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Tradable development rights under uncertainty: an experimental approach

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Abstract: Tradable development rights (TDR) are discussed as a mechanism to reduce land consumption while ensuring an efficient implementation of profitable building projects. We present a novel laboratory experiment on the feasibility of TDR and simulate the acquisition and trading of development rights. In particular, we investigate the effects of uncertainty in the revenues of land consumption projects. Overall, we find that TDR are reallocated as suggested by theory, although higher uncertainty has substantial detrimental effects on the distribution of land consumption projects and thus aggregate welfare. This enables us to formulate distinct policy implications for the design of TDR systems.

Keywords: auction, economic experiment, land consumption, tradable planning permits, urban sprawl

JEL Classification: C91; C92; D8

1. Introduction

Tradable development rights (TDR) are discussed as a policy instrument to reduce urban sprawl and foster a more sustainable land use. Such market-oriented planning instruments are increasingly considered in scientific and political discourses as a viable extension of urban containment strategies (van der Veen et al., 2010), suggesting that they show superior efficiency in achieving reductions of land consumption (Miller, 1999; Nuissl and Schroeter-Schlaack, 2009). Implementing a quantitative constraint - i.e. a cap - on development rights along with a trading mechanism and floating prices would constitute a system enabling policy-makers to accomplish reductions in land use with near-perfect precision at minimal cost. Furthermore, planners and land-owners are expected to use land more efficiently in a system of TDR, fostering inner-city development and gaining a greater awareness of the ecological problems that stem from excessive urban sprawl (Levinson, 1997; Henger and Bizer, 2010).

The United States was the first nation to implement TDR on a large scale in more than 30 federal states from the 1970s onwards, within very different regional and institutional contexts (Pruetz, 1997). The heterogeneity of the programs in question makes overarching evaluations of their efficacy challenging. While several studies have provided initial empirical results on universal success factors for TDR (e.g. Kaplowitz et al., 2008; Pruetz and Standridge, 2009; Tan and Beckman, 2010; Chan and Hou, 2015), the empirical evidence that can be utilized for providing generalizable policy advice remains limited (Bengston et al., 2004; Kopits et al., 2008). This is problematic as TDR are increasingly considered as a means of establishing sustainable land use policies in numerous developed nations, including the Netherlands (Janessen-Jansen, 2008), Italy (Micelli, 2003), Australia (Harman and Choy, 2011), Switzerland (Mengini et al., 2015), China (Wang et al., 2009) and Germany (Henger and

Bizer, 2010), where the current administration has decided to develop and test a nation-wide system of TDR (Coalition Treaty, 2013).

In this paper, we argue that empirical evidence derived from economic laboratory studies can be considered a worthwhile addition to the existing purely theoretical analyses, local case studies and supra-regional surveys. Laboratory experiments can answer specific counterfactual research questions that remain inaccessible for theoretical and empirical studies relying on field data (Greenstone and Gayer, 2009; Falk and Heckman, 2009; Chetty, 2015). Therefore, we propose a research design that enables us to simulate a system of TDR and measure agents' reactions to changes in core institutional parameters. This is achieved through a novel experimental design that simulates the allocation and trading of development rights as well as the ensuing realization of building projects using the development rights acquired beforehand in the game. Our setting implements a fairly general concept of a TDR system applicable to different institutional and national contexts. In addition to providing evidence on the overall efficiency and welfare implications of a TDR system, we investigate a key feature of land consumption projects, namely the investment risk associated with acquiring, trading and using development rights. This research question builds upon a broad strand of literature in experimental economics showing that individual decision-making under risk leads to substantially different outcomes than those predicted by benchmarks of rational decision-making (see e.g. Camerer et al., 2011). Consequently, we ask how subjects and the overall system react when the revenues of land consumption projects are prone to uncertainty and potentially yield negative returns compared to a situation with fixed, positive returns. This enables us to show whether markets cease to allocate development rights efficiently when faced with uncertainty in future revenues as a crucial property of investments in TDR and thus fail to maximize welfare. Consequently, the overall viability of a TDR market may depend on a specific sector's volatility in revenues.

The subsequent section of this paper justifies our methodological choice and reviews the relevant literature, while our experimental design and benchmark model are outlined in sections three and four, respectively. The experimental results are presented in section five, before section six discusses our results and provides a conclusion.

2. TDR and laboratory experiments

Evaluating the policy options of implementing TDR on a large scale is associated with the lack of generalizable empirical evidence presented to justify the choice of specific institutional mechanisms. While a number of theoretical publications have laid out the potential advantages of TDR (for a basic setup, see Thorsnes and Simons, 1999; recent theoretical contributions are provided by Ward, 2013; Vejchodska, 2015), few specific institutional implications can be derived from these studies due to their level of abstraction and the ubiquitous assumption of rational agents that forms the basis for the optimistic predictions about the efficiency of TDR. At the same time, a similarly large body of overview studies for heterogeneous institutional and social contexts has been presented, providing determinants of successful implementations of TDR (for studies based on qualitative measures, see e.g. Santos et al., 2015; Harman et al., 2015; Kaplowitz et al., 2008; Machemer and Kaplowitz, 2002; Pruetz and Standridge, 1999; Danner, 1997; studies primarily using quantitative measures include Menghini et al., 2015; Kopits et al., 2008; Lynch and Musser, 2001; Lynch and Lovell, 2003). While an overall consensus has been established in the literature concerning a number of success factors of TDR systems (such as strong demand for additional development zones and receiving areas customized to the demands of the respective communities (Pruetz and Standridge, 2009)), we argue that these conclusions remain closely tied to specific regional and institutional contexts. Accordingly, they are not fully generalizable and often inapplicable to other nations' implementation of TDR.

We suggest that laboratory experiments can provide additional insights into the policy-oriented discussion of TDR and fruitfully complement the existing literature. Laboratory experiments can effectively provide a link between theoretical studies with a perfect internal validity yet disputable external validity in a world of non-rational agents and case studies with a perfect external validity yet a lower generalizability. Proponents of laboratory studies in policy-related discussions argue that experimental evidence combines a high internal validity (ensured by controlling all environmental factors) with a high external validity by testing actual human behavioral patterns in situations that resemble certain institutions relevant for policy-makers (see e.g. Charness and Fehr, 2015 and Santos, 2011 for comprehensive discussions as well as Greenstone and Gayer, 2009 with a focus on environmental policy).[1] A successful example of this approach - i.e. using laboratory experiments to provide policy-makers with information on the effects of different potential institutional choices – can be found conducted in the run-up to the 2005 implementation of tradable CO_2 certificates within the European emissions trading system (ETS). A long-standing scientific discussion was established that built upon theoretical modeling of the trading system and subsequently provided experimental evidence from which distinct policy implications could be deducted (see Convery, 2009 as well as Grimm and Illieva, 2013 for comprehensive overviews of the discussion as well as Stranlund et al., 2014 for a recent experimental contribution). Another recent example is the experimental investigation of water quality trading markets, furthered e.g. by Jones and Vossler (2014).

Our paper aims to contribute similarly to the study of the optimal design of TDR. We present empirical evidence on the validity of theoretical assumptions concerning individual behavior

[1] The debate on the merits and potential disadvantages of applying behavioral economics to the design of public policies has been conducted for more than a decade by now. Among the central contributions are Falk and Fehr (2003), Falk and Heckman (2009), Madrian (2014) and Chetty (2015), who present the core arguments.

within a TDR system and deduct more general behavioral patterns applicable to policy-making. We can build upon a small number of previous papers that have tested specific aspects of a system of TDR. For instance, Henger (2013) compares the performance of student participants and municipal planners, finding that both groups achieve a fairly efficient allocation of certificates. Moreover, Meub et al. (2017) consider the influence of political business cycles within a TDR system, while Meub et al. (2017) investigate the efficiency of different mechanisms for allocating development rights, Meub et al. (2016) show the impact of macroeconomic shocks on a system of TDR and Proeger et al. (2016) experimentally consider the influence of communication regimes on the efficiency of TDR schemes.

