment (Ue), in which the two states were assigned extreme probabilities. The values and probabilities of e_l and e_h in the the balanced uncertainty treatment (Ub) and the unbalanced uncertainty treatment (Ue) are presented in Table 1. In both the balanced uncertainty treatment (Ub) and the unbalanced uncertainty treatment (Ue), the marginal damage e was drawn randomly with replacement from the respective distribution by the computer for each group for each round, and the realized value of e in each round was revealed after the production decision for that round was made.

In terms of the profits participants would receive from production, participants were given one of four types of marginal benefit schedules classified as low (LO), medium-low (ML), medium-high (MH), and high (HI) marginal benefit types, respectively, with two individuals per group in each category.[17] The marginal benefit schedules were given by $\pi_i = A_i - \alpha_i q_i$ for $i =$LO, ML, MH, and HI, with respective parameters $A_i = (35, 30, 55, 50)$, and $\alpha_i = (10, 5, 10, 5)$. The functions were truncated at zero profits and production q_i was restricted to be a positive integer. Subjects knew only their own marginal benefit schedules, which remained constant during the 9 rounds of each of the policy treatments.

Table 2 shows, for each marginal benefit type, the marginal benefit schedule, the permit and experimental cash endowment, and the quantity predicted by the theory model for each policy scenario. Initial endowment, marginal benefits, marginal damages, and prices, were all defined in terms of tokens, the experimental currency. Tokens had a

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[16] Our choice to have 8 subjects acting as firms in each of the experimental markets is consistent with the previous experimental economics literature. Muller and Mestelman (1998) note that between 8 and 12 individuals are typically recruited for each experimental permit market, a convention followed by the studies included in Issac and Holt (1999).

[17] Inducing valuations for fictitious goods in this manner is common practice in economic experiments and has been formally justified in Smith (1976).

corresponding value in dollars announced prior to the beginning of the experiment which was used to convert experimental earnings to their dollar value.

All twelve groups were first exposed to the baseline scenario (BS), after which half of them played the price control scenario (PS) and the other half played the quantity control scenario (QS). Each policy treatment consisted of eight rounds (plus an initial trial round) in which individuals chose the number of units (quantity) of the good they wanted to produce. Participants did not know in advance the total number of rounds in each game.

In each round of each treatment, subjects were given 20 seconds to make their production decision. After the 20-second production-decision stage, subjects were given time (a maximum of 15 seconds under the no policy scenario BS and the price control scenario PS, and a maximum of 20 seconds under the quantity control scenario QS) to review the results and profits from the production decision that round. In each round of the quantity control scenario QS, subjects had a maximum of 90 seconds (which we call the 'permit market period') to decide how many permits to hold and complete their permit trading before making their production decision.[18]

Under the no policy scenario (BS), there is no cost for producing units of the good, and the individual before-damage earnings in each round are the sum of the production profits. Tokens are then deducted from each subject's account based on the total quantity produced in the group (Q, which is the sum of the individual quantity each of the 8 participants in the subject's group decided to produce) to reflect the emission damages. The final earnings in each round is given by equation (2) plus the initial endowment (M_i). The optimal individual quantity $q_{BS,i}$ predicted by theory is given by equation (4).

Under the price control scenario (PS), a fee ($t = 21$) for each unit produced of the fictitious good was announced and each individual's earnings are reduced by tq_i and augmented by M_i compared to equation (2). The optimal individual quantity $q_{PS,i}$ predicted by theory is given by equation (6).

Under the quantity control scenario (QS), there is no price to be paid per unit produced of the fictitious good. Instead, participants needed a permit for every unit of production, and a limit on the total quantity that can be produced ($Q = 20$) in the group was introduced as a cap on the total number of permits in the group. This aggregate quantity is based on the aggregate marginal benefit function and corresponds to the amount that would be produced if t was the fee charged for producing each unit. The total number of permits in the group is among the information that is provided to subjects on their computer screen. Permits were distributed to every member of the group; the allocation of permits is given in Table 2. Subjects were allowed to make bids to buy a permit from others and make offers to sell a permit to others, and/or accept offers/bids from others. This is translated into the constraint in equation (8) which allows in principle for the possibility that individuals do not use all the permits they hold. The optimal individual quantity $q_{QS,i}$ predicted by theory is given by equation (9), and the per round earnings are given by equation (7) plus M_i. Although

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[18] Plott and Gray (1990) suggest that a continuous double auction mechanism requires eight seconds per equilibrium transaction. From Table 2, each LO subject is predicted to sell three units, and each ML subject is predicted to sell two, for a predicted total of ten equilibrium transactions, or 80 seconds. Appendix B provides evidence that suggests that subjects had enough time to trade all the permits they would have liked.

the distribution of permits was not equitable, the symmetric partition of the group into high and low marginal benefit minimized the possibility of agents exerting market power in non-monopolized double-auction markets.

In the permit market period of each round of the quantity control (QS) treatments, individuals were allowed to sell and buy permits under a continuous double auction mechanism prior to entering the production decision stage. In this experiment, current valid bids (asks) were shown ranked from highest to lowest (lowest to highest) at every point in time, and trade occurred when a buyer (seller) accepted the current ask (bid).[19] Once an agreement was reached, the new highest bid and lowest ask were shown at the top of their respective lists. In the production decision stage, individuals could only produce a quantity of the good that was less than or equal to the number of permits they hold, which precluded the development of strategies involving non-compliance (Murphy and Stranlund 2007).

The aggregate demand for the good is derived from adding the inverse marginal benefit schedules of the eight subjects in each market. Setting the aggregate demand for the good equal to the aggregate marginal damage of 24 (3 tokens times 8 subjects), the social optimum is reached at 20 units produced in the group.[20] This optimal quantity could be achieved by imposing a limit on the total production by the group equal to 20, or by charging a tax between 18 and 21 per unit. As seen in the theory model, the optimal tax is lower than the aggregate marginal damage (24) since subjects already account for the marginal damage their own production inflicts on themselves. We set the tax at 21 per unit, which is equal to the sum of individual damages on the rest of the group per unit produced. From Table 2 one can verify that such tax level would yield the respective theoretical prediction q_{PS} for each subject when using the respective marginal benefit schedule and $e = 3$.

Our sample size of six independent groups per policy scenario and four independent groups in each marginal damage environment is consistent with the number of groups used in the literature on experimental studies on emission trading and common pool resource dynamics. Canonical papers in the experimental economics literature, including that of Plott and Smith (1978) on exchange institutions, and that of Plott (1983) analyzing policy instruments for the correction of externalities, have used 2 groups per treatment in single group sessions in their experiments. Recent experimental studies on emission trading and common pool resource dynamics, such as Klaasen, Nentjes, and Smith (2005) and Suter et al. (2012), have used 1 and 2 groups per treatment, respectively, while the experimental designs in the permit markets in Murphy and Stranlund (2006), Murphy and Stranlund (2007), Anderson and Sutinen (2006), and Stranlund, Murphy, and Spraggon (2011) use 3 groups per treatment.

As we show below, although we do not have many independent group observations, the variation in results among groups with the same policy treatment and marginal damage environment is relatively small. The results therefore do not appear to be driven by any outlier groups.

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[19] This version of the continuous double auction institution that incorporates the so-called *rank queue* facilitates convergence towards equilibrium (Smith and Williams 1983). See Friedman (1991) for an updated overview and history of this trading mechanism used for example in the New York Stock Exchange. The layout of the permit market stage of this experiment builds upon that used by Zetland (2008, Ch.7) in the context of water rights in southern California.

[20] Aggregate quantity in the competitive equilibrium in the absence of policy is 44 units.

A major benefit of conducting an experiment with a larger number of groups is an increase in statistical power that allows detection of a given effect size. As we show below, in spite of our small number of observations, we are able to parametrically identify statistically significant effects of the treatments under study.

In Appendix B, we analyze and address several other possible concerns about our experimental design, including possible concerns about the complexity of the quantity control scenario (QS), and provide evidence that subjects under the quantity control scenario (QS) were given enough time to trade all the permits they would have liked to trade.

5 Predicted Effects of Behavioral Responses

5.1 Predicted aggregate effects

Table 3 summarizes the predicted effect of behavioral responses on aggregate quantities (or emissions) and permit prices, relative to the standard case in the absence of behavioral responses, according to our theory model. In the case of tradable permits, the predicted effects apply to both the case in which all permits are used and the case in which some permits are left unused.[21]

Behavioral responses such as endowment effects (Tversky and Kahneman 1991), fairness considerations (Fehr and Schmidt 1999), and cognitive costs (Kahneman 2003) may cause price and quantity instruments to lead to different outcomes even in the absence of uncertainty about either marginal abatement costs or marginal damages.

Under a tradable permits policy, market participants exhibiting endowment effects may respond by being more reluctant to sell their (endowed) permits, while market participants exhibiting fairness concerns can affect inequities in different market participants' contributions to the externality by buying additional permits in order to achieve outcomes that appear more fair to them.

Thus, under both endowment effects and fairness concerns, our theory predicts that under a quantity instrument permit prices would be higher than they would be in the absence of behavioral responses. The predicted increases in permit prices follow from equation (13) (and also equation (A.3) in Appendix A) for endowment effects, and equation (17) (and also equation (A.7) in Appendix A) for fairness concerns. Our theory also predicts that, owing to cognitive costs, individuals may be more likely to make sub-optimal decisions under a quantity control than under a price control.

Under a price instrument, market participants exhibiting endowment effects may respond by being more reluctant to use their initial financial (cash) endowment to pay the tax, leading them to produce less than they would in the absence of endowment effects.

Fairness concerns have less of an effect on market participants under a price instrument than under a quantity instrument, since under a price instrument individuals can only affect inequities in different market participants' con-

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[21] We explore the case in which some permits are left unused in Appendix A.

tributions to the externality by increasing their own emissions contribution, which they may perceive to have little impact on the behavior of others and which has the adverse effect of increasing the overall externality.

Thus, under a price instrument, our theory predicts that emissions Q would be lower in the presence of endowment effects but possibly higher in the presence of fairness concerns.

Under marginal damage uncertainty, decisions from regulatees who are also victims of the externality might be better explained by principles from prospect theory (Kahneman and Tversky 1979) than those from the standard expected utility theory. Under prospect theory, market participants may overweight high damage events and/or exhibit risk seeking to avoid losses, thus leading to different decisions under uncertainty.

On its own, the overweighting of high damage events would increase perceived marginal damages e_i, and thus reduce the quantity produced under a price control but have no effect on permit prices P under a quantity control. On its own, risk seeking to avoid losses would reduce permit prices P under a tradable permits policy and reduce production under a price control.

The combined effect of both the overweighting high damage events and risk seeking to avoid losses is less straightforward, however. When both the overweighting of high damage events and risk seeking over losses are combined, the slope V' of the marginal utility from losses will be smaller due to the convexity of the utility $V(\cdot)$ from losses, thus pushing permit prices upwards under a quantity control and pushing production upwards under a price control. As a consequence, the combined effect of both features of prospect theory on permit prices P under a quantity control and on the quantity produced Q under a price control are ambiguous. The results for aggregate quantities under the tax instrument in the presence of overweighting of high damage events and risk seeking to avoid losses follow from the discussion in Section 3.2.3, while the result for permit prices is based on equation (25) (and also equation (A.11) in Appendix A).

5.2 Predicted heterogeneous effects

Allowing for heterogeneity in the individual marginal benefit and endowments in our experiment enables us to further distinguish among the different behavioral responses. Table 4 summarizes the results from our theoretical model for the effects of behavioral responses on individual quantities (or emissions) by marginal benefit type, relative to the individual quantities (or emissions) in the standard case in the absence of behavioral responses.

