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Emissions Trading with Shares and Coupons[1] when Control over Discharges is Uncertain

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Proposed Running Head
Emissions Trading with Shares and Coupons

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Abstract

Two important decisions in designing markets for tradable emissions permits are whether to allow banking of permits (coupons) and whether to allow trading in entitlements to future permits (shares). Banking is predicted to reduce price instability when firms trade in a reconciliation market after the quantity of emissions has been determined. Tradable shares are a common feature in proposals for emissions trading in Canada. We conduct a laboratory experiment to investigate how bankable coupons and tradable shares affect efficiency and prices under uncertainty. Cognitive demands on the subjects are reduced by computerized advice on the optimal allocation of coupons across periods and the implied marginal values of coupons and shares. Banking, share trading and uncertainty conditions are introduced in a complete factorial design with three observations per cell. High efficiencies are observed across all treatments. Uncertainty in the control of emissions leads to substantial price instability when banking is not allowed. Banking virtually eliminates the instability, but reduces the efficiency of the market institution. Share trading reduces trading volumes, increases price stability and improves efficiency.

INTRODUCTION

Two important decisions in designing markets for tradable emissions permits are whether to allow banking and whether to allow trading in entitlements to future permits. Banking refers to the ability to carry unused emission permits forward from one compliance period to the next. Banking is sometimes considered undesirable since it reduces the regulator's control over the temporal distribution of emissions. This could lead to a concentration of emissions in certain time periods, which would increase pollution damages if the damage function is convex. Banking is particularly desirable when firms cannot control emissions precisely during a compliance period. In this case, they may arrive at the end of the compliance period with a surplus or deficit of permits. An emissions trading plan can provide for a reconciliation market in which firms clear these surpluses or deficits. This market may be unstable, however. If banking is not allowed, an excess supply of permits in the reconciliation period may lead to extremely low prices for permits while excess demand may drive prices very high [4,5].

Explicit trading in entitlements to future permits is a feature of several emission trading plans under discussion in Canada. These proposals distinguish between *coupons* and *shares*. A coupon gives permission to discharge a unit quantity of waste. A share represents an entitlement to a specified fraction of the total available coupons to be issued in future periods. For example, a firm holding 10 percent of the shares in an emissions trading market would receive 10 percent of the coupons issued in any year, even if the absolute number of coupons is variable. In a world of complete and perfect contingent future markets in coupons, shares would be redundant. But in the practical world of environmental regulation, shares may have some advantages in allowing more secure long term planning for firms acquiring or selling coupons and in providing an explicit method for allocating any future variation in aggregate allowable emissions.

Emissions trading plans under discussion in Canada typically provide both for trading in shares and for banking coupons[3], while plans implemented in the United States tend not to provide a formal mechanism for trading entitlements and have, in at least one case, restricted banking.[4] Neither design feature has been fully investigated in the laboratory. Previous experiments have shown that markets with bankable coupons achieve somewhat lower efficiencies than those typically observed in markets with no intertemporal trading, perhaps because banking makes the experimental environment more complex. No controlled investigation of the independent effects of banking or of trading in shares has been reported, however. In light of the policy importance of emission trading, further experimentation seems warranted.

This paper reports an experiment designed to investigate the contribution of bankable coupons and tradable shares to the efficiency and stability of emission trading markets. The design is noteworthy in two respects. First, it explicitly incorporates uncertainty by making net emissions stochastic and by introducing a reconciliation market in which traders who find themselves short of coupons can clear their positions. As a result the sequence of coupon trading, production decision, and reconciliation market is modelled more explicitly than in other emission trading experiments. Second, it reduces cognitive demands on traders by providing computerized advice on intertemporal optimization of share and coupon holdings. A *planner* simulates the operations research department of a large firm by computing the operating-cost-minimizing allocation of an arbitrary holding of shares and coupons. A *wizard* uses the planner to compute the marginal value of coupons or shares given the trader's current holdings. We first provide a fuller motivation of the experimental design, then report our procedure, results and some conclusions.