The experiment reported in this paper extends the previous studies by providing evidence on individual decision-making under risk and its consequences for the overall efficiency within a TDR system. Decision-making under uncertainty has been among the primary subjects for experimental economists examining the validity of neoclassical assumptions on rational behavior. It has become a standard assumption that subjects' behavior can substantially deviate from benchmark models of rational decision-making assuming risk-neutral behavior in numerous economic and institutional contexts (see e.g. Camerer et al., 2011 and Cox and Harrison, 2008 for introductions to the literature; see Charness et al., 2013 and Crosetto and Filippin, 2013 for the state of research on risk preferences). These more realistic insights about dealing with risk necessarily imply very different policy recommendations than those derived from theoretical models merely assuming risk-neutral agents. Therefore, it remains an open question whether and how agents in an actual TDR system will successfully cope with the uncertainties associated with investing resources in development rights to conduct building projects. Risk preferences might substantially influence the distribution of TDR, auction and market prices and consequently overall efficiency. Our experimental design can shed light upon this question by investigating subjects' reactions to uncertainty in future revenues while implementing the core features of a TDR system.

3. Experimental design

3.1 Implementation of TDR in an experimental framework

Our experimental design aims to implement a fairly general concept of TDRs, enabling the transfer of insights to different national or institutional contexts. Our basic approach resembles the cap & trade system for CO_2 emissions, whereby certificates are issued by a public authority and used by different agents for their production. Whenever the expected income from a production does not compensate the costs of the number of certificates required, the production will not be undertaken. Overall, given a redistribution of issued certificates through a trading system, only the most profitable units of productions are realized.

This approach is transferred to land consumption, whereby we assume that agents aim to realize building projects that yield revenue in the future. These agents could potentially be municipalities, firms or individual residents. There is an authority – most likely a public institution or large private landowner – who sets a cap on overall land consumption and allocates certificates (i.e. development rights) in accordance with the cap. Similar to CO_2 markets, certificates are issued in two distinct ways: a certain amount is allocated for free ("grandfathered") by a predetermined allocation formula and the remaining certificates are auctioned. Hence, all agents receive a number of TDR by default and bid on additional ones, both of which they can subsequently use to realize their building projects or – if more profitable – sell to other agents. Accordingly, "sending sites" and "receiving sites" are determined in a market process, optimally by redistributing TDR to the most profitable sites. We further assume heterogeneous agents within a market, which simulates different sizes of the public institutions or landowners and translates to a different number of projects available and certificates grandfathered to the respective agents.

Besides providing evidence on the working mechanism of a laboratory-based TDR-scheme, we investigate the element of risk in the context of acquiring and using certificates for land consumption. We argue that the uncertain outcome of investing and conducting building projects within a system of TDR could substantially alter its feasibility and distort the efficient allocation of certificates. This basic feature of land use decisions is implemented by assigning different degrees of profitability to each project, which are equally likely to realize at the end of the game. We thus assert how participants react to varying degrees of profitability as one representation of underlying risk.

3.2 Overview of the game

Note that the general experimental design uses the framework introduced by Meub et al. (2016). In the game, groups ("markets") of six participants are matched to interact for 15 periods. These subjects generate payoffs by realizing projects and trading certificates. There are two types of projects available. First, there are Type A projects, which generate between 0- and 100ECU, whereby 100ECU converts to 1€ at the end of the game. These projects require eight certificates to be realized and thus represent land consuming building projects. Independent of their distinct value, all Type A projects require the same number of certificates, whereby this simplification is intended to keep the game comprehensible for the participants. Second, an outside option is given by Type B projects that always pay 10ECU.

Prior to the first period, subjects are randomly assigned to a specific player type determining their endowment of available projects and certificates. Independent of the player type, all subjects are initially endowed with a budget of 700ECU. Each period of the game comprises three stages.

Within the first stage, subjects accumulate certificates that are required to conduct Type A projects. Half of the 24 certificates issued in each period are grandfathered, whereas the other half are auctioned in a uniform price auction with sealed bids. Accordingly, subjects' bids for certain quantities are ranked by price and the lowest bid that is granted certificates determines the uniform price.

A double auction market constitutes the second stage of each period, during which subjects can simultaneously buy and sell certificates within their budget constraint, i.e. there is no borrowing to buy certificates. The secondary market is open for two minutes and there are no transaction costs. This setting enables subjects to gamble and try to generate income by taking advantage of price dynamics and thus expand or reduce their budget and stock of certificates.

At the end of each period, subjects have to choose between using certificates to realize a project of Type A or relying on the outside option of realizing a Type B project, meaning that they had to choose Type B if they chose not to conduct a Type A project. Only one project can be realized per period. While participants can conduct projects in each period, their payoff is not granted until the final period. This design choice implements a core feature of building projects – namely their duration and the delay until investments pay off – and again provides funds that can be invested anew. Certificates can be kept across periods, i.e. our design allows for banking of certificates. However, all remaining certificates lose their value after the final period. Subjects receive feedback on their decisions after each period.

Table 1 summarizes the properties of the game by listing all player types with their available projects and certificates.

project	type	A-1	A-2	A-3	A-4	A-5	A-6	B			
	value	100	80	60	40	20	0	10			
	certificates	8	8	8	8	8	8	0			
									total	**certificates period (total)**	
										#grandfathered	#auctioned
agent	**1**	10	8	6	4	2	0	15	**45**	4(60)	-
	2	8	10	6	4	2	0	15	**45**	3(45)	-
	3	6	8	10	4	2	0	15	**45**	2(30)	-
	4	4	6	8	10	2	0	15	**45**	1(15)	-
	5	2	4	6	8	10	0	15	**45**	1(15)	-
	6	0	2	4	6	8	10	15	**45**	1(15)	-
	total	**30**	**38**	**40**	**36**	**26**	**10**	**90**	**270**	**12(180)**	**12(180)**

Table 1. Overview of the different player and project types as well as the respective certificates.

Note: The table first provides details on the different projects, whereby six Type A projects with different values are available, each requiring eight certificates. The Type B project is the outside option in each period and thus does not require certificates. Furthermore, the table shows details on the different player types (on the lower left half): there are six player types, endowed with varying numbers of projects. Overall, each player type has 45 projects available. The lower right hand side shows the number of certificates provided to the respective player type in each period and - in brackets - during the entire game.

3.3 Treatment conditions

Our treatments introduce risk in project revenues as a key feature of all investment projects, which similarly translates to land consumption projects that typically take some time before revenues are realized. Risk has to be considered to hold outstanding importance as it potentially distorts the efficient allocation of certificates in a cap & trade system.

The two treatments *LOW RISK* and *HIGH RISK* differ in terms of the associated risk in project revenues, which is summarized in table 2. The three degrees of profitability for each period are equally likely to realize, i.e. with a probability of 1/3.

Project	*BASELINE*			*LOW RISK*			*HIGH RISK*		
	low	medium	high	low	medium	high	low	medium	high
A-1	-	100	-	50	100	150	-100	100	300
A-2	-	80	-	40	80	120	-80	80	240
A-3	-	60	-	30	60	90	-60	60	180
A-4	-	40	-	20	40	60	-40	40	120
A-5	-	20	-	10	20	30	-20	20	60
A-6	-	0	-	0	0	0	0	0	0
B	-	10	-	10	10	10	10	10	10

Table 2. Overview of project values with respect to treatment conditions.