From our experimental design, endowment effects and fairness concerns have opposite impacts on individual quantities under a quantity control: while endowment effects would increase production by low (LO) and medium-low (ML) marginal benefit subjects and decrease production by medium-high (MH) and high (HI) marginal benefit subjects, fairness concerns would decrease production by low (LO) and medium-low (ML) marginal benefit subjects and increase production by medium-high (MH) and high (HI) marginal benefit subjects. As seen in equation (14) of our theory model, individuals with a relatively larger endowment effect will produce relatively more than individuals with a smaller or no endowment effect. Likewise, as seen in equation (18) of our theory model, individuals with relatively higher fairness concerns will produce relatively more than individuals with lower or no fairness concerns. In our design, low (LO) and medium-low (ML) marginal benefit subjects have a larger permit endowment than medium-high (MH) and high (HI) marginal benefit subjects, and thus are more likely to exhibit endowment effects but less likely to exhibit fairness concerns.

When attitudes towards risk deviate from the expected utility framework, the predicted impacts on individual quantities under a tax policy follow from equation (31) of the theory model. On its own, the overweighting of high damage events under a tax regime may have less of a negative effect on the production of individuals with low marginal benefits, who have lower gains and therefore larger marginal utility in gains. On its own, risk seeking to avoid losses under a tax regime may have more of a negative effect on the production of individuals with higher marginal benefits since the marginal utility of gains decreases as the gain increases, increasing the ratio of marginal utilities over losses and gains. Although the combined effect of both the overweighting of high damage events and risk seeking to avoid losses under a tax regime is ambiguous, it is more likely to have a positive effect on the production of individuals with low marginal benefits due to their larger marginal utility in gains.

In the case of tradable permits, from equation (26), overweighting of high damage events alone does not have an impact on individual quantities. In constrast, risk seeking to avoid losses tends to increase production from subjects with low marginal benefits at the expense of reduced production from subjects with high marginal benefits. The combination of both effects results in ambiguous predictions for the individual quantities.

6 Results

6.1 Aggregate quantity (or emissions) produced

Table 5 shows the means and standard deviations of the aggregate quantity (or emissions) produced by each group per round for each of the different treatment combinations. Figure 2 presents graphs of the mean and standard deviation of the aggregate quantity as a function of treatment round for each of the different treatment combinations. The solid blue lines indicate the mean and the dotted blue lines indicate one standard deviation above and below the mean. The red lines indicate the theoretical prediction for aggregate quantity for each policy treatment. Although we do not have many independent group observations, there do not appear to be any outlier groups, as the variation in results among groups with the same policy treatment and marginal damage environment is relatively small.[22]

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[22] Appendix C presents summary statistics and graphs of the aggregate quantity produced from a third game the subjects played, in which groups treated with the price control (PS) in the second game were treated with the quantity control (QS) in the third game, and vice versa. We choose not analyze the third game in this paper since play in the third game may be confounded by experiences from the policy treatment in the second game, and would therefore complicate our econometric analysis and interpretation. Nevertheless, as seen in Table C.1 and Figure C.1 in Appendix C, the summary statistics, levels, and trends for the aggregate quantities (or emissions) of this third game are similar to those for the price control (PS) and

Table 6 presents the results from panel regressions of the aggregate quantity produced by marginal damage environment on a dummy for the quantity policy treatment, a dummy for the last 4 rounds, and an interaction between the dummy for the quantity policy treatment and the dummy for the last 4 rounds. The regressions use group observations from all rounds (trial round excluded) of the policy treatments, yielding four groups with eight periods each. We use a population-averaged linear panel model with a first-order autocorrelation error structure.

To examine our hypotheses in Table 3 regarding the predicted effect of behavioral responses on aggregate quantities (or emissions) according to our theory model, we use the regression results from Table 6 to conduct hypothesis tests comparing the aggregate quantity produced by policy treatment with their respective theoretical prediction and also with each other. The results are reported in Table 7. The first two rows of Table 7 present the difference between the observed aggregate quantity produced and the theoretical prediction (20 units). The last row in Table 7 shows the difference between the observed outcomes under the two policies (the treatment effect).

For robustness, to allow for the possibility that the behavior of subjects facing uncertain marginal damages may depend on the state in the previous round, we also run similar regressions also including a dummy for having had the bad state e_l in the previous round as a regressor in the regressions for the balanced uncertain marginal damage environment (Ub) and the unbalanced uncertain marginal damage environment (Ue). As seen in the results of these regressions in Table C.2 in Appendix C, and in the results of hypothesis tests comparing the aggregate quantity produced by policy treatment with their respective theoretical prediction and also with each other are reported in Table C.3 in Appendix C, our results are robust to whether we control for the state in the previous round.[23]

The following three results can be gleaned from Table 5, Figure 2, Table 6, Table 7, Table C.2 in Appendix C, and Table C.3 in Appendix C.

Result 1: In the price control scenario (PS), the aggregate quantity produced is larger than predicted under the balanced uncertain marginal damage environment (Ub) and equal to the theoretical prediction under the certain marginal damage environment (C) and the unbalanced uncertain marginal damage environment (Ue).

Support: Table 5 and Figure 2 suggest this result, which is confirmed by the deviations $Q_{PS} - 20$ reported in the first row in Table 7 which are positive and statistically significant for Ub in both early and later rounds, but are not significant for either C or Ue. Tables C.2 and C.3 in Appendix C show similar results as well.

Evidence for: Fairness concerns when marginal damages are uncertain; Prospect theory

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the quantity control (QS) in the second game in Table 5 and Figure 2, respectively. Behavioral responses that arise as a result of prior experience with alternative policy instruments is beyond the scope of this paper, but a topic we hope to further examine in future work.

[23] We also run a set of regressions also including an interaction between having had the bad state e_l in the previous round and the dummy for the quantity policy treatment. As this additional interaction term was not significant at even a 10% level in any of the regressions, and as the results are also similar, we do not report these additional results.

The finding in Result 1 that the aggregate quantity produced is equal to the theoretical prediction in the price control scenario (PS) under the certain marginal damage environment (C) suggests that there are no behavioral responses resulting from an endowment effect, or fairness concerns in the price control scenario under the certain marginal damage environment.

As summarized in Table 3, when damages are uncertain, the combined effect of both aspects of prospect theory on emissions Q are ambiguous. The finding in Result 1 that the aggregate quantity produced is larger than the theoretical prediction in the price control scenario (PS) under the balanced uncertain marginal damage environment (Ub) suggests that the combined effect on production of overweighting of high damage events and risk seeking to avoid losses may be positive. A higher aggregate quantity in the price control scenario (PS) may also be evidence of fairness concerns. Under the unbalanced uncertain marginal damage environment (Ue), the finding in Result 1 that the aggregate quantity produced is equal to the theoretical prediction in the price control scenario (PS) suggests that the combined effect of both aspects of prospect theory is zero or that neither overweighting of high damage events nor risk seeking to avoid losses are present.

Result 2: In the quantity control scenario (QS), the aggregate quantity produced is equal to the theoretical prediction under each of the three marginal damage environments.

Support: Table 5 and Figure 2 (as well as Table C.2 in Appendix C) suggest this result, which is confirmed by the non-statistically significant deviations $Q_{QS} - 20$ reported in the second row in Table 7 (as well as Table C.3 in Appendix C).

Evidence against: Cognitive costs

Unlike in the standard model, in the presence of behavioral responses, it is possible that some permits are left unused. Nevertheless, Result 2 that the aggregate quantity produced is equal to the theoretical prediction in the quantity control scenario (QS) suggests that permits tend to be all used.

Result 2 that the aggregate quantity produced is equal to the theoretical prediction in the quantity control scenario (QS) suggests that there are no behavioral responses resulting from cognitive costs that make subjects more likely to deviate from the optimal decision under the quantity control scenario (QS) than under the price control scenario (PS).

Result 3: The aggregate quantity produced is larger under the price control scenario (PS) compared to the quantity control scenario (QS) in early rounds under the balanced uncertain marginal damage environment (Ub) and in later rounds under the unbalanced uncertain marginal damage environment (Ue). In all other cases, the difference is not statistically significant.

Support: Table 5 and Figure 2 (as well as Table C.2 in Appendix C) suggest this result, which is confirmed by the differences $Q_{PS} - Q_{QS}$ reported in the last row in Table 7 (as well as Table C.3 in Appendix C) which are positive and statistically significant for early rounds of Ub and later rounds of Ue, but are not significant for any other case.

Evidence for: Fairness concerns when marginal damages are uncertain; Prospect theory

The finding in Result 3 that, under the certain marginal damage environment (C), there is no statistically significant difference between the aggregate quantity produced under the price control scenario (PS) and the quantity control scenario (QS) suggests that there are no behavioral responses under the certain marginal damage environment.

The finding in Result 3 that, in early rounds under the balanced uncertain marginal damage environment (Ub) and in later rounds under the unbalanced uncertain marginal damage environment (Ue), aggregate quantity is higher under the price control scenario (PS) compared to the quantity control scenario (QS), combined with Result 2 that there are no deviations in aggregate quantity from their theoretical predictions under the quantity control (QS), is a possible outcome of fairness concerns and/or prospect theory.

Thus, in contrast to the standard economic theory, we find that price and quantity controls lead to different outcomes when marginal damages are uncertain, which provides evidence for the presence of behavioral responses.

6.2 Individual quantities (or emissions) produced

Allowing for heterogeneity in the individual marginal benefit and endowments in our experiment enables us to further distinguish among the different behavioral responses. In order to examine our hypotheses in Table 4 on the effects of behavioral responses by marginal benefit type on individual quantities, we also conduct an empirical analysis that makes use of the variation across individual observations under the two policy interventions. In particular, we run separate regressions for each marginal benefit type of the quantity produced by each individual subject in each round in the price control (PS) and quantity control (QS) treatments on a dummy for the quantity policy treatment, a dummy for the last 4 rounds, and an interaction between the dummy for the quantity policy treatment and the dummy for the last 4 rounds. We use a population-averaged linear panel model with a first-order autocorrelation error structure. The regressions are marginal benefit type specific and are reported in three separate tables, one for each marginal damage environment. These are Tables 8, 9, and 10, respectively. Each regression represents a subject type-treatment combination and therefore uses observations from eight subjects (two of each type in each of the four groups) over eight periods each, for a total of 64 observations. Table 11 shows the results of hypothesis tests for the differences between actual individual quantity produced and the theoretical prediction of individual quantity produced (1, 1, 3, and 5 for LO, ML, MH, and HI respectively) as well as for the difference between the observed outcomes under the two policies (the treatment effect) resulting from these regressions.

For robustness, to allow for the possibility that the behavior of subjects facing uncertain marginal damages may depend on the state in the previous round, we also run similar regressions also including a dummy for having had the bad state e_l in the previous round as a regressor in the regressions for the balanced uncertain marginal damage environment (Ub) and the unbalanced uncertain marginal damage environment (Ue). As seen in the results of these regressions in Tables C.4 and C.5 in Appendix C, and in the results of hypothesis tests comparing the aggregate quantity produced by policy treatment with their respective theoretical prediction and also with each other as reported in Table C.6 in Appendix C, our results are robust to whether we control for the state in the previous round.[24]

The following three results for individual quantity produced can be gleaned from Tables 8, 9, 10, and 11, as well as Tables C.4, C.5, and C.6 in Appendix C, and complement the previous analysis of aggregate quantity produced.