PREVIOUS LITERATURE

Considerable attention is being paid to the use of tradable emission permits to achieve environmental objectives at low cost [1,2,3,9,20]. Trading in permits (henceforth *coupons*) has three advantages over traditional methods of regulation. First, it promotes cost-efficiency achieving target emission reductions. Firms with low marginal abatement costs have an incentive to increase abatement in order to sell their coupons to firms with high abatement costs. The aggregate cost of the targeted abatement level is reduced as the cheapest abatement alternatives are exploited first. Second, the informational burden placed on regulators is reduced because the allocation of abatement effort across firms is determined through market forces rather than central direction. Third, the explicit price of coupons provides a continuing incentive for firms to develop and invest in new pollution control technologies.[5]

Approximations to emission trading schemes have been implemented with varying degrees of success in the United States [8,13]. A variety of reasons have been proposed to explain why these programs have not delivered the full cost savings theoretically predicted. Among these are high transaction costs imposed on participants through complex sets of trading procedures and uncertainty concerning the continuation of the program. The U.S. Clean Air Act Amendments of 1990 addressed some of these concerns and provided for a major program of sulphur oxide (SO_x) coupon trading. Central to this program is a revenue neutral discriminative price auction for coupons administered by the Chicago Board of Trade on behalf of the United States Environmental Protection Agency (U.S. EPA)[6]. The coupons traded in this market come either from a small fraction of the total issue of coupons reserved for this purpose by the EPA or from voluntarily submissions by firms. Interested parties submit sealed bids for these units. The revenues from the auction are distributed to the firms offering units; sellers receive the bid price for any traded coupon voluntarily submitted and the average price of all reserved coupons for their share of the mandatory coupons.

Most laboratory investigations into coupon trading have been related in one way or another to the EPA auction, especially to its revenue neutral features. Hahn [12] conducted an early investigation of revenue neutral auctions. Ledyard and Szakaly-Moore [15] study the performance of double auction and competitive revenue neutral auctions in the laboratory and find that the double auction institution yields higher market efficiencies and more stable prices than the competitive revenue neutral auction. Laboratory investigations specifically related to the EPA program were conducted at the Universities of Colorado [7] and Arizona [10,11]. In general, these latter experiments showed that the proposed U.S. market mechanism, as implemented in the laboratory, achieved only about one half of the potential cost savings. The Arizona experiments showed incomplete arbitrage between the discriminative sealed bid auction and a computerized double auction market and some evidence of speculative bubbles in coupon prices. Subjects appeared to experience difficulty in banking coupons in both the Colorado and Arizona experiments, overbanking at Colorado and substantially underbanking at Arizona. A somewhat different line of experimentation was followed by Cason and Plott [6], who showed that the revenue neutral auction mechanism implemented by the U.S. EPA contains a perverse incentive encouraging both sellers and buyers of coupons to submit bids below their true valuation of coupons.

A particularly interesting investigation of the effect of uncertainty on emission trading markets was conducted in the context of the California RECLAIM program[4,5]. This program, intended for the control of both nitrogen oxides (NO_x) and reactive organic gases, was originally designed without any provisions for banking of coupons. The investigators argued that a reconciliation market would be required for firms that had used more coupons than intended and that price spikes and troughs would develop in the reconciliation market if all possibilities for intertemporal substitution of permits were eliminated. They further argued that a system of overlapping coupons, in which some annual coupons would expire in June (say) while others expired in December, would eliminate these spikes. They confirmed their predictions in an experiment with one session in each condition.

Canadian governments are actively considering proposals for emissions trading, especially in nitrogen oxides (NO_x). One plan [17,18,19] called for a *Basic Emissions Trading Approach* (BETA) in which two assets are traded: *coupons* allowing discharge of NO_x and *shares* entitling the holder to a proportionate share in future distributions of coupons. Many discussion papers in Canada continue to adopt the coupons and shares formula [9,20] although the most recent proposals seem to have abandonned it [14]. Neither the theoretical properties nor the empirical performance of the BETA is well understood.

Only one laboratory experiment involving shares and coupons has been reported. Muller and Mestelman [16] compared a laboratory implementation of the BETA proposal to the results obtained by Cronshaw and Brown Kruse [7] and by Franciosi, Isaac, Pingry and Reynolds [11]. This implementation showed efficiencies significantly higher than those found by Franciosi, Isaac, Pingry and Reynolds and by Cronshaw and Brown Kruse for the same technical parameters. Possible explanations for this improvement included the reduced complexity of our market environment and the more intensive training provided to subjects. This experiment, however, did not investigate the separate effects of coupon banking and tradable shares in a controlled environment.