Note: The table provides the different projects (A1-6, B) and the different potential outcomes conditional on treatments. Each of the three potential outcomes (low, medium, high) is equally likely to be realized. Consequently, the expected profitability is equal in all three treatments.

Participants are provided with this distribution of potential project payoffs in the instructions of the respective treatment. Furthermore, the distribution in payoffs is displayed to the participants before each auction when an overview of available projects is provided and in the third stage of each period when subjects make their choice whether or not to realize projects. While subjects are aware of the risk associated with conducting Type A projects, they are shown which of the three degrees of profitability has realized after the final period, along with their payoff for the projects. We thus avoid potential path dependencies in a group's decision triggered by particularly good or bad outcomes within the first periods of the game.

3.4 Experimental procedure

Table 3 provides an overview of our treatments as well as the respective number of participants. Note that the benchmark treatment (*BASELINE*) is also used in Meub et al. (2016).

Treatment	Risk condition	No. of participants	No. of societies
BASELINE	no	48	8
LOW RISK	low	54	9
HIGH RISK	high	48	8
Total		**150**	**25**

Table 3. Overview of the different treatments and the number of participants.

The experiments were conducted in the Laboratory for Behavioral Economics at the University of Goettingen using z-Tree (Fischbacher, 2007) and ORSEE (Greiner, 2004). There were 5 sessions in November 2015, whereby subjects were only allowed to participate in one session. We ensured a common understanding of the game prior to each experimental session by having subjects answer mandatory control questions. The original instructions for the game were in German can be obtained from the authors upon request; an English translation is provided in the appendix. The sessions had an average duration of 80 minutes and the average individual payment amounted to 14.3€, including a show up-fee of 4€. Subjects were students of different academic disciplines (with 38.5% students of economics and business administration), they were on average 24.8 years old and 56.9% were female.

4. Theoretical framework and expected results

General properties of the game: BASELINE

Our basic setup implements a cap & trade system to achieve the regulatory goal of restricting land consumption. Considering a situation without a cap, table 1 emphasizes that each agent would conduct one Type A project in each of the 15 periods, which gives a total of 90 Type A projects for a society of six players throughout the game. However, the implemented cap only allows for half of these projects to be realized given that only 24 tradable planning permits are issued in each period and eight of them are required to conduct one Type A project. Hence, the cap reduces the number of land consuming Type A projects from 90 to 45. Thereby, an agent's willingness to pay (WTP) – as derived by her endowment of projects – determines whether or not she carries out projects in the equilibrium, assuming optimal behavior and an efficient reallocation of certificates.

An agent's maximal achievable income by using eight certificates is 100ECU for conducting a Type A-1 project with an outside option of 10ECU for conducting a Type B project. Accordingly, the WTP for one certificate is calculated by (100ECU – 10ECU)/8= 11.25ECU. While prices should not exceed this value they might well be lower, given that there are only 30 Type A-1 projects and thus there should be 15 Type A-2 projects carried out with an agent's WTP at (80ECU-10ECU)/8= 8.75ECU. However, agents are not aware of this distribution of projects, which leads to the expectation of certificate prices being within the range between 8.75ECU and 11.25ECU. At these fair prices, certificates should be optimally redistributed such that 30 Type A-1 and 15 Type A-2 projects are carried out and – due to the implemented cap – 45 Type B projects.

The auctioning of certificates transfers income from agents to the auctioneer in accordance with agents' WTP. The income of the auctioneer is a share of the total wealth generated by realized projects and is irrelevant when assessing the overall efficiency of the system. However, the political feasibility of a regulatory cap & trade system might crucially depend on a distribution of wealth between the auctioneer and the involved agents considered to be fair by its participants. As mentioned above, prices as unit auction prices should reflect agents' WTP. Overall, 180 certificates (12 in each of the 15 periods) are auctioned, whereby – based upon the distribution of Type A projects – we could assume two-thirds of the certificates being sold at a unit prices that equal the maximal WTP of 11.25ECU and one-third being sold at the lower bound of fair prices given by 8.75ECU.

Table 4 summarizes these theoretical considerations and predictions for an efficient cap & trade system.

project	**type**	A-1	A-2	B	
	value	100	80	10	
	certificates	8	8	0	
					total
land consumption	**# realizations**	30	15	45	**90**
wealth	**total value**	3000	1200	450	**4650**
certificates	**# bought**	120	60	0	**180**
	# free	120	60	0	**180**
income	**agents**	1650	675	450	**2775**
	auctioneer	1350	525	0	**1875**

Table 4. Theoretical predictions in equilibrium.

Behavior under the treatment condition of risk

Our two treatment conditions introduce risk to the general setting of the game. If we assume that agents are risk neutral, all theoretical predictions remain valid. Risk-neutral agents act according to expected payoffs of projects and thus the WTP and the expected income distribution derived above remains unchanged.

However, agents might well have risk-loving or risk-averse preferences, whereby an agent's WTP might be driven by her risk preferences rather than solely by available projects. For risk-loving agents, ceteris paribus, the WTP is higher in the risk treatments as there is the possibility to generate more income from the same projects. By contrast, for risk-averse agents, the WTP is lower following the reverse argument. In *HIGH RISK*, the differences in WTP should be higher than in *LOW RISK* as the spread in potential income from one project is higher and income might even become negative. Similarly, the auctioneer's income crucially depends on the distribution of risk preferences and it might be higher or lower compared to the expected 1875 ECU in *BASELINE*.

Considering overall welfare as measured by total value generated by realized projects, risk preferences are irrelevant if agents are homogenous. Furthermore, risk preferences are not harmful if those agents endowed with the most valuable projects are also the most risk-loving. In this case, the adjustments in WTP according to risk preferences would coincide with the ranking of agents according to their available projects. Put simply, if risk preferences are distributed such that projects continue to be conducted as determined by the WTP in the absence of risk, the cap & trade system upholds its theoretical efficiency. However, it appears unlikely that land consumption projects are always distributed according to agents' risk preferences; rather, it is more likely that agents characterized by their risk preferences are randomly distributed across potential project endowments, which is simulated in our experiment. Therefore, we expect realized projects to be distributed differently in the risk treatments, i.e. being influenced by the distribution of risk preferences and thus distorting the overall efficiency.

To illustrate these expected changes due to the treatment conditions, consider the simplified case of two agents in *LOW RISK* or *HIGH RISK*: agent *cautious* has a Type A-1 project with an expected payoff of 100ECU and agent *gambler* has a Type A-2 project with an expected payoff of 80ECU.

Without risk, agent *cautious* would bid 11.25ECU per certificate in an auction, leaving her with a minimum profit of 10ECU when granted the certificates, which is equal to the outside option. Under risk, her WTP might be considerably lower as the expected payoff of 10ECU is less favorable than the 10ECU certain profit of the outside option; accordingly, her WTP becomes (11.25ECU – $\textit{risk premium}^{cautious}$).

Agent *gambler* would bid 8.75ECU per certificate in the absence of risk, again leaving her with a certain profit equal to the outside option of 10ECU. However, as *gambler* favors risk, she is willing to pay more per certificate if there is an upside outcome of more than the 80ECU, even if it is mirrored by a symmetric downside outcome; accordingly, her WTP becomes (8.75ECU + $\textit{risk premium}^{gambler}$). Consequently, the efficiency of the certificate allocation only holds if (11.25ECU – $\textit{risk premium}^{cautious}$) > (8.75ECU + $\textit{risk premium}^{gambler}$). If this condition is violated, the less valuable project is realized and a loss in expected aggregate income of 20ECU results.