Result 4: Under the certain marginal damage environment (C):

(i) The individual quantity produced in the price control scenario (PS) is higher than the theoretical prediction for the medium-low marginal benefit subjects (ML) in late rounds but the difference between individual quantity produced and the theoretical prediction is not statistically significant for any other marginal benefit group.

(ii) The individual quantity produced in the quantity control scenario (QS) is higher than the theoretical prediction for the low marginal benefit (LO) and medium-low marginal benefit (ML) subjects and lower than the theoretical prediction for the medium-high marginal benefit (MH) and high marginal benefit (HI) subjects.

(iii) The difference between the individual quantity produced in the price control scenario (PS) and the individual quantity produced in the quantity control scenario (QS) is negative for low marginal benefit (LO) and positive for medium-high marginal benefit (MH) subjects. In all other cases, the difference between the individual quantity produced under the price control scenario (PS) and that under the quantity control scenario (QS) is not statistically significant.

Support: (i), (ii), and (iii) are from the first, second, and third rows, respectively of each panel in Table 11 (as well as Table C.6 in Appendix C) for the certain marginal damage environment (C).

Evidence for: Fairness concerns when marginal damages are certain; Endowment effects when marginal damages are certain

Result 4(i) that the individual quantity produced in the price control scenario (PS) is higher than the theoretical prediction for the medium-low marginal benefit subjects (ML) in late rounds under the certain marginal damage environment (C) is evidence for fairness concerns.

Result 4(ii) that the individual quantity produced in the quantity control scenario (QS) is higher than the theoretical prediction for the low marginal benefit (LO) and medium-low marginal benefit (ML) subjects and lower than the theoretical prediction for the medium-high marginal benefit (MH) and high marginal benefit (HI) subjects provides possible evidence for an endowment effect as predicted in Table 4, and is consistent with the results from a different

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[24] We also run a set of regressions also including an interaction between having had the bad state e_l in the previous round and the dummy for the quantity policy treatment. As this additional interaction term was not significant at even a 10% level in any of the regressions, and as the results are also similar, we do not report these additional results.

emissions trading environment in Murphy and Stranlund (2006). Subjects with lower marginal benefits from producing are those with a larger permit endowment and may be more reluctant to sell permits, leading to a positive difference between individual quantity produced under the price and quantity control for MH subjects and negative difference for LO subjects.

Result 4(iii) shows that there are differences in individual quantity produced between the price control (PS) and quantity control (QS) treatments under the certain marginal damage environment (C), even though Result 3 showed that these differences are not statistically significant at the aggregate level. This suggests that, at the aggregate level, the negative difference in individual quantity produced between the price control (PS) and quantity control (QS) treatments for low marginal benefit (LO) subjects may cancel the positive difference in individual quantity produced between the price control (PS) and quantity control (QS) treatments for the medium-high marginal benefit (MH) subjects.

Result 5: Under the balanced uncertain marginal damage environment (Ub):

(i) The individual quantity produced in the price control scenario (PS) is higher than the theoretical prediction for the low marginal benefit subjects (LO) in early rounds but the difference between the individual quantity produced and the theoretical prediction is not statistically significant for any other marginal benefit group.

(ii) The individual quantity produced in the quantity control scenario (QS) is higher than the theoretical prediction for the medium-low marginal benefit (ML) subjects and lower than the theoretical prediction for the high marginal benefit (HI) subjects in late rounds. The individual quantity produced is also lower than predicted for the medium-high marginal benefit (MH) subjects in early rounds.

Support: (i) and (ii) are from the first and second rows, respectively, of each panel in Table 11 (as well as Table C.6 in Appendix C) for the balanced uncertain marginal damage environment (Ub).

Evidence for: Fairness concerns when marginal damages are uncertain; Endowment effects when marginal damages are uncertain; Prospect theory

Result 5(i) that the individual quantity produced in the price control scenario (PS) is higher than the theoretical prediction for the low marginal benefit subjects (LO) in early rounds under the balanced uncertain marginal damage environment (Ub) is evidence for fairness concerns.

Result 5(ii) that the individual quantity produced under the quantity control scenario (QS) under the balanced uncertain marginal damage environment (Ub) is higher than the theoretical prediction for medium-low marginal benefit (ML) subjects but lower than the theoretical prediction for high marginal benefit (HI) subjects may be indicative of the presence of an endowment effect as reported in Table 4. Subjects with lower marginal benefits from producing are those with a larger permit endowment and may be more reluctant to sell permits, leading to a positive difference between the individual quantity produced under the price and quantity control for HI subjects. Result 5(ii) provides possible evidence for prospect theory as well, since risk seeking to avoid losses and risk aversion in gains may be respectively large and small for ML subjects, and the opposite for HI subjects.

Result 6: Under the unbalanced uncertain marginal damage environment (Ue):

(i) The individual quantity produced in the price control scenario (PS) is higher than the theoretical prediction for the low marginal benefit subjects (LO) but the difference between the individual quantity produced and the theoretical prediction is not statistically significant for any other marginal benefit group.

(ii) The individual quantity produced in the quantity control scenario (QS) is higher than the theoretical prediction for the low marginal benefit (LO) and medium-low marginal benefit (ML) subjects and lower than the theoretical prediction for the high marginal benefit (HI) subjects.

Support: (i) and (ii) are from the first and second rows, respectively, of each panel in Table 11 (as well as Table C.6 in Appendix C) for the unbalanced uncertain marginal damage environment (Ue).

Evidence for: Fairness concerns when marginal damages are uncertain; Endowment effects when marginal damages are uncertain; Prospect theory

Result 6(i) that the individual quantity produced in the price control scenario (PS) is higher than the theoretical prediction for the low marginal benefit subjects (LO) under the unbalanced uncertain marginal damage environment (Ue) is evidence for fairness concerns.

Result 6(ii) that the individual quantity produced under the quantity control scenario (QS) under the unbalanced uncertain marginal damage environment (Ue) is higher than the theoretical prediction for low marginal benefit (LO) and medium-low margin benefit (ML) subjects but lower than the theoretical prediction for high marginal benefit (HI) subjects may be indicative of the presence of an endowment effect. Result 6(ii) provides possible evidence for prospect theory as well, since risk seeking to avoid losses and risk aversion in gains may be respectively large and small for LO and ML subjects, and the opposite for HI subjects.

6.3 Permit prices

Table 12 shows average permit prices and permit sales by marginal damage environment. Both appear close to their theoretical prediction of 24 and 10, respectively, in every case except for sales under the balanced uncertain marginal damage environment (Ub).

To examine our hypotheses in Table 3 regarding the predicted effect of behavioral responses on permit prices according to our theory model, we analyze the impact of the marginal damage environment on the permit market outcomes using data on the prices at which each permit was traded. More specifically, we perform a regression analysis suitable for long panels that allows a more flexible error structure. We regress the natural log of the permit price on the marginal damage environment, the round, the characteristics of the buyer in the transaction, and the characteristics of the seller in the transaction. We include the following characteristics of both the buyer and the seller in the transaction as regressors: marginal benefit type, age, gender, years of college, major, experience in experiments, and two variables that measure the subject's social and environmental concern. We use a generalized least squares model with a group-specific first-order autocorrelation error structure. The time variable in the permit price regressions is given by the order in which trades were completed within a group during the whole treatment (i.e., the time variable is not reset every round). Table 13 only reports the estimated coefficients for the marginal damage environment (the certainty treatment being the baseline case) and the round. Result 7 below summarizes our findings based on tests of the equality of the coefficients for marginal damage environment (C, Ub, Ue).

Result 7: Permit prices are higher under uncertain marginal damage environments. In later rounds, prices are highest under the unbalanced uncertain marginal damage environment (Ue) and lowest under the certain marginal damage environment (C).

Support: Hypothesis tests for differences in prices under different marginal damage environments based on the results presented in Table 13 show that these prices are significantly different from each other.

Evidence for: Prospect theory

As seen in Table 3, according to our theory model, under uncertain marginal damage environments, the overweighting of high damage events combined with risk seeking to avoid losses from prospect theory would have a positive effect on the permit price, while risk seeking to avoid losses from prospect theory alone should have a negative effect on the permit price.

Result 7 suggests that under the balanced uncertain marginal damage environment (Ub), the positive effect of combining overweighting of high damage events and risk seeking to avoid losses prevails, yielding a higher price with respect to that under the certain marginal damage environment (C). Under the unbalanced uncertain marginal damage environment (Ue), there may be a further positive effect on prices due to a higher reluctance to sell from low marginal benefit (LO) and medium-low marginal benefit (ML) subjects, who may be more prone to overweight the probability of the bad state given the small potential gains from individual production and the relatively large potential losses from group production.

As shown in Section 3.2.2, the presence of fairness concerns increases the shadow price of both a permit bought and a permit sold by the same amount. In contrast, in the presence of endowment effects, the shadow price of a permit sold is higher than that of a permit bought (the difference being the marginal disutility δ_i from selling a permit). In Table 14, we present results from random effects Tobit regressions in which the dependent variable is the bid-ask spread for each subject who offered both to buy and sell permits in a single round. The bid-ask spread is the price asked to sell a permit minus the bid price to buy one. A positive spread would suggest the presence of endowment effects, while no spread rules out endowment effects. For each marginal damage environment, we run a random effects Tobit regression of the bid-ask spread of subjects who offered both to buy and sell permits in a single round, on dummies for their marginal benefit type and on the round. The number of observations is limited by the number of subjects who offered both to buy and sell permits in a single round (about 20% of the total number of subjects in each regression). Our panel is unbalanced because not all of these subjects offered to buy and sell in all rounds.

Result 8: The bid-ask spread is positive under all marginal damage environments but declines over time under the certain marginal damage environment (C) and the balanced uncertain marginal damage environment (Ub).

Support: Coefficient estimates from Table 14 show a statistically significant positive coefficient for the constant term and a negative coefficient on the round under C and Ub.

Evidence for: Endowment effects when marginal damages are uncertain; Endowment effects when marginal damages are certain

The positive bid-ask spread in Result 8 suggests the presence of endowment effects, at least among subjects who offered both to buy and sell permits in a single round. The declining spread under the certain marginal damage environment (C) and the balanced uncertain marginal damage environment (Ub) in Result 8 suggests the presence of a learning effect or a declining endowment effect consistent with findings in Baldurson and Sturluson (2011), Kujal and Smith (2008b), List (2004), and Plott and Zeiler (2005), at least among subjects who offered both to buy and sell permits in a single round. The bid-ask spread does not decline in groups that were exposed to the unbalanced uncertain marginal damage environment (Ue).

7 Conclusion

Standard economic theory predicts that, when regulating environmental externalities, quantity instruments such as tradable permits and price instruments such as taxes will produce identical outcomes when transaction costs are negligible and marginal abatement costs are known with certainty by the regulator, even when marginal damages are uncertain from the perspective of the regulator. In practice, however, behavioral responses on the part of market participants may cause price and quantity instruments to lead to different outcomes. Some of these behavioral responses include endowment effects, fairness concerns, attitudes towards risk deviating from the expected utility framework, and cognitive costs.

In this paper, we develop a theory model to compare the equilibria under price and quantity instruments with and without behavioral responses. We then conduct a laboratory experiment to evaluate the effects of uncertainty in marginal damages on the outcomes of price and quantity instruments when marginal abatement costs are known with certainty.