In summary, while emission trading programs continue on the regulatory agenda, many design issues remain unresolved. Two of these are the desirability of tradable shares and bankable coupons. Previous experiments suggest that the complexity of emission trading markets has reduced efficiency and that banking will be particularly important in the context of uncertainty. Our goal in this paper is to investigate whether bankable coupons and tradable shares promote efficient exchange and price stability in a trading environment which both reflects uncertain control of emissions and reduces the cognitive demands placed on the subjects.

PROCEDURE

Parameters

We construct a laboratory market in which eight subjects representing four types of firm trade coupons and shares. In every period each firm produces a fixed level of output and receives a fixed gross revenue. Gross emissions either are constant or vary randomly around an expected value. We refer to the latter as the case of uncertainty. Emissions may be abated at an increasing marginal cost. Net emissions equal gross emissions less abatement. Although abatement effort is chosen with certainty, net emissions are random when gross emissions are uncertain. We define *complete abatement* as the abatement effort required to reduce expected net emissions to zero. Abatement cost savings, the difference between the cost of complete abatement and the cost of the actual abatement effort, rise at a diminishing rate as expected net emissions increase.

The four types of firm differ in initial size (as measured by expected gross emissions) and by abatement cost. Expected gross emissions are 20, 20, 10 and 10 for firm-types A, B, C and D respectively. Types A and C have low marginal abatement costs relative to types B and D. Shares are distributed in proportion to expected gross emissions: 6, 6, 3 and 3 for firm-types A, B, C and D respectively. Each period firms receive a coupon dividend in proportion to their holdings of shares. A reduction in aggregate emissions is imposed by reducing this dividend from two to one coupon per share after the fourth period.

To prevent their prior attitudes about environmental policy from influencing their behaviour, subjects are not told they will be trading emissions coupons, but rather that they are producing a product requiring a scarce input that is being rationed. They must surrender one coupon for each unit of input they actually use. Under conditions of certainty with no banking allowed, the marginal value of a coupon is equal to the marginal abatement cost savings shown in Table I. Because subjects participated in more than one session (see below), these induced values were varied by a scale factor ranging from one to four to prevent subjects becoming familiar with the equilibrium values. The conversion rate from Laboratory to Canadian dollars was adjusted to yield approximately equivalent payoffs. All data reported in this paper have been normalized by deflation by the scale factor.

The marginal abatement cost savings induce a demand curve for net emissions and hence for coupons. The supply of coupons is 72 coupons in each of periods one to four and 36 coupons in each of the remaining eight periods. If agents bank optimally, 48 coupons will be redeemed each period.[7] In the case of uncertainty, agents may find that they used one more or one fewer units of input than they intended. Unexpected emissions must be covered by a coupon and so the supply of coupons available for redemption against expected use falls or rises each period by the sum of unexpected emissions in each period.

The Market Institution

Each experimental session consists of 12 periods, each period divided into six sub-periods or *phases*: share market, distribution, primary coupon market, production decision, production result, and reconciliation. In some treatments one or more phases are dropped.

During the *share market phase* subjects trade shares in a computerized double auction market. This phase only occurs under treatments with tradable shares. The share market phase is followed by the *distribution phase,* in which subjects receive coupons according to their current holdings of shares and the previously announced coupon dividend rate for that period. The distribution phase does not require any intervention from the subjects. During the *primary coupon market phase*, subjects again trade coupons in a computerized double-auction market.

During the *production decision phase*, subjects choose the number of units of the input to use and consequently the number of coupons they will need. In the *production result phase*, which occurs once all production plans have been submitted, subjects are informed of their *actual* input use and of the cash generated from current production. Under the uncertainty treatment, actual input use may differ from planned input use by an amount specified in advance by the investigators. In the present case these errors were drawn from a uniform distribution over the values (-1, 0, +1).[8] This feature models measurement error (as discussed by Carlson and Sholtz [5]) or other errors in determining emissions. Such other errors might include unforeseen changes in output or changes in the availability of a substitute for the rationed input.