As the expected aggregate income of all participants is the main policy objective, a cap & trade system might lose the core advantage assumed by its proponents, i.e. efficiency in the allocation of certificates. Our experiment investigates these potential distortions and allows us to identify additional effects and problems associated with risk in land consumption project revenues.

Despite heterogeneous risk preferences, our theoretical framework only considers homogenous agents, i.e. endowed with identical cognitive abilities, as well as perfect foresight and understanding of the game. This precludes speculation motives and path dependencies in auction or market prices as subjects are fully capable of a perfect ex-ante analysis and rational decision-making. Although these assumptions are highly unlikely to be met by experimental participants, the predictions deducted above serve as useful benchmarks in evaluating the observed behavior and identifying typical behavioral patterns that might explain distortions to the system's efficiency.

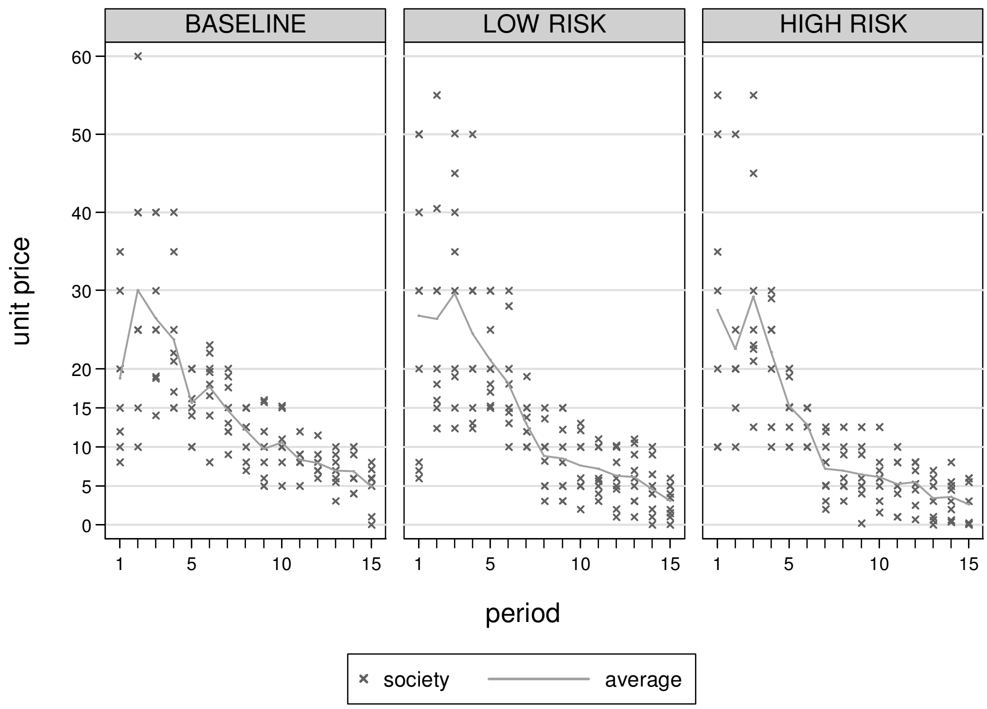
5. Results

We present our results in the order of the game's three stages and according to the treatment conditions: first, we investigate auction prices and distributional effects between agents and the auctioneer; second, price dynamics and trade volumes in the secondary market are analyzed; and third, we illustrate which projects are carried out and which land consumption results. To provide an overarching conclusion, we assess the overall efficiency of the cap & trade system and evaluate differences in income with respect to agent types.

5.1 Auctioning of certificates

In each period, half of the issued certificates are auctioned in a uniform price auction. As shown in our theoretical analysis (section 4), prices should not exceed the fair value of 11.25ECU, assuming agents are risk neutral. Figure 1 illustrates auction prices over periods with respect to treatment conditions.

Figure 1. Price dynamics in auctions by treatments



It can be seen that price dynamics across periods are fairly similar. Prices significantly exceed the fair value at the beginning, before gradually decreasing to a level further below the fair value. The decrease in prices initially appears to be rather steep yet it becomes weaker from about period 7 onwards. Table 5 summarizes the unit auction prices at the society level and provides statistical evidence.

		BASELINE	*LOW RISK*	*HIGH RISK*
unit prices	period<=7	**20.99** (2.23)	**22.78** (8.11)	**19.5** (5.01)
	period >7	**8.43** (2.12)	**6.54** (3.18)	**5.00**** (3.18)
	overall	**14.29** (1.55)	**14.12** (2.70)	**11.77**** (1.71)

Table 5. Averages and standard deviations of unit auction prices by treatment

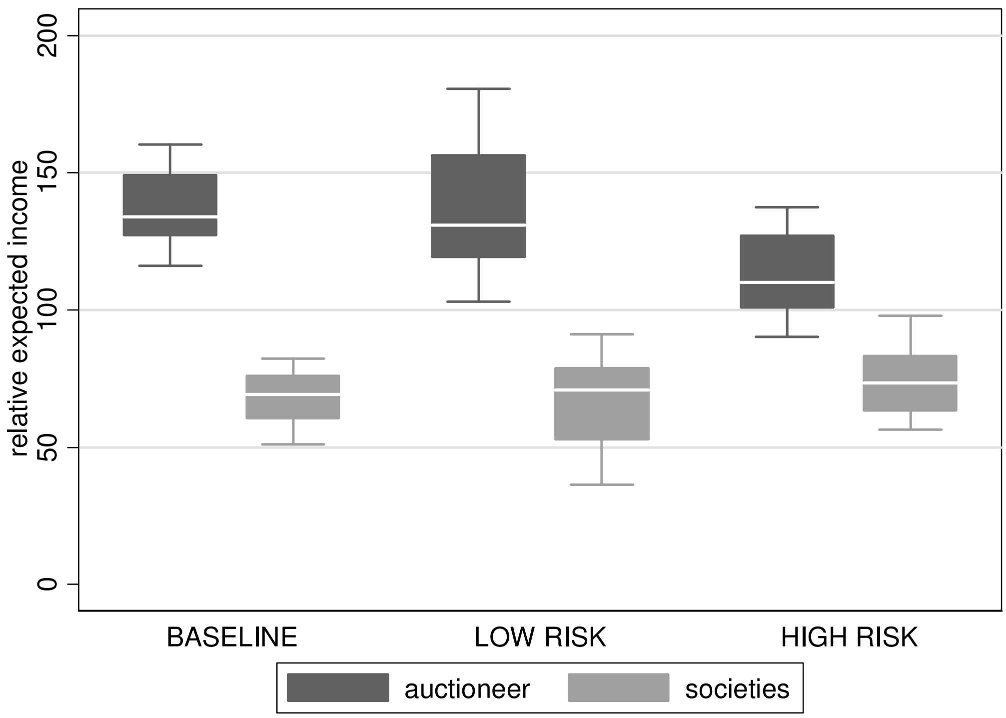
Note: Applying a Wilcoxon-Rank-Sum test against *BASELINE where* *, ** and *** indicate p-values smaller than 0.1, 0.05 and 0.01, respectively; standard deviations in parentheses. Unless mentioned otherwise, all calculations and tests are carried out at the society level.

For all treatments, prices are substantially lower in the second half of the game (Wilcoxon-Sign-Rank test; for *BASELINE* z=2.521 and p=.0117, for *LOW RISK* z=2.666 and p=.0077, for *HIGH RISK* z=2.521 and p=.0117). On average, prices in *HIGH RISK* are closest to our theoretical predictions and, more interestingly, they are significantly lower than in *BASELINE* and *LOW RISK*.