In our model and experiment, regulated agents themselves suffer the damages from their externality generation. There are many situations in which the regulated agents themselves suffer from marginal damages from their own externality generation, including pollution problems, such as air pollution and climate change, in which pollution by one agent adversely affects all agents, including the polluter itself; and common-pool resource problems, such as overfished fisheries,[25] groundwater exploitation, and road congestion, in which the use of the common pool resource by one agent adversely affects all agents, including the user himself. Our model is particularly well suited to the case of climate change, in which the welfare of all individuals could be affected by both the benefits of economic activity and the damages from the greenhouse gas emissions resulting from this economic activity.[26] Our theoretical model and experimental design also apply to systems in which countries or regions trade carbon permits, such as those studied by Bohm and Carlen (1999), Bohm and Carlen (2002), and Klaasen, Nentjes, and Smith (2005). Importantly, our design accommodates schemes in which individuals participate in so-called personal carbon trading. In a personal carbon trading mechanism, individuals (all of whom are affected by carbon emissions) are endowed with tradable carbon allowances.

Greenhouse gas emissions that may cause global climate change have marginal damages that are uncertain and are being regulated through different mechanisms, including taxes and emission permits. Carbon taxes are already in place in several countries. Examples of tradable permit systems in climate change policy that resemble our model include: (1) permit trading among European countries for emissions not covered under the European Union Emissions Trading Scheme and (2) personal carbon trading. The former is an ongoing enforceable policy, while the latter is a proposal originated in the United Kingdom that has been explored more recently in Starkey (2012a), Starkey (2012b), and Zanni, Bristow, and Wardman (2013).

Our theory predicts that under a quantity instrument, permit prices would be higher in the presence of either endowment effects or fairness concerns than they would be in the absence of behavioral responses. Under a price instrument, our theory predicts that emissions would be lower in the presence of endowment effects but possibly

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[25] For the regulation of fisheries, taxes have seldom been proposed but different systems of tradable fishing quotas have been implemented (Wilen, Cancino, and Uchida 2012).

[26] The debate over the optimal market-based policy for the correction of externalities has been revitalized due to concerns regarding global climate change resulting from anthropogenic greenhouse gas emissions (see Nordhaus (2007), and Stavins (2008) for discussions of policy instrument choice in the context of climate change policy).

higher in the presence of fairness concerns. Owing to cognitive costs, our theory predicts that individuals may be more likely to make sub-optimal decisions under a quantity control than under a price control.

Market participants whose attitudes towards risk deviate from the expected utility framework and are instead better explained by prospect theory may overweight high damage events and/or exhibit risk seeking to avoid losses. Our theory predicts that, on its own, the overweighting of high damage events would increase perceived marginal damages, and thus reduce the quantity produced under a price control but have no effect on permit prices under a quantity control. On its own, risk seeking to avoid losses would reduce permit prices under a tradable permits policy and reduce production under a price control .

The combined effect of both the overweighting high damage events and risk seeking to avoid losses is less straightforward, however. When both the overweighting of high damage events and risk seeking over losses are combined, the slope of the marginal utility from losses will be smaller due to the convexity of the utility from losses, thus pushing permit prices upwards under a quantity control and pushing production upwards under a price control. As a consequence, the combined effect of both features of prospect theory on permit prices under a quantity control and on the quantity produced under a price control are ambiguous.

There are several interesting results from our experiment. In terms of aggregate emissions, the quantity-equivalence of quantity and price instruments cannot be rejected when marginal damages are known with certainty. When marginal damages are uncertain, however, the implementation of an optimal tax can lead to more emissions compared to those achieved with a tradable permit system capped at the optimal amount of emissions. This latter finding could be the result of overweighting of high damage events combined with risk seeking to avoid losses, whose combined effect increases production. This is because as overweighting gets more severe, the slope of the value function in losses will be smaller due to the convexity of the value function in the loss domain, thus pushing production upwards. Although such motivation is present regardless of the policy in place, under a tradable permits policy the aggregate limit can not be exceeded, whereas under a tax policy regulated agents can produce as much as they wish provided the tax is paid. As a consequence, attitudes towards risk deviating from the expected utility framework cause the emissions resulting from a quantity control to differ from those resulting from a price control. A higher aggregate quantity under the price control may also be evidence of fairness concerns that lead individuals to affect inequities in different market participants' contributions to the externality by increasing their own emissions contribution.

Our findings based on aggregate outcomes are complemented by our analysis of individual decisions, which enables us to further distinguish among the different behavioral responses. When marginal damages are certain, aggregate production under price and quantity instruments were not statistically different from each other, thus suggesting the absence of behavioral responses when marginal damages are certain. In contrast, the analysis of individual production shows that low marginal benefit subjects, who received a relatively larger permit endowment, experienced endowment effects that make them reluctant to sell their permits. We also find that the low and medium-low marginal benefit subjects are more affected by overweighting of high damage events combined with risk seeking to avoid losses under uncertain damages, putting upward pressure on their production in the tax treatment. Our result that the individual quantity produced in the price control scenario can be higher than the theoretical prediction for the low and medium-low marginal benefit subjects is also evidence for fairness concerns that lead individuals to affect inequities in different market participants' contributions to the externality by increasing their own emissions contribution.

In contrast with previous studies that compared carbon reductions under a personal carbon trading and a tax based on survey exercises, our experiment involving real stakes shows that these reductions could be different depending on whether marginal damages are uncertain and whether the relevant level of analysis is the individual or the group.

A final set of results from our experiment emerge from an analysis of the permit prices. According to our theory model, under uncertain marginal damage environments, the overweighting of high damage events combined with risk seeking to avoid losses from prospect theory would have a positive effect on the permit price, while risk seeking to avoid losses from prospect theory alone should have a negative effect on the permit price. According to the results of our experiment, permit prices are higher under the two uncertain marginal damage environments, and the prices are the highest when the bad state involves a small probability but extremely bad event. Our results therefore show that the combined effect of overweighting of high damage events and risk seeking to avoid losses dominate risk seeking to avoid losses alone under the quantity instrument. These findings are in agreement with those from the analysis on aggregate quantities summarized above.

According to our theory model, in the presence of endowment effects, the shadow price of a permit sold is higher than that of a permit bought (the difference being the marginal disutility from selling a permit). Using data on those subjects who bid to both buy and sell permits, we find suggestive evidence for the presence of endowment effects that decrease over time in environments with certain damages and uncertain but non-extreme events, at least among subjects who offered both to buy and sell permits in a single round. Conversely, when the possibility of an extreme event is present, reluctance to sell due to overweighting may cause the endowment effects to persist over time, at least among subjects who offered both to buy and sell permits in a single round.

The results from our experiment therefore provide evidence for behavioral responses, possibly from endowment effects, fairness concerns, and/or attitudes towards risk deviating from the expected utility framework, that cause price and quantity instruments to lead to different outcomes. We do not find evidence for cognitive costs that make deviations from the optimal decision more likely under a quantity instrument than under a price instrument.

Our research suggests several possible avenues for future research. First, while our experiment enables us to examine if price and quantity instruments lead to different outcomes, and therefore whether behavioral responses that cause price and quantity instruments to lead to different outcomes may be present, we are not able to separately identify the different behavioral responses or quantify the relative contribution of each. In future work we hope to pursue empirical and/or experimental methods to separately identify each of the behavioral responses, to quantify the relative contribution of each behavioral response to any divergence between price and quantity instruments, and to analyze what factors affect the relative importance of each behavioral response.

A second possible avenue for future research is to better understand the effects of the interaction between endowment effects and the overweighting of high damage events. In our theory model we show that, while the overweighting of high damage events and risk seeking to avoid losses would each reduce the quantity produced under a price control on its own, the combined effect of both overweighting bad events and risk seeking to avoid losses on the quantity produced under a price control is ambiguous. In this paper, we analyze each of these two components of prospect theory separately as well as their interactions with each other, but analyze prospect theory separately from endowment effects. In future work, we hope to explore and analyze the effects of combining loss aversion in the form of endowment effects with the overweighting of high damage events.

A third possible avenue for future research is to examine if behavioral responses differ depending on whether the regulated agents themselves suffer the damages from their externality generation. In this paper, we focus on the situation in which regulated agents suffer the damages from the externality generation. As explained above, such a situation applies to many environmental and natural resource problems, including air pollution, climate change, personal carbon trading, fisheries, groundwater exploitation, and road congestion. Nevertheless, it is possible that behavioral responses may differ if regulated agents do not also suffer the damages from the externality generation.

In addition to behavioral responses, there may be other possible reasons why price instruments might perform differently from quantity instruments, both in theory and in practice, including technological innovation, imperfect competition, cost uncertainty, and stock pollutants. A fourth avenue for future research is to develop a framework to compare among these different explanations for why price and quantity instruments may lead to different outcomes, and to assess how behavioral responses may interact with these other considerations.

A fifth possible avenue for future research is to analyze if behavioral responses differ based on the number of participants in the permit market. Having a large number of participants in the permit market could attenuate any behavioral responses, since each individual may then perceive that they have little impact on the behavior of others, just as they do under a tax system, thus possibly restoring the equality between price and quantity instruments.

A sixth possible avenue for future research is to harness the behavioral responses to better design policy. Yoeli et al. (2017) argue that regulatory and market-based policies should be combined with behavioral interventions grounded in extensive behavioral science research to increase consumers' conservation of energy and other resources.

Our results have important implications for the design of policy. If price and quantity instruments are no longer equivalent when marginal damages are uncertain because of behavioral responses, policy-makers should consider the possibility of behavioral responses in the design of policy and in their choice of whether to use a price or quantity instrument. In particular, our results suggest that when marginal damages are uncertain, a tradable permit system capped at the optimal amount of emissions may be preferable to an optimal tax, since behavioral responses may cause the latter to lead to more emissions. In addition, despite the standard economic theory that equilibrium outcomes under a quantity instrument are not affected by whether permits are allocated freely or via an auction (Hahn and Stavins 2011), our results suggest that, when deciding whether to allocate permits freely or via an auction, policymakers may wish consider the possibility that freely allocating permits may lead to endowment effects that may raise permit prices higher than the equilibrium permit price in the absence of behavioral responses.

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Figure 1: Value function over gains and losses under prospect theory

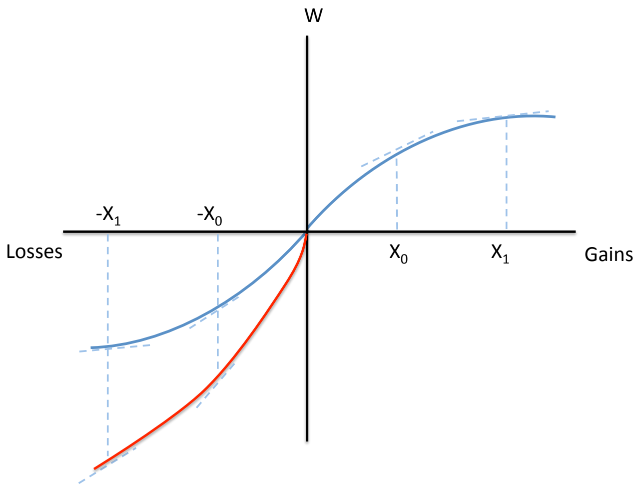


Table 1: Summary of experimental design and procedures

Subjects	Ninety-six undergraduate students from the University of California. Average payment per subject was USD 15 USD, which included a USD 5 fee for showing up to the experiment. The rest of their earnings depended on their cumulative performance in the two games. Experimental subjects were only allowed to participate in one session.
Groups	Twelve independent 8-person groups.
Sessions	Seven 1-hour sessions, consisting of five 2-group sessions and two single-group sessions, conducted in a computer room at the University of California at Davis.
Marginal damage type	C: $e = 3$. Ub: $e_l = 0$ or $e_h = 6$ with 1/2 probability each. Ue: $e_l = 2$ or $e_h = 12$ with probabilities 9/10 and 1/10, respectively. The expected values of e under the two uncertainty treatments were equal to that from the certainty treatment.
Marginal benefit types	Participants were given one of four types of marginal benefit schedules classified as low (LO), medium-low (ML), medium-high (MH), and high (H) marginal benefit types, respectively, with two individuals per group in each category. Marginal benefit schedules derived from linear functions $\pi_i = A_i - \alpha_i q_i$ where i =LO, ML, MH, and HI with respective parameters $A_i = (35, 30, 55, 50)$, and $\alpha_i = (10, 5, 10, 5)$. The functions were truncated at zero profits and production q_i was restricted to be a positive integer (see Table 2).
Treatments	Each treatment consisted of a policy treatment (BS, PS, or QS) combined with a marginal damage environment (C, Ub, or Ue). All groups started the experiment with BS followed by either PS or QS (six groups in each). Each group played only under one of the three marginal damage environments (four groups in each).
Stages	Policy treatments played in one of two orders: BS-PS or BS-QS. Each policy treatment consisted of 8 rounds (plus an initial trial round) in which individuals chose the number of units (quantity) of the good they wanted to produce. Participants did not know in advance the total number of rounds in each game.
Rounds	In each round of each treatment, subjects were given 20 seconds to make their production decision. After the 20-second production-decision stage, subjects were given time (a maximum of 15 seconds under the no policy scenario (BS) and the price control scenario (PS), and a maximum of 20 seconds under the quantity control scenario (QS)) to review the results and profits from the production decision that round. In each round of the quantity control scenario (QS), subjects had a maximum of 90 seconds (which we call the 'permit market period') to decide how many permits to hold and complete their permit trading before making their production decision.