During the *reconciliation phase* subjects trade coupons in a computerized double auction market to eliminate any coupon deficit or unwanted coupon surplus. We choose not to allow subjects to plan a coupon deficit during the production decision phase. Nevertheless, when uncertainty is present, actual use may exceed coupon holdings. In this case, the subject has a coupon deficit that must be cleared by purchasing more coupons. Similarly, subjects may deliberately incur a coupon surplus (in the production decision phase) that they choose to sell rather than to bank. The reconciliation period allows such subjects to trade.

In the *coupon-redemption phase*, subjects redeem the number of coupons corresponding to their actual input. Subjects with a coupon deficit pay a per-unit penalty which is greater than any other firm's marginal abatement cost. Subsequently, eliminating the deficit becomes a first charge against any coupons acquired in the following period.[9] The coupon-redemption phase does not require any intervention on the subject's part.

After the coupon-redemption phase the next period begins with a share market (if enabled) and a new distribution of coupons. There is no share market in the last period of the session. At the end of the session, subjects' earnings are converted to Canadian dollars and paid privately in cash.

The Planner and the Wizard

The market institution just described places substantial cognitive demands on the subjects. When banking is allowed, the marginal value of a coupon is not determined directly by the schedule in Table I, but rather by the place in the schedule that the coupon would occupy if all current coupons and anticipated coupon dividends are allocated optimally over the remaining periods of the session. Similarly, the marginal value of a share is derived from the incremental value of the coupons it bears. These values are the output of simple, deterministic maximization problems. In the field, the operations research department of a participating firm could certainly compute these marginal values, given any trial holding of shares and coupons. Accordingly, we provide our subjects with a *production planner* that simulates an operations research department. The production planner is shown in a window on the computer screen. Subjects can enter any trial quantity of coupons and shares. The production planner computes the abatement cost-minimizing allocation of current and anticipated coupons over time and reports the allocation, the corresponding profit, and the change from the current holdings.

Accordingly, we also provide subjects with advice from trading and production *wizards*. The trading wizard uses the production planner to compute the current marginal value of coupons or shares, depending on the phase of the market, and displays its advice in a window during the primary coupon market, the reconciliation market, and share market phases of the period. The production wizard simply displays the operating profit-maximizing number of input units to use during the production decision phase.[10] We stress that the advice generated by the wizard requires no more information than one would expect to be available to firms in a naturally occurring market.

Computer Implementation

The experiment was run in the McMaster Experimental Economics Laboratory. The program is adapted from RNA3, a computer program developed by Shawn LaMaster and colleagues at the University of Arizona for use in the experiments reported by Franciosi, Isaac, Pingry and Reynolds. Major changes have been made in program control and in screen layouts, while preserving the core of the double auction mechanism.

Figure 1 displays the information presented to the subject during the Share Phase. The status window shows the subject's inventory of shares, coupons and cash at all times. A market window displays the current ask and bid. The clock window displays time remaining in the market. In the top right corner, the Wizard displays its trading advice. Subjects should be able to infer from this their maximum willingness-to-pay for a coupon (i.e. their maximum bid) and their minimum willingness-to-accept payment for a coupon (i.e. their minimum ask). The Planner, which can be directly accessed during trading, allows subjects to calculate their profits for any trial number of shares or coupons while taking into account all previous decisions made in the current period. The trial numbers are adjusted using the arrow keys. A similar screen displays the information during the Primary Coupon Market. In this case the Wizard displays advice about the value of additional coupons rather than shares. During the production phase, the screen displays information on coupons owned and coupons intended to be used ("Planned Input") with the implied effect of these decisions on this period's cash balance. The Planner shows the profit maximizing allocation of an alternative bundle of shares and coupons while the Wizard displays the number of coupons that should be used to minimize total cost if no further trading occurs. The reconciliation market screen is essentially the same as the share and coupon market screens. The wizard's advice is modified to account for the penalty imposed on coupon deficits.[11]

Experimental Design, Subjects, and Training

The treatment variables are the presence or absence of banking (*B* or *NB*), the presence or absence of trading in shares (*S* or *NS*), and the presence or absence of uncertainty concerning actual input use (*U* or *NU*). We choose a complete 2x2x2 factorial design with three observations per cell to achieve the maximum information from our experimental budget (see Table II).

The sessions were run in July, August, November, and December 1994. In July, subjects were drawn from the summer population of the Hamilton region and for the most part were students. Twenty-four subjects were recruited for