Result 1a: *Independent of the underlying risk in project revenues, unit auction prices initially exceed fair values, yet tend to gradually decrease in a TDR system. High underlying risk reduces auction prices.*

Recall that all payments in auctions transfer to income for the public authority auctioning the certificates. Figure 2 depicts the auctioneer's and societies' total expected income relative to the theoretical values derived above. A society's total expected income is derived by aggregating the expected values of realized projects and subtracting aggregate payments in the auctions.

Figure 2. Distribution of income between auctioneer and societies by treatment



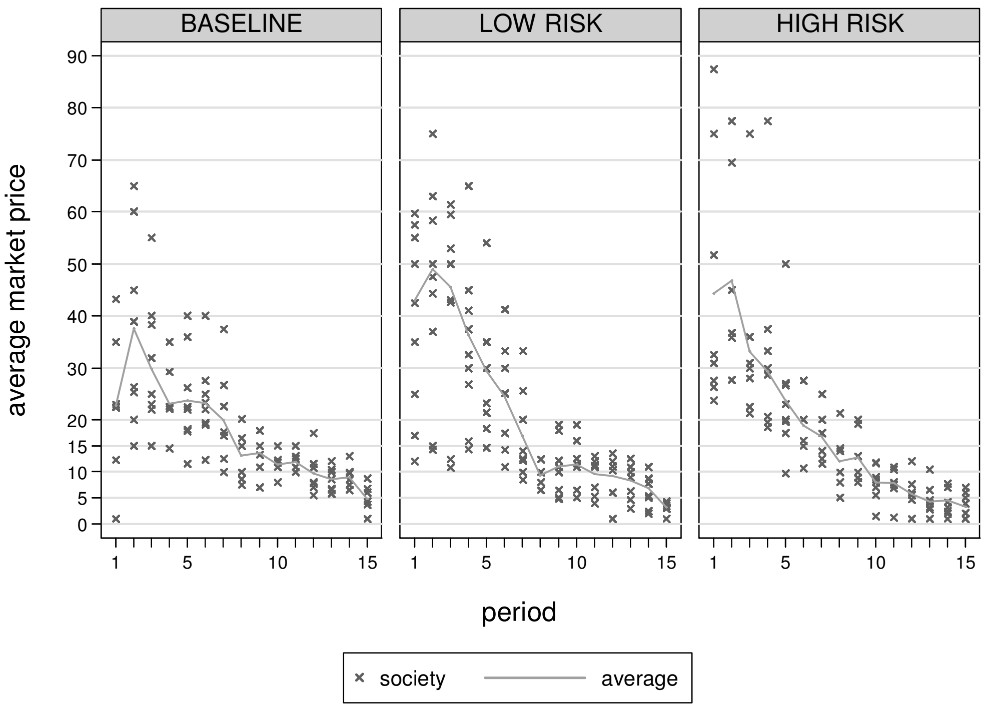
It can be seen that the auctioneer outperforms the theoretical benchmark, while societies perform worse. This finding corresponds to Figure 1 and provides evidence of fairly high prices in the initial periods, which benefit the auctioneer to a greater extent than the lower prices during later periods diminish her income. Another interesting result from this illustration is the substantially lower income discrepancy in *HIGH RISK* compared to *BASELINE* or *LOW RISK*. It appears that agents confronted with a high level of uncertainty become more cautious throughout the game when bidding in the auction to accumulate certificates, which in turn substantially reduces the auctioneer's income. Overall, these findings can be explained by the prevalence of risk-averse behavior among agents.

Result 1b: *Auctions in a TDR system redistribute income from agents to the auctioneer to a much greater extent than suggested by theory. This effect is weaker when the underlying risk is high as agents bid less and show risk-averse behavior.*

5.2 Trading of certificates

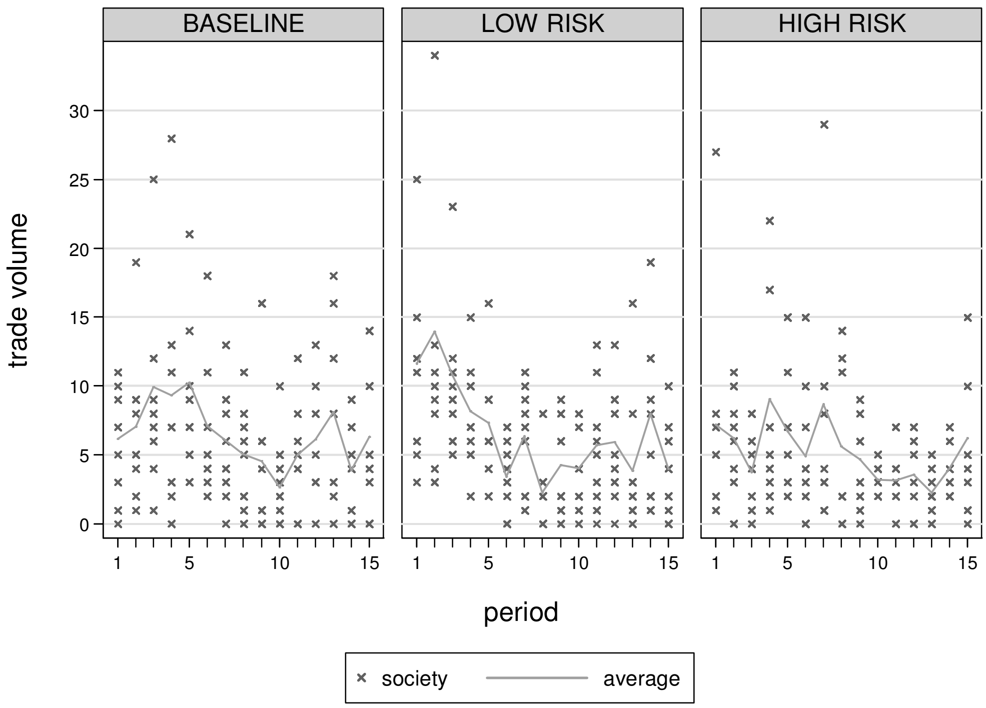
In a secondary market, agents are able to buy and sell certificates at any price, restricted only by their current budget. Figure 3 provides an overview of the respective price dynamics and Figure 4 depicts the trading volumes.

Figure 3. Price dynamics in markets by treatments



Similar to the pattern in unit auction prices, average market prices and price volatility tend to substantially deteriorate over the course of the game for all treatments (Wilcoxon-Sign-Rank test; for *BASELINE* z=2.521 and p=.0117, for *LOW RISK* z=2.666 and p=.0077, for *HIGH RISK* z=2.521 and p=.0117). For trade volumes, the same pattern can be identified as volumes almost halve between the first and second half of the game (Wilcoxon-Sign-Rank test; for *BASELINE* z=1.820 and p=.0687, for *LOW RISK* z=2.547 and p=.0109, for *HIGH RISK* z=2.240 and p=.0251). Table 6 summarizes these findings and shows that there are no statistically significant differences across treatments.

Figure 4. Market volume dynamics by treatment



		BASELINE	*LOW RISK*	*HIGH RISK*
market prices	period<=7	**27.28** (7.14)	**36.46** (14.56)	**31.80** (13.56)
	period >7	**9.70** (1.88)	**8.25** (3.39)	**7.26** (3.73)
	overall	**19.41** (3.20)	**25.30** (9.99)	**20.06** (3.00)
trade volumes	period<=7	**7.53** (2.88)	**7.56** (3.81)	**6.73** (3.01)
	period >7	**4.95** (2.13)	**4.54** (2.56)	**3.89** (1.75)
	overall	**6.16** (2.51)	**6.22** (3.19)	**5.32** (2.00)

Table 6. Price averages and standard deviations of market prices by treatment

Note: Applying a Wilcoxon-Rank-Sum test against *BASELINE* where *, ** and *** indicate p-values smaller than 0.1, 0.05 and 0.01, respectively; standard deviations in parentheses. Unless mentioned otherwise, all calculations and tests are carried out at the society level.