Table 2: Marginal benefit (MB) schedules, endowments, and predicted quantities

	LO	ML	MH	HI
Marginal benefit from producing:				
1 unit	25	25	45	45
2 units	15	20	35	40
3 units	5	15	25	35
4 units	0	10	15	30
5 units	0	5	5	25
6 units	0	0	0	20
7 units	0	0	0	15
8 units	0	0	0	10
9 units	0	0	0	5
10 units	0	0	0	0
Theoretical prediction for q_{BS}	3	5	5	9
Theoretical prediction for q_{PS}	1	1	3	5
Theoretical prediction for q_{QS}	1	1	3	5
Token endowment (BS and PS)	160	140	90	10
Token endowment (QS)	120	160	150	180
Permit endowment (QS)	4	3	2	1

Table 3: Possible behavioral responses and their predicted effect on permit prices P and aggregate quantities (or emissions) Q

Behavioral Response	**Predicted impact under:**			
	Price Control (PS)		**Quantity Control (QS)**	
	Certainty (C)	Uncertainty (U)	Certainty (C)	Uncertainty (U)
1. Endowment effects	↓Q	↓Q	↑P	↑P
2. Fairness concerns	Small ↑Q	Small ↑Q	↑P	↑P
3. Prospect theory: Overweighting of high damage events	No predicted deviation	↓Q	No predicted deviation	No predicted deviation
4. Prospect theory: Risk seeking to avoid losses	No predicted deviation	↓Q	No predicted deviation	↓P
5. Prospect theory: Both effects combined	No predicted deviation	Ambiguous	No predicted deviation	Ambiguous
6. Cognitive costs	No predicted deviation	No predicted deviation	Deviation	Deviation

Table 4: Possible behavioral responses and their predicted effect on individual quantities (or emissions) q_i by marginal benefit type

Behavioral Response	**Predicted impact on q_i under:**			
	Price Control (PS)		**Quantity Control (QS)**	
	LO & ML	MH & HI	LO & ML	MH & HI
1. Endowment effects	↓	↓	↑	↓
2. Fairness concerns	Small ↑	Small ↑	↓	↑
3. Prospect theory: Overweighting of high damage events	Smaller ↓	↓	No deviation	No deviation
4. Prospect theory: Risk seeking to avoid losses	↓	Larger ↓	↑	↓
5. Prospect theory: Both effects combined	More likely to ↑	Ambiguous	Ambiguous	Ambiguous
6. Cognitive costs	No deviation	No deviation	Deviation	Deviation

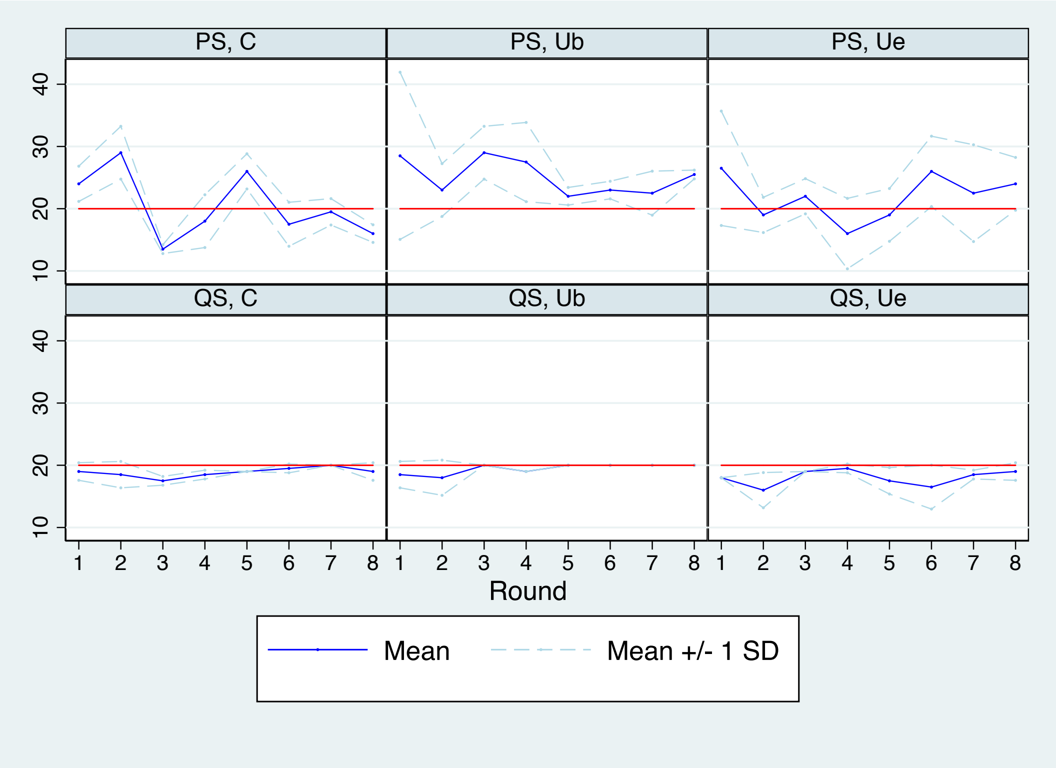
Notes: For endowments effects, fairness concerns, and cognitive costs: the predicted impacts apply whether or not marginal damages are uncertain. For prospect theory: the predicted impacts only apply when marginal damages are uncertain; there is no predicted deviation when marginal damages are known with certainty.

Table 5: Mean and standard deviation of aggregate quantity produced by treatment combination

MD Environment	Price Control (PS)		Quantity Control (QS)	
	Rounds 1-4	Rounds 5-8	Rounds 1-4	Rounds 5-8
Certainty (C)	21.13	19.75	18.38	19.38
	(6.77)	(4.53)	(1.19)	(0.74)
Uncertainty-b (Ub)	27.00	23.25	18.88	20.00
	(6.57)	(2.12)	(1.55)	(0.00)
Uncertainty-e (Ue)	20.88	22.88	18.13	17.88
	(6.01)	(5.08)	(1.81)	(1.96)
Theoretical prediction	20		20	

Note: Standard deviations are in parentheses.

Figure 2: Aggregate quantity produced per round by treatment combination



Notes: Each treatment consists of a policy treatment (PS or QS) combined with a marginal damage environment (C, Ub, or Ue). The solid blue lines indicate the mean and the dotted blue lines indicate one standard deviation above and below the mean. The red lines indicate the theoretical prediction for aggregate quantity for each policy treatment.

Table 6: AR1 population-averaged panel regressions of aggregate quantity produced

Dependent variable is aggregate quantity produced			
	Certainty	Uncertainty-b	Uncertainty-e
Quantity Control (QS)	-3.012	-8.363 ***	-2.996
	(1.666)	(1.923)	(2.534)
Last 4 Rounds	-1.775	-3.956 *	1.888
	(1.696)	(1.848)	(2.273)
Quantity Control (QS) * Last 4 Rounds	2.855	5.085	-2.588
	(2.398)	(2.614)	(3.215)
Constant	21.342 ***	27.225 ***	21.419 ***
	(1.178)	(1.36)	(1.792)
# Observations	32	32	32
# Groups	4	4	4

Notes: Standard errors are in parentheses. The regressors *Quantity Control (QS)* and *Last 4 Rounds* are both dummy variables. Significance codes: *p<0.05, **p<0.01, ***p<0.001

Table 7: Hypothesis tests based on regression estimates for aggregate quantity produced

Difference	Certainty		Uncertainty-b		Uncertainty-e	
	Rounds 1-4	Rounds 5-8	Rounds 1-4	Rounds 5-8	Rounds 1-4	Rounds 5-8
$Q_{PS} - 20$	1.34	-0.43	7.23 ***	3.27 *	1.42	3.31
$Q_{QS} - 20$	-1.67	-0.59	-1.14	-0.01	-1.58	-2.28
$Q_{PS} - Q_{QS}$	3.01	0.16	8.36 ***	3.28	3.00	5.59 *

Notes: The theoretical prediction for aggregate quantity produced under both the quantity control scenario and the price control scenario is 20 units. Significance codes: *p<0.05, **p<0.01, ***p<0.001

Table 8: AR1 population-averaged panel regressions of individual quantity produced under Certainty (C)

Dependent variable is individual quantity produced	LO	ML	MH	HI
Quantity Control (QS)	0.994 *	0.792	-1.388 *	-1.378
	(0.450)	(0.802)	(0.556)	(0.928)
Last 4 Rounds	0.050	0.504	0.123	0.133
	(0.346)	(0.593)	(0.507)	(0.899)
Quantity Control (QS) * Last 4 Rounds	0.124	-0.504	0.254	0.170
	(0.489)	(0.840)	(0.717)	(1.272)
Constant	1.135 ***	1.795 **	2.809 ***	4.320 ***
	(0.318)	(0.567)	(0.393)	(0.656)
# Observations	64	64	64	64
# Subjects	8	8	8	8

Notes: Standard errors are in parentheses. The regressors *Quantity Control (QS)* and *Last 4 Rounds* are both dummy variables. Significance codes: *p<0.05, **p<0.01, ***p<0.001

Table 9: AR1 population-averaged panel regressions of individual quantity produced under Uncertainty-b (Ub)

Dependent variable is individual quantity produced	LO	ML	MH	HI
Quantity Control (QS)	-1.723	0.523	-0.432	-2.875 **
	(1.137)	(0.908)	(0.517)	(0.939)
Last 4 Rounds	-1.368	-0.407	0.547	-0.626
	(1.007)	(0.567)	(0.511)	(0.799)
Quantity Control (QS) * Last 4 Rounds	1.250	0.939	0.469	0.149
	(1.424)	(0.802)	(0.722)	(1.130)
Constant	3.618 ***	1.615 *	2.690 ***	5.736 ***
	(0.804)	(0.642)	(0.366)	(0.664)
# Observations	64	64	64	64
# Subjects	8	8	8	8

Notes: Standard errors are in parentheses. The regressors *Quantity Control (QS)* and *Last 4 Rounds* are both dummy variables. Significance codes: *p<0.05, **p<0.01, ***p<0.001

Table 10: AR1 population-averaged panel regressions of individual quantity produced under Uncertainty-e (Ue)

Dependent variable is individual quantity produced	LO	ML	MH	HI
Quantity Control (QS)	0.154	0.262	0.036	-1.951 *
	(0.522)	(0.474)	(0.664)	(0.944)
Last 4 Rounds	-0.109	-0.148	0.167	0.815
	(0.486)	(0.451)	(0.579)	(0.726)
Quantity Control (QS) * Last 4 Rounds	-0.276	0.553	-0.848	-0.896
	(0.688)	(0.638)	(0.818)	(1.026)
Constant	2.247 ***	1.459 ***	2.860 ***	4.287 ***
	(0.369)	(0.335)	(0.470)	(0.668)
# Observations	64	64	64	64
# Subjects	8	8	8	8

Notes: Standard errors are in parentheses. The regressors *Quantity Control (QS)* and *Last 4 Rounds* are both dummy variables. Significance codes: *p<0.05, **p<0.01, ***p<0.001

Table 11: Hypothesis tests based on regression estimates for individual quantity produced

Subject type	Difference	Certainty		Uncertainty-b		Uncertainty-e	
		Rounds 1-4	Rounds 5-8	Rounds 1-4	Rounds 5-8	Rounds 1-4	Rounds 5-8
LO	$q_{PS}-1$	0.13	0.18	2.62 ***	1.25	1.25 ***	1.14 **
	$q_{QS}-1$	1.13 ***	1.30 ***	0.89	0.78	1.40	1.02 **
	$q_{PS}-q_{QS}$	-0.99 *	-1.12 *	1.72	0.47	-0.15	0.12
ML	$q_{PS}-1$	0.80	1.30 *	0.62	0.21	0.46	0.31
	$q_{QS}-1$	1.59 **	1.59 **	1.14	1.67 **	0.72 *	1.13 ***
	$q_{PS}-q_{QS}$	-0.79	-0.29	-0.52	-1.46	-0.26	-0.82
MH	$q_{PS}-3$	-0.19	-0.07	-0.30	0.24	-0.14	0.03
	$q_{QS}-3$	-1.58 ***	-1.20 **	-0.74	0.27	-0.10	-0.78
	$q_{PS}-q_{QS}$	1.39 *	1.13 *	0.43	-0.04	-0.04	0.81
HI	$q_{PS}-5$	-0.68	-0.81	0.74	0.11	-0.71	0.10
	$q_{QS}-5$	-2.06 **	-2.02 **	-2.14 ***	-2.62 ***	-2.66 ***	-2.75 ***
	$q_{PS}-q_{QS}$	1.38	1.21	2.87 **	2.73 **	1.95 *	2.85

Notes: The theoretical predictions of individual quantity produced are 1, 1, 3, and 5 for low (LO), medium-low (ML), medium-high (MH), and high (HI) marginal benefit types, respectively. Significance codes: *p<0.05, **p<0.01, ***p<0.001

Table 12: Mean and standard deviation of permit price and permit sales by marginal damage environment

MD environment	Permit price		Permit sales	
	Rounds 1-4	Rounds 5-8	Rounds 1-4	Rounds 5-8
Certainty (C)	29.62	23.61	9.38	13.00
	(10.28)	(9.89)	(5.71)	(8.54)
Uncertainty-b (Ub)	22.20	23.55	15.25	13.88
	(4.97)	(1.78)	(4.20)	(4.32)
Uncertainty-e (Ue)	24.63	26.21	11.5	8.38
	(5.88)	(7.62)	(4.24)	(2.67)
Theoretical prediction	24		10	

Notes: Standard deviations are in parentheses.

Table 13: Permit prices: Generalized least squares with group-specific AR1 error

Dependent variable is log permit price		
	Rounds 1-4	Rounds 5-8
Uncertainty-b (Ub)	-0.064	0.387 ***
	(0.130)	(0.076)
Uncertainty-e (Ue)	-0.006	0.605 ***
	(0.129)	(0.094)
Round	-0.019	0.038 *
	(0.024)	(0.015)
Constant	3.467 ***	2.408 ***
	(0.248)	(0.183)
Characteristics of buyer in transaction[b]	Y	Y
Characteristics of seller in transaction[b]	Y	Y
# Observations	289	282
# Groups	6	6

Notes: Standard errors are in parentheses. The regressors *Uncertainty-b (Ub)* and *Uncertainty-e (Ue)* are both dummy variables. Significance codes: *p<0.05, **p<0.01, ***p<0.001

[b] These characteristics are: marginal benefit type, age, gender, years of college, major, experience in experiments, and two variables that measure the subject's social and environmental concern.

Table 14: Bid-ask spread: Random effects Tobit

Dependent variable is individual bid-ask spread	Certainty	Uncertainty-b	Uncertainty-e
Medium-low (ML) marginal benefit type	3.791	1.019	6.137
	(5.161)	(2.457)	(5.405)
Medium-high (MH) marginal benefit type	0.343	-2.417	-0.705
	(5.659)	(2.621)	(5.432)
High (HI) marginal benefit type	0.553	-2.373	6.433
	(4.938)	(2.689)	(5.329)
Round	-1.011**	-0.793 ***	-0.303
	(0.392)	(0.212)	(0.296)
Constant	13.006 ***	11.183 ***	8.867 *
	(3.856)	(2.075)	(4.059)
# Observations	49	75	66

Notes: Standard errors are in parentheses. The regressors *Medium-low (ML) marginal benefit type*, *Medium-high (MH) marginal benefit type*, and *High (HI) marginal benefit type* are all dummy variables. Significance codes: *p<0.05, **p<0.01, ***p<0.001

Appendix

A Behavioral Responses When Some Permits Are Left Unused

Unlike in the standard model, in the presence of behavioral responses, it is possible that some permits are left unused. We explore this possibility for each behavioral response below.

A.1 Endowment effects: Some permits are left unused

If some permits are left unused in equilibrium in the presence of endowment effects, this means that for some agents i the individual permit constraint in equation (8) is non-binding, and therefore that the multiplier μ_i on their individual permit constraint is 0. For example, μ_i could be zero for some agent i if their marginal disutility δ_i from selling a permit is sufficiently large. From the first-order condition:

$$\tau - e - \mu_i - \delta_i = 0, \tag{A.1}$$

for an agent i with $\mu_i = 0$, the equilibrium permit price must be $\tau = e + \delta_i$. In fact, if more than one agent produces less than her final permit holdings, it must be the case that all these agents have the same δ_i.

From the first-order condition:

$$A_i - \alpha_i q_i - e - \mu_i = 0, \tag{A.2}$$

agents who keep permits unused (and therefore have $\mu_i = 0$) produce the same quantity as that under no policy. Adding up the N functions in (12) combined with the condition $\sum_i L_i > \sum_i q_i$ yields a larger permit price than that resulting when all the permits are used:

$$\tau > eN + \frac{\sum_i \frac{\delta_i}{\alpha_i}}{\sum_i \frac{1}{\alpha_i}}. \tag{A.3}$$

Combining this last equation with $\tau = e + \delta_i$, it can be shown that the necessary magnitude of the marginal disutility δ_i from selling a permit in order for total production to be smaller than the total number of permits is the following:

$$\delta_i > e(N-1) + \frac{\sum_i \frac{\delta_i}{\alpha_i}}{\sum_i \frac{1}{\alpha_i}}. \tag{A.4}$$

From equation (A.4) as the number of agents (N), the externality (e), and number of agents experiencing endowment effects increase, the endowment effect of an agent needs to be stronger in order for it to result in some permits being left unused.

A.2 Fairness concerns: Some permits are left unused

If some permits are left unused in equilibrium in the presence of fairness concerns, this means that for some agents i the individual permit constraint in equation (8) is non-binding, and therefore that the multiplier μ_i on their individual permit constraint is 0. For example, μ_i could be zero for some agent i if their disutility γ_i from inequity is sufficiently large.

From the first-order condition:

$$\tau - e - \mu_i - \gamma_i \frac{N}{N-1} = 0, \tag{A.5}$$

for an agent i with $\mu_i = 0$, the equilibrium permit price must be $\tau = e + \gamma_i \frac{N}{N-1}$. In fact, if more than one agent produces less than her final permit holdings, it must be the case that all these agents have the same γ_i.

From the first-order condition:

$$A_i - \alpha_i q_i - e - \mu_i = 0, \tag{A.6}$$

agents who keep permits unused (and therefore have $\mu_i = 0$) produce the same quantity as that under no policy. Adding up the N functions in (16) combined with the condition $\sum_i L_i > \sum_i q_i$ yields a larger permit price than that resulting when all the permits are used:

$$\tau > eN + \frac{\frac{N}{N-1} \sum_i \frac{\gamma_i}{\alpha_i}}{\sum_i \frac{1}{\alpha_i}}. \tag{A.7}$$

Combining this last equation with $\tau = e + \gamma_i \frac{N}{N-1}$, it can be shown that the necessary magnitude of the disutility γ_i from inequity in order for total production to be smaller than the total number of permits is the following:

$$\gamma_i > e \frac{(N-1)^2}{N} + \frac{\sum_i \frac{\gamma_i}{\alpha_i}}{\sum_i \frac{1}{\alpha_i}}. \tag{A.8}$$

From equation (A.8) as the number of agents N, the externality e, and number of agents experiencing fairness concerns increase, the fairness concerns from an agent need to be stronger in order for it to result in some permits being left unused.

A.3 Prospect theory: Some permits are left unused

If some permits are left unused in equilibrium in the presence of attitudes towards risk deviating from the expected utility framework, this means that for some agents i the individual permit constraint in equation (8) is non-binding, and therefore that the multiplier μ_i on their individual permit constraint is 0. For example, μ_i could be zero for some agent i if his perceived marginal damages e_i is sufficiently large.

From the first-order condition:

$$U_i'\tau - V_i'e_i - \mu_i = 0, \tag{A.9}$$

for an agent i with $\mu_i = 0$, the equilibrium permit price must be $\tau = e_i\frac{V_i'}{U_i'}$. In fact, if more than one agent produces less than her final permit holdings, it must be the case that all these agents have the same $e_i\frac{V_i'}{U_i'}$.

From the first-order condition:

$$U_i'\pi' - V_i'e_i - \mu_i = 0, \tag{A.10}$$

agents who keep permits unused (and therefore have $\mu_i = 0$) do not necessarily produce the same quantity as that under no policy. Adding up the N functions in (24) combined with the condition $\sum_i L_i > \sum_i q_i$ yields a larger permit price than that resulting when all the permits are used:

$$\tau > eN\frac{\sum_i \frac{1}{\alpha_i}}{\sum_i \frac{V_i'/U_i'}{\alpha_i}}. \tag{A.11}$$

Combining this last equation with $\tau = e_i\frac{V_i'}{U_i'}$, it can be shown that the necessary magnitude of $e_i\frac{V_i'}{U_i'}$ for total production to be smaller than the total number of permits is the following:

$$e_i\frac{V_i'}{U_i'} = eN\frac{\sum_i \frac{1}{\alpha_i}}{\sum_i \frac{V_i'/U_i'}{\alpha_i}}. \tag{A.12}$$

From equation (A.12) as the number of agents (N) and the externality (e) increase, the agent's attitudes towards risk needs to deviate further from the expected utility framework in order for them to result in the destruction of permits.

A.4 Cognitive costs: Some permits are left unused

Since a tradable permit system may be hard for individual agents to understand, individual agents facing severe cognitive costs may end up sub-optimally leaving some permits unused under a quantity control.

B Validity of the Experimental Design

In this Appendix, we analyze and address several possible concerns about our experimental design.