Result 2a: *Average prices in the secondary market for certificates in a TDR system substantially decrease over time after initially exceeding fair values. The underlying risk has no influence on this pattern of price dynamics.*

Result 2b: *Independent of the underlying risk, certificate trade volumes in the secondary market decrease over time in a TDR system.*

It is important to note that prices in the secondary market are substantially higher than the unit auction prices.[2] This finding is somewhat surprising and hints at a persistent distortion in a cap & trade system that leads to strong redistribution effects among agents. As an explanation, one might assume that speculation motives drive prices in the secondary market or that subjects caught up in the action of trading certificates are unable to properly assess price dynamics. However, it appears reasonable to expect that subjects are able to account for

[2] Testing for differences between unit auction and market prices in the first half of the game by applying a Wilcoxon-Sign-Rank test gives z=-3.240 and p=.0251 for *BASELINE*, z=-2.666 and p=.0077 for *LOW RISK* and z=-2.521 and p=.0117 for *HIGH RISK*. For the second half, the test gives z=-1.540 and p=.1235 for *BASELINE*, z=-2.192 and p=.0284 for *LOW RISK* and z=-2.521 and p=.0117 for *HIGH RISK*.

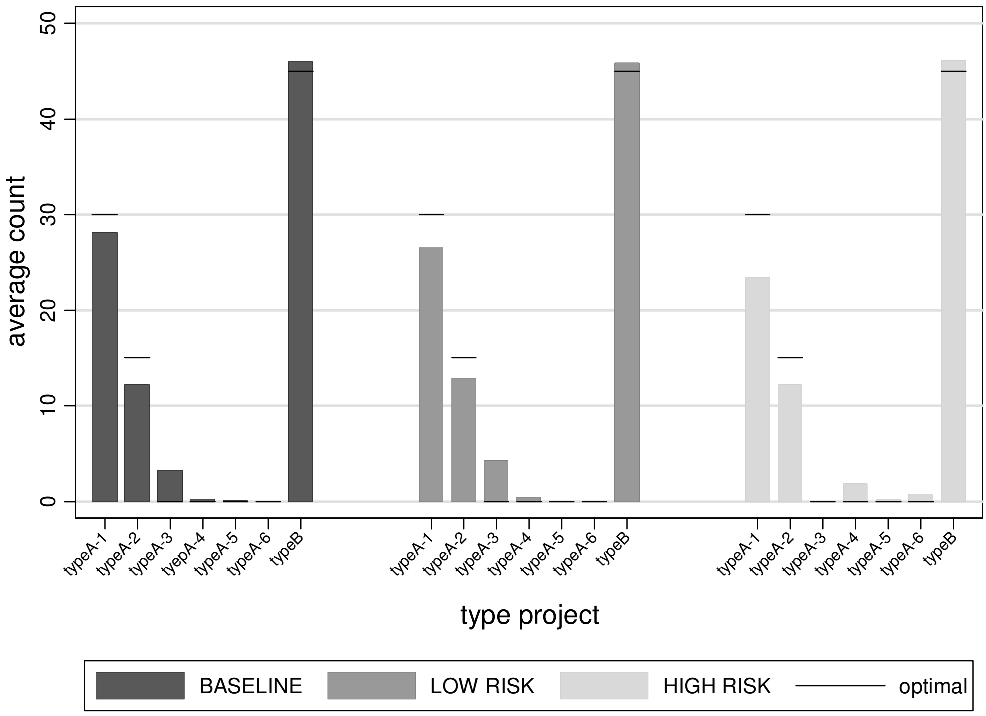
overshooting prices in the secondary market by bidding more in the auctions to gather certificates. Nonetheless, differences remain rather constant over time as for *BASELINE/LOW RISK/ HIGH RISK* market prices in the second half of the game remain about 16%/26%/45% higher than unit auction prices. Another plausible explanation is the endowment effect (Kahneman et al., 1991). This well-established behavioral bias involves agents valuing some good in their possession higher than the same good when they do not possess it, i.e. a persistent divergence of a person's willingness to pay and willingness to accept. Accordingly, certificates acquired in the auction and passing in the possession of a particular agent might be valued at a premium and might thus only be offered at higher prices than those paid in the auctions. Following this interpretation, the persistent divergence of prices does not result from speculation motives, but rather from the behavioral effect of agents perceiving that they should receive a subjectively appropriate compensation for their loss in property.

Result 2c: *Prices in the secondary market persistently exceed unit auction prices, which points to a potentially inherent distortion in TDR systems.*

5.3 Project realizations and land consumption

As outlined in section 3, agents can only carry out one project in each period of Type A or B. Type A projects require the use of certificates and generate certain expected payoffs. Type B projects are of a uniform value, yet their realization does not require certificates. Figure 5 summarizes the average number of projects actually carried out by treatment, as well as depicting the theoretical optimum that maximizes aggregate welfare, which is given at 30 Type A-1 projects, 15 Type A-2 projects and 45 Type B projects per society.

Figure 5. Project realizations by treatment

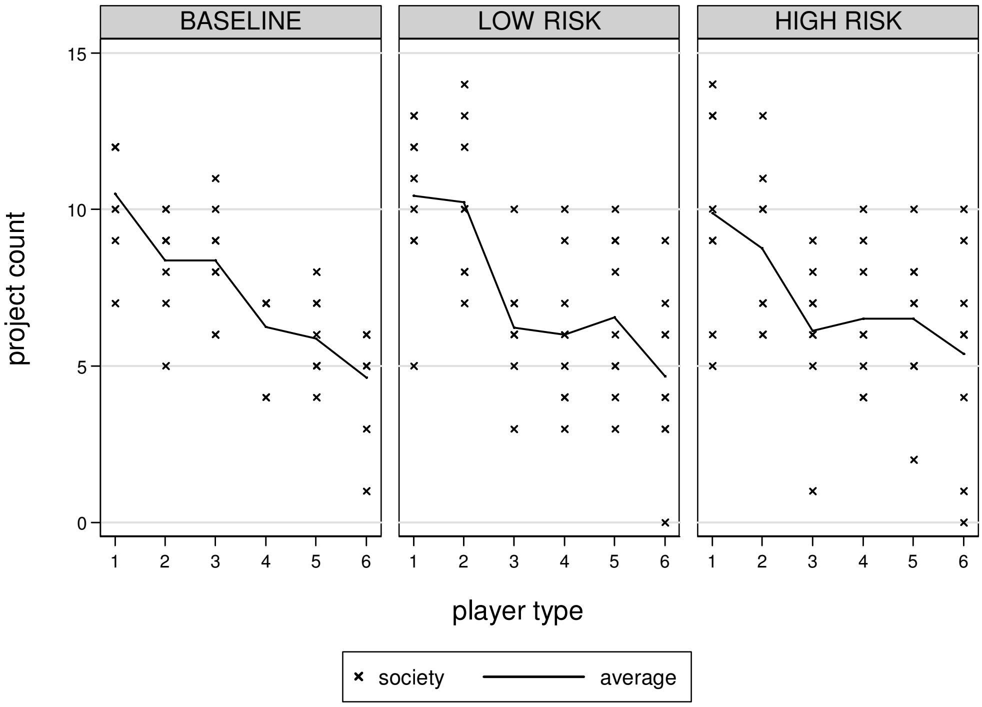


The distribution of project realizations is quite similar for *BASELINE* and *LOW RISK*. By contrast, the realization of Type A-1 projects worth 100ECU is lower in *HIGH RISK*, i.e. there are significantly fewer Type A-1 projects conducted compared to *BASELINE* (Wilcoxon-Rank-Sum test; against *LOW RISK* z=1.179 and p=.2385, against *HIGH RISK* z=2.763 and p=.0057). Overall, almost all certificates are consumed on average; thus, almost the maximum of 45 Type A projects is carried out on average. Consequently, the distribution between project realizations (Type A) and the outside option (Type B) fulfills the expectations induced by the design of the cap & trade system.

Result 3a: *The cap & trade system tends to allocate certificates such that the expected pattern of project realizations and the outside option is established and the objective of reducing land consumption is achieved with near-perfect precision. However, given high risk, the distribution of realized projects shifts towards less valuable projects.*

Another interesting aspect when considering land consumption is given by the distribution of realized projects across the different types of agents. Figure 6 shows the number of realized projects with respect to agent types by treatment.

Figure 6. Distribution of realized projects over player type by treatment



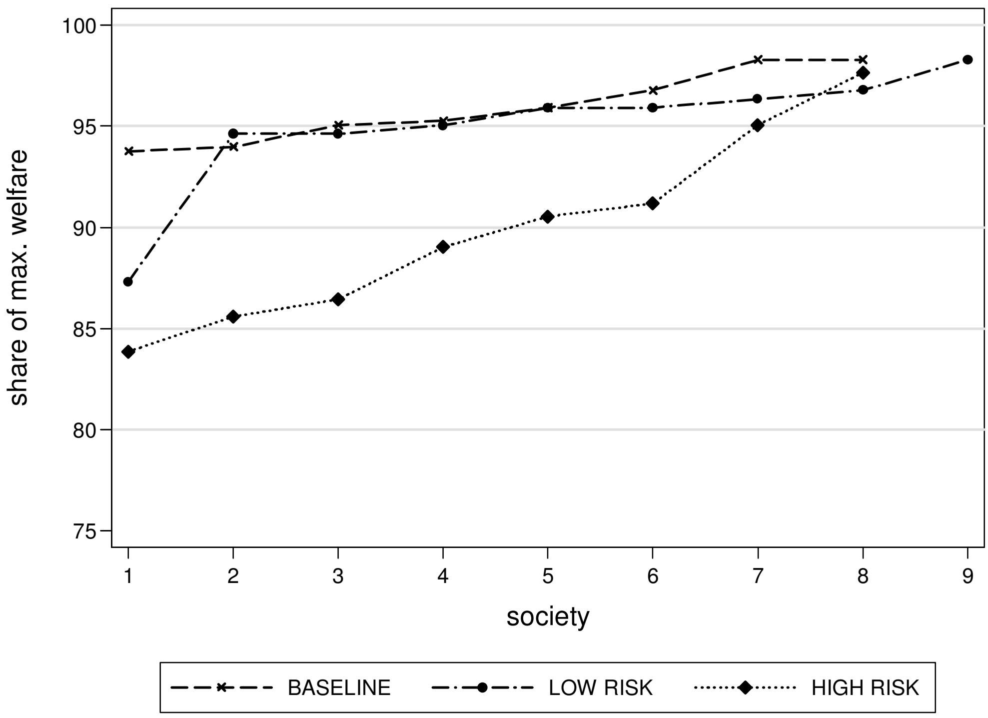
Evidently, there are no substantial differences across treatments, since a pattern of decreasing project realizations along with the "size" of the agent emerges for all levels of underlying risk. The number of certificates grandfathered seems to be the predominant factor in determining which agents realize projects. The redistribution of certificates resembles the basic pattern expected from the design of the cap & trade system, although this relation is somewhat weaker once there is risk in project revenues as the heterogeneity in realized projects conditional on agent type tends to increase.

Result 3b: *The number of realized projects depends on an agent's endowment in land consumption projects and her number of certificates grandfathered. This relation weakens with increasing underlying risk.*

5.4 Efficiency and welfare analysis

Finally, we consider the overall efficiency and the resulting welfare consequences of our treatments. Recall that the only potential source of inefficiency in a cap & trade system lies in the under-consumption of certificates or the realization of less valuable projects caused by a non-optimal allocation of certificates. As stated in Result 3a, the realization of Type A-1 projects is lower when underlying risk is high. Figure 7 illustrates the consequences of such inefficiencies in the distribution of realized projects by comparing the share of the maximal feasible welfare achieved by each society by treatment, whereby societies are ranked in terms of their level of efficiency.

Figure 7. Share of maximum welfare over societies by treatment



While there are no substantial differences between *BASELINE* and *LOW RISK* (Wilcoxon-Rank-Sum test; z=0.291 and p=.7713), societies in *HIGH RISK* perform inferiorly as the second best society only slightly outperforms the weakest society of *BASELINE* (z=2.472 and p=.0134).

Result 4: *A TDR system to reduce land consumption achieves lower levels of aggregate welfare when the associated risk in revenues of land consumption projects is high. This is due to an inefficient distribution of certificates, which leads to a realization of projects with inferior value.*

6. Discussion and conclusion

In this study, we suggest that experimental empirical evidence can contribute to studying the determinants of successful TDR systems by providing complementary insights to previous theoretical- and case study-based investigations. This methodological approach to the question of an optimal design of TDR systems necessarily has certain restrictions. For instance, given that laboratory experiments require a number of assumptions and simplifications to achieve a high degree of internal validity and understanding among participants, not all complexities of real-world applications of TDR can be implemented. Similarly, student participants might act differently than actual agents in charge of land use decisions. While both of these aspects place certain limitations on the direct applicability of our results, we nonetheless argue that the counterfactual results of experimental studies providing ceteris paribus analyses of the impact of core parameters to a system of TDR yield valuable insights unattainable by field data. We suggest that the uncertainty associated with obtaining, trading and using TDR constitutes is one of these key features in land use decisions and needs to be taken into account when considering policy options and institutional designs. Therefore, we use a novel experimental design that captures the core aspects of a TDR system. Two additional treatments are conducted to assess the impact of varying degrees of investment risk. Our experimental setting enables us to observe the individual and overall market effects of the treatment variable and formulate policy implications for the design of TDR systems in economic contexts associated with different degrees of risk.

Overall, three distinct behavioral patterns emerged in our study. First, higher levels of investment risk reduce the average prices paid in auctions, leading to lower levels of redistribution from agents to the auctioning institution. Second, prices for certificates in auctions and the secondary market persistently diverge regardless of treatment conditions. This result has been shown in previous experimental studies on TDR (Meub et al., 2017, 2017, 2016) and can be interpreted as resulting from the endowment effect (Kahneman et al., 1991). While more pronounced for conditions of higher risk, this effect adds to the redistribution of income among agents. Third, participants' risk preferences have a substantial impact on the project realizations, whereby risk-loving players who might control fewer valuable projects tend to buy certificates from risk-averse players who might control more valuable projects. This precludes the realization of the most valuable projects and the allocation of TDR becomes inefficient. Accordingly, certificates are partly reallocated according to risk preferences – i.e. based upon their expected utility – whereby they cease to be fully allocated according to the expected value of projects, which would be the aggregate welfare maximizing condition.

At an aggregate level, the TDR system consistently proves efficient in situations of low and no risk in future revenues of land consumption projects. Certificates are reallocated efficiently to agents who can realize the most valuable projects; while prices and price volatility are initially high, they gradually decrease; trade volumes react similarly. There is a persistent gap between certificate prices in the auctions and the secondary market, which this does not affect overall welfare. For conditions of high investment risk, welfare substantially decreases due to an inefficient allocation of certificates. Auction prices are consistently lower, which reduces the redistribution in favor of the auctioneer. Trading volumes and prices in the secondary markets are largely unaffected by conditions of higher risk in land consumption projects.