B.1 Complexity of quantity control scenario (QS)

One possible concern regarding our experimental design is that the quantity control scenario (QS) may have a much higher level of complexity than the price control scenario (PS), and therefore that differences in behavior between these two treatments may be due to the (much) higher level of complexity in the quantity control scenario (QS). For example, Plott (1983) addresses the complexity of the permit treatment by using experienced subjects.

We address this concern in several ways. First, our quantity control scenario (QS) and price control scenario (PS) are relatively straightforward, as subjects only needed to compare their value tables to their costs of producing. These costs included the damage from group production under both the no policy scenario (BS) and the price control scenario (PS), and a per unit tax under the price control scenario (PS).

Second, to minimize game misconceptions such as those analyzed in Plott and Zeiler (2005), we were careful to write the instructions very clearly, and we provided ample time during the experiment for instructions and for subjects to ask questions before starting each treatment.

Third, to assess whether subjects were given enough time to understand what was going on and to make their decisions, or if they were instead hurried or rushed, we analyze how much time it took them to decide their decisions each round.

In each round of the quantity control scenario (QS), subjects had a maximum of 90 seconds (which we call the 'permit market period') to decide how many permits to hold before making their production decision. During the permit market period, subjects were able to look continuously at their profit tables while buying and selling permits so that they could decide how many permits to hold by the end of the permit market period. Their permit holdings at the end of the permit market period were equal to their initial endowment plus permits bought minus permits sold during the permit market period. Table B.1 presents the mean and standard deviation of the time that subjects actually took each round to decide their permit holdings, as determined by the time of last action (either trading or submitting an offer to trade) in the permit market period which preceded the production decision. As the mean time was well below 90 seconds, the time constraint did not appear to be binding. Furthermore, for each marginal damage (MD) environment-last action combination, the mean time to decide how many permits to hold was lower for the last 4 rounds than for the first 4 founds, which is possible evidence for learning and better understanding by the last 4 rounds.

In each round, subjects had a maximum of 20 seconds to decide how much quantity to produce. For the quantity control scenario (QS), the production decision took place after the permit market period during which subjects had de-

Table B.1: Time taken (in seconds) to decide permit holdings

MD Environment	Trade		Offer	
	Rounds 1-4	Rounds 5-8	Rounds 1-4	Rounds 5-8
Certainty (C)	56.5	49.9	50.7	50.3
	(25.3)	(27.2)	(31.3)	(26.8)
Uncertainty-b (Ub)	62.0	52.5	61.8	55.3
	(23.2)	(27.5)	(24.5)	(26.2)
Uncertainty-e (Ue)	53.5	55.8	55.8	45.2
	(25.5)	(25.7)	(26.0)	(30.1)

Notes: Table reports the mean time taken (in seconds) to decide permit holdings. Standard deviations are in parentheses. The unit of observation is the buyer, seller, or offerer. In each round, subjects had a maximum of 90 seconds (which we call the 'permit market period') to decide how many permits to hold. Time taken (in seconds) to decide permit holdings is based on time of last action (either trading or submitting an offer to trade) during the permit market period that round.

cided how many permits to hold. Importantly, for the quantity control scenario (QS), the individual quantity produced was not automatically set equal to final permit holdings at the end of the permit market period because purposely the experiment allowed subjects to produce less than their permit holdings if they desired. Table B.2 presents the mean and standard deviation of the time that subjects actually took each round to decide how much quantity to produce. As the mean time was well below 20 seconds for all treatments, and as the time one standard deviation above the mean was also below 20 seconds for all treatments, the time constraint did not appear to be binding for any treatment. In fact the mean time that subjects took each round to decide how much quantity to produce was actually the lowest for the quantity control treatment (QS), which provides evidence to suggest that subjects were not especially rushed or time constrained for the quantity control treatment (QS), even if it may have been more complex. Furthermore, for each treatment, the mean time to decide production was lower for the last 4 rounds than for the first 4 founds, which is possible evidence for learning and better understanding by the last 4 rounds.

Table B.2: Time taken (in seconds) to decide production

MD Environment	No Policy (BS)		Price Control (PS)		Quantity Control (QS)	
	Rounds 1-4	Rounds 5-8	Rounds 1-4	Rounds 5-8	Rounds 1-4	Rounds 5-8
Certainty (C)	10.80	8.13	10.83	7.36	4.91	2.81
	(5.63)	(5.30)	(6.52)	(5.74)	(3.67)	(2.86)
Uncertainty-b (Ub)	10.62	7.67	9.80	8.53	3.83	2.28
	(5.01)	(5.22)	(5.95)	(6.15)	(4.30)	(3.06)
Uncertainty-e (Ue)	11.66	8.10	8.78	8.23	4.14	2.91
	(5.50)	(5.52)	(6.47)	(6.04)	(4.35)	(2.58)

Notes: Table reports the mean time taken (in seconds) to decide production. Standard deviations are in parentheses. Subjects had a maximum of 20 seconds each round to decide how much quantity to produce.

Subjects in the quantity control scenario (QS) therefore had a maximum of 110 seconds each round to make both their permit holdings and production decisions (90 seconds to decide how many permits to hold, plus 20 seconds to make their production decision). Table B.3 presents the mean and standard deviation of the time that subjects actually took each round to decide both how many permits to hold and subsequently how much quantity to produce. As the mean time was well below 110 seconds for each marginal damage (MD) environment, and as the time one standard deviation above the mean was also below 110 seconds for marginal damage environment (MD), the time constraint did not appear to be binding for the quantity control scenario (QS). Furthermore, for each treatment, the mean time to decide permit holdings and subsequent production was slightly lower for the last 4 rounds than for the first 4 founds, which is possible evidence for learning and better understanding by the last 4 rounds.

Table B.3: Time taken (in seconds) to decide permit holdings and production

MD Environment	Rounds 1-4	Rounds 5-8
Certainty (C)	60.5	56.2
	(30.2)	(27.4)
Uncertainty-b (Ub)	71.2	65.0
	(24.7)	(26.5)
Uncertainty-e (Ue)	67.7	57.7
	(23.3)	(28.5)

Notes: Table reports the mean time taken (in seconds) to decide permit holdings and production. Standard deviations are in parentheses. Subjects in the quantity control scenario (QS) had a maximum of 110 seconds each round to make both their permit holdings and production decisions (90 seconds to decide how many permits to hold, plus 20 seconds to make their production decision).

After making their production decision, subjects had a maximum of 20 seconds in each round of the quantity control scenario (QS) to review the results and profits from their production decision that round. Table B.4 presents the mean and standard deviation of the time that subjects actually took each round to review the results and profits. As the mean time to review the results and profits after the quantity control scenario (QS) was well below 20 seconds, and as the time one standard deviation above the mean was also below 20 seconds, the time constraint did not appear to be binding for the quantity control scenario (QS). In fact, the mean time that subjects took each round to review the results and profits was actually slightly lower under the quantity control treatment (QS) than under the price control scenario (PS), even though subjects under the price control scenario (PS) were given less time (a maximum of 15 seconds in each round instead of a maximum of 20 seconds), which provides evidence to suggest that subjects were not especially rushed or time constrained for the quantity control treatment (QS), even if it may have been more complex. Furthermore, for each treatment, the mean time to decide production was slightly lower for the last 4 rounds than for the first 4 founds, which is possible evidence for learning and better understanding by the last 4 rounds.

Thus, subjects appear to have been given enough time to understand what was going on and to make their decisions about permit holdings and production, and also enough time to review the results and profits from their decisions each round.

Table B.4: Time taken (in seconds) to review results and profits

MD Environment	No Policy (BS)		Price Control (PS)		Quantity Control (QS)	
	Rounds 1-4	Rounds 5-8	Rounds 1-4	Rounds 5-8	Rounds 1-4	Rounds 5-8
Certainty (C)	12.04	9.34	11.34	10.33	10.47	9.52
	(4.41)	(5.19)	(7.14)	(7.34)	(6.81)	(6.49)
Uncertainty-b (Ub)	11.06	7.74	14.16	11.31	9.13	7.59
	(5.01)	(5.22)	(5.70)	(4.20)	(6.22)	(6.32)
Uncertainty-e (Ue)	13.05	7.88	13.48	11.59	9.44	6.84
	(7.09)	(4.93)	(5.39)	(5.09)	(6.04)	(5.70)

Notes: Table reports the mean time taken (in seconds) to review results and profits. Standard deviations are in parentheses. Subjects had a maximum of 20 seconds each round to review the results and profits after the quantity control scenario (QS). Subjects had a maximum of 15 seconds each round to review the results and profits after the no policy scenario (BS) and the price control scenario (PS).

A fourth way in which we address the possible concern regarding our experimental design that the quantity control scenario (QS) may have a much higher level of complexity than the price control scenario (PS) is that we include cognitive costs that make subjects more likely to deviate from the optimal decision under the quantity control scenario (QS) than under the price control scenario (PS) as one of the possible behavioral responses we examine. According to the results of our experiment, however, we find no evidence for cognitive costs that make subjects more likely to deviate from the optimal decision under the quantity control scenario (QS) than under the price control scenario (PS).

B.2 Time to trade

Another possible concern about our experimental design is whether subjects under the quantity control scenario (QS) were given enough time to trade all the permits they would have liked to trade.

According to Plott and Gray (1990), a continuous double auction mechanism requires on average eight seconds per equilibrium transaction. As shown in Table 2, each LO subject is predicted to sell three units, and each ML subject is predicted to sell two, for a predicted total of ten equilibrium transactions, or 80 seconds, which is less than the 90 seconds subjects were given each round to make all their permit trades.

As seen in Table B.1 above, the mean time that subjects under the quantity control scenario (QS) actually took each round to decide how many permits to hold was well below the maximum 90 seconds they were given, which is evidence that subjects may have had enough time to trade all the permits they would have liked.

Similarly, as seen in Table B.1 above, the mean time that subjects under the quantity control scenario (QS) actually took each round to decide both how many permits to hold and subsequently how much quantity to produce was well below the maximum 110 seconds they were given, time constraints did not appear to be binding for the quantity control scenario (QS).

Tables B.5 and B.6 present the mean and standard deviation of the time that subjects actually took to complete a sale offer and a purchase offer, respectively, by marginal damage (MD) environment. Sale offers took on average 4.4 to 6.3 seconds to complete, and purchase offers took on average 3.8 to 12.5 seconds to complete.

Table B.5: Time taken (in seconds) to complete a sale offer

MD Environment	Rounds 1-4	Rounds 5-8
Certainty (C)	5.7	4.3
	(8.9)	(8.7)
	[51]	[71]
Uncertainty-b (Ub)	4.4	5.6
	(5.5)	(8.7)
	[96]	[80]
Uncertainty-e (Ue)	5.1	6.3
	(8.8)	(14.4)
	[65]	([32]

Notes: Table reports the mean time taken (in seconds) to complete a sale offer. Standard deviations are in parentheses. Number of observations in brackets. The unit of observation is the offer.

Table B.6: Time taken (in seconds) to complete a purchase offer

MD Environment	Rounds 1-4	Rounds 5-8
Certainty (C)	8.8	3.8
	(13.7)	(6.6)
	[24]	[33]
Uncertainty-b (Ub)	8.0	8.0
	(9.9)	(10.6)
	[26]	[31]
Uncertainty-e (Ue)	9.1	12.5
	(12.0)	(20.9)
	[27]	[35]

Notes: Table reports the mean time taken (in seconds) to complete a purchase offer. Standard deviations are in parentheses. Number of observations in brackets. The unit of observation is the offer.