Two core implications can be derived from a policy perspective. Primarily, it has been shown that a TDR system is an efficient mechanism for reallocating development rights to the most valuable building projects for conditions of low and no risk in revenues of land consumption projects. Despite overshooting at first, prices gradually decrease. The divergence of auction and trading prices leads to strong redistribution effects among agents yet has no overall welfare implications. Secondarily, when considering situations of higher investment risk, certificates are allocated to risk-loving agents who potentially do not control the most valuable building projects. Particularly in situations in which the profitability of potential building projects available to participants in a TDR system is very heterogeneous and investment risks are high, the welfare losses due to risk-related behavioral effects may become substantial. Accordingly, TDR might not be the best policy choice for these particular economic contexts.

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Appendix: Instructions for the *BASELINE* treatment. The differences for *LOW/HIGH RISK* are indicated in braces.

OVERVIEW OF THE GAME

You can earn money in this game by realizing projects and trade with certificates. At the beginning, you will be randomly assigned to a group of 6 players, which will remain constant during the 15 periods of the game. All prices and values in the game will be paid in ECU with up to two positions after decimal point. 100 ECU convert to 1€ for your payoff.

Projects

Overall, each player has 30 projects of **Type A** and 15 projects of **Type B**. Both types of projects have different values, which are shown in this table:

Type of project	Project value (in ECU)
A	0 bis 100
B	10

{Note: The table does not apply to *BASELINE*. The numbers for low and high refer to *LOW* {*HIGH*} *RISK* respectively. The numbers for medium apply to both treatments.}

Type of project	Potential project value (in ECU)		
	low	medium	high
A1	50 {-100}	100	150 {300}
A2	40 {-80}	80	120 {240}
A3	30 {-60}	60	90 {180}
A4	20 {-40}	40	60 {120}
A5	10 {-20}	20	30 {60}
A6	0	0	0
B	10	10	10

In each period, only one project can be realized. {*BASELINE*: Before the game starts, the values of all Type A projects will be assigned and shown to you.} All players are assigned different Type A projects. {*LOW/HIGH RISK*: Type A projects have variable project values, which lead to low, medium or high payoffs, each with the same probability (1/3). Which project values have realized will be shown to you at the end of the game.}

Certificates

For the realization of Type A projects, you need 8 certificates each, Type B projects do not require certificates. Certificates are assigned to you at the beginning of each period and auctioned. Additionally, certificates can be traded among the players. In the game, you receive an endowment of 700 ECU which you can use to buy certificates at the auction and from the other players. You can also sell certificates and thus increase your payoff.

Your payoff

The payoffs you receive in the course of the game, as well as the sum of all {*LOW/HIGH RISK*: actually} realized projects add up to your final payoff. Further, a basic payoff of 400 ECU will be added.

COURSE OF THE GAME

Each of the 15 periods follows an identical course, which consists of three phases.

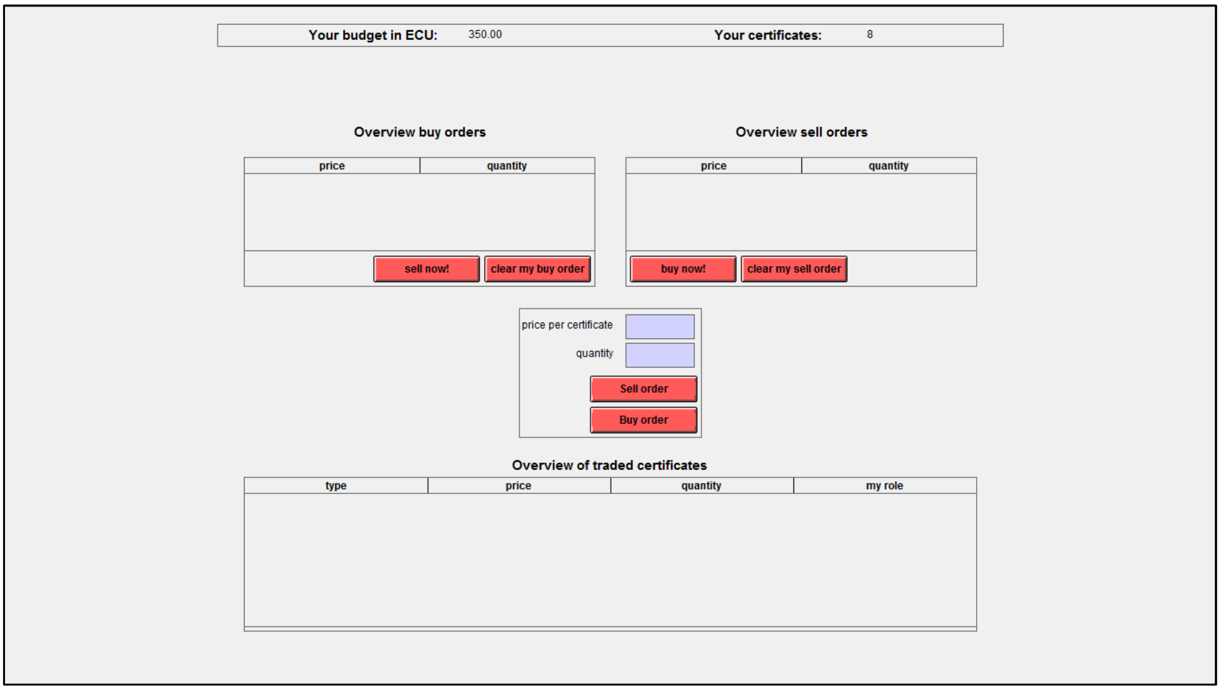
Phase 1: Allocation and auctioning of certificates

At the beginning of each period, 12 certificates are allocated. The number of certificates a player receives is determined randomly at the beginning of the game and does not change during the game.

Additionally, after the allocation, 12 certificates are auctioned. Depending on your current funds, you can bid for a number of certificates of your choosing at a unitary price. The 12 highest bids will receive the certificates to the price of the lowest successful bid.

Phase 2: Trading of certificates

Following the allocation and auctioning, this phase lets you trade with the other five players, i.e. buy and sell certificates. You can offer a trade yourself and also accept offers from other players. To clarify this, you see the respective screen of the trading phase below:



Offering a trade

In the lower box, you can enter a price (in ECU) and the respective amount of certificates that you would like to buy.

- **By clicking "searching"**, all players are shown your buying desire in the left box. Once another player agrees to your offer, you will receive the respective number of certificates. The total value (price x quantity) of the trade will be withdrawn from your funds.
- **By clicking "offering"**, all players are shown your sell offer in the box on the right. Once another player accepts your offer, you sell the respective number of certificates. The total value (price x quantity) of the trade will be added to your funds.

Accepting another player's offer

In the boxes on the right and left side, you can see all current buy and sell offers for certificates. If you choose an offer and click on "sell now!" or "buy now!", you make the trade with the respective player.

You are allowed to trade as often as you please. You can also make multiple sell and buy offers at the same time. The trading phase ends automatically once **2 minutes** have passed.

Phase 3: Realizing projects

In the third phase of the game, you can realize one of your projects. You will receive the respective payoffs ({*LOW/HIGH RISK*: actually realized} project value in ECU) at the end of the game. After the third phase, the next period begins. Certificates that are not used in one period can be saved for subsequent periods. Note, however, that you will not receive a payoff for certificates that remain unused until the end of period 15!