Table B.7 presents the the mean and standard deviation of the average time that subjects actually took each round for each trade that round. The mean of the time taken per trade ranged 5.8 to 11.6 seconds per trade. This is consistent with that prediction of Plott and Gray (1990) that a continuous double auction mechanism requires on average eight seconds per equilibrium transaction.

In each round, subjects had a maximum of 90 seconds (which we call the 'permit market period') to complete all their trades. Table B.8 presents the mean and standard deviation of the time remaining (out of the 90 seconds) after the last permit trade in each round. There was time remaining out of the 90 seconds in the trading period for each

Table B.7: Time taken (in seconds) per trade

MD Environment	Observations	Rounds 1-4	Rounds 5-8
Certainty (C)	8	11.6	8.0
	8	(7.6)	(4.1)
Uncertainty-b (Ub)	8	5.8	6.2
	8	(1.5)	(1.7)
Uncertainty-e (Ue)	8	8.2	11.1
	8	(3.4)	(3.8)

Notes: Table reports the mean time taken (in seconds) per trade. Standard deviations are in parentheses. The unit of observation is the round.

marginal damage (MD) environment, which suggests that subjects may have had enough time to trade all the permits they would have liked.

Table B.8: Time (in seconds) remaining after last trade

MD Environment	Observations	Rounds 1-4	Rounds 5-8
Certainty (C)	8	12.8	14.8
	8	(14.9)	(15.4)
Uncertainty-b (Ub)	8	6.5	9.1
	8	(13.2)	(10.5)
Uncertainty-e (Ue)	8	7.1	4.9
	8	(6.0)	(4.9)

Notes: Table reports the mean time (in seconds) remaining after last trade. Standard deviations are in parentheses. The unit of observation is the round. In each round, subjects had a maximum of 90 seconds (which we call the 'permit market period') to complete all their trades.

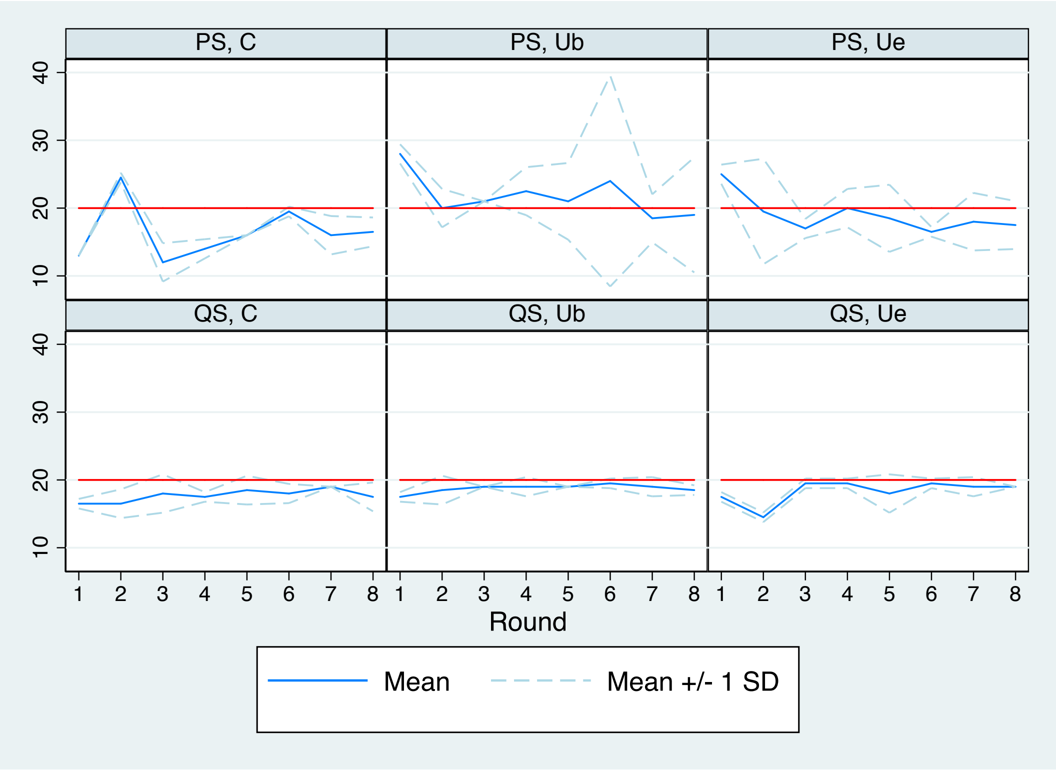
C Supplemental Tables and Figures

Table C.1: Mean and standard deviation of aggregate quantity produced by treatment combination (Third game)

MD Environment	Price Control (PS)		Quantity Control (QS)	
	Rounds 1-4	Rounds 5-8	Rounds 1-4	Rounds 5-8
Certainty (C)	15.88	17.00	17.13	18.25
	(5.51)	(2.07)	(1.55)	(1.39)
Uncertainty-b (Ub)	22.88	20.63	18.50	19.00
	(3.76)	(7.52)	(1.20)	(0.76)
Uncertainty-e (Ue)	20.38	17.63	17.75	18.88
	(4.47)	(2.92)	(2.25)	(1.36)
Theoretical prediction	20		20	

Note: Standard deviations are in parentheses.

Figure C.1: Aggregate quantity produced per round by treatment combination (Third game)



Notes: Each treatment consists of a policy treatment (PS or QS) combined with a marginal damage environment (C, Ub, or Ue). The solid blue lines indicate the mean and the dotted blue lines indicate one standard deviation above and below the mean. The red lines indicate the theoretical prediction for aggregate quantity for each policy treatment.

Table C.2: AR1 population-averaged panel regressions of aggregate quantity produced, controlling for state in previous round

Dependent variable is aggregate quantity produced	Certainty	Uncertainty-b	Uncertainty-e
Quantity Control (QS)	-3.012	-7.196 ***	-0.082
	(1.666)	(1.528)	(2.519)
Bad state in previous round		1.089	-5.117
		(0.903)	(2.809)
Last 4 Rounds	-1.775	-2.767 *	3.517
	(1.696)	(1.421)	(1.887)
Quantity Control (QS) * Last 4 Rounds	2.855	3.757	-4.947
	(2.398)	(1.984)	(2.689)
Constant	21.342 ***	25.569 ***	19.347 ***
	(1.178)	(1.290)	(1.743)
# Observations	32	28	28
# Groups	4	4	4

Notes: Standard errors are in parentheses. The regressors *Quantity Control (QS)*, *Bad state in previous round* and *Last 4 Rounds* are all dummy variables. Significance codes: *p<0.05, **p<0.01, ***p<0.001

Table C.3: Hypothesis tests based on regression estimates for aggregate quantity produced, controlling for state in previous round

Difference	Certainty		Uncertainty-b		Uncertainty-e	
	Rounds 1-4	Rounds 5-8	Rounds 1-4	Rounds 5-8	Rounds 1-4	Rounds 5-8
$Q_{PS} - 20$	1.34	-0.43	5.57 ***	2.80 **	-0.65	2.86
$Q_{QS} - 20$	-1.67	-0.59	-1.63	-0.64	-0.73	-2.16
$Q_{PS} - Q_{QS}$	3.01	0.16	7.20 ***	3.44 **	0.08	5.03 *

Notes: The theoretical prediction for aggregate quantity produced under both the quantity control scenario and the price control scenario is 20 units. Significance codes: *p<0.05, **p<0.01, ***p<0.001

Table C.4: AR1 population-averaged panel regressions of individual quantity produced under Uncertainty-b (Ub), controlling for state in previous round

	Dependent variable is individual quantity produced			
	LO	ML	MH	HI
Quantity Control (QS)	-2.234 *	0.755	-0.194	-2.608 *
	(1.111)	(0.955)	(0.574)	(1.058)
Bad state in previous round	-0.177	0.597 *	-0.275	0.241
	(0.492)	(0.266)	(0.368)	(0.473)
Last 4 Rounds	-1.137	-0.415	0.480	-0.447
	(0.921)	(0.572)	(0.545)	(0.882)
Quantity Control (QS) * Last 4 Rounds	1.675	0.948	0.300	-0.112
	(1.289)	(0.808)	(0.762)	(1.233)
Constant	3.364 ***	1.511 *	2.859 ***	5.451 ***
	(0.863)	(0.695)	(0.500)	(0.824)
# Observations	56	56	56	56
# Subjects	8	8	8	8

Notes: Standard errors are in parentheses. The regressors *Quantity Control (QS)*, *Bad state in previous round* and *Last 4 Rounds* are all dummy variables. Significance codes: *p<0.05, **p<0.01, ***p<0.001

Table C.5: AR1 population-averaged panel regressions of individual quantity produced under Uncertainty-e (Ue), controlling for state in previous round

	Dependent variable is individual quantity produced			
	LO	ML	MH	HI
Quantity Control (QS)	0.424	0.646	0.887	-1.897
	(0.604)	(0.510)	(0.721)	(0.998)
Bad state in previous round	-0.378	-1.871 **	-0.836	0.307
	(0.891)	(0.700)	(0.884)	(1.110)
Last 4 Rounds	0.12	0.146	0.620	0.880
	(0.519)	(0.427)	(0.573)	(0.746)
Quantity Control (QS) * Last 4 Rounds	-0.521	0.225	-1.492	-0.900
	(0.747)	(0.614)	(0.820)	(1.063)
Constant	2.093 ***	1.154 ***	2.251 ***	4.200 ***
	(0.411)	(0.349)	(0.497)	(0.690)
# Observations	56	56	56	56
# Subjects	8	8	8	8

Notes: Standard errors are in parentheses. The regressors *Quantity Control (QS)*, *Bad state in previous round* and *Last 4 Rounds* are all dummy variables. Significance codes: *p<0.05, **p<0.01, ***p<0.001

Table C.6: Hypothesis tests based on regression estimates for individual quantity produced, controlling for state in previous round

Subject type	Difference	Certainty		Uncertainty-b		Uncertainty-e	
		Rounds 1-4	Rounds 5-8	Rounds 1-4	Rounds 5-8	Rounds 1-4	Rounds 5-8
LO	$q_{PS}-1$	0.13	0.18	2.36 **	1.23	1.09 **	1.11 **
	$q_{QS}-1$	1.13 ***	1.30 ***	0.13	0.67	1.52 ***	1.01 **
	$q_{PS}-q_{QS}$	-0.99 *	-1.12 *	2.23 *	0.56	-0.42	0.10
ML	$q_{PS}-1$	0.80	1.30 *	0.51	0.10	0.15	0.30
	$q_{QS}-1$	1.59 **	1.59 **	1.27	1.80 **	0.80 *	1.17 ***
	$q_{PS}-q_{QS}$	-0.79	-0.29	-0.75	-1.70	-0.64	-0.87
MH	$q_{PS}-3$	-0.19	-0.07	-0.14	0.34	-0.75	-0.13
	$q_{QS}-3$	-1.58 ***	-1.20 **	-0.33	0.44	0.14	-0.73
	$q_{PS}-q_{QS}$	1.39 *	1.13 *	0.19	-0.11	-0.88	0.61
HI	$q_{PS}-5$	-0.68	-0.81	0.45	0.00	-0.80	0.08
	$q_{QS}-5$	-2.06 **	-2.02 **	-2.16 **	-2.72 ***	-2.70 ***	-2.72 ***
	$q_{PS}-q_{QS}$	1.38	1.21	2.61 *	2.72 **	1.90	2.80 **

Notes: The theoretical predictions of individual quantity produced are 1, 1, 3, and 5 for low (LO), medium-low (ML), medium-high (MH), and high (HI) marginal benefit types, respectively. Significance codes: *p<0.05, **p<0.01, ***p<0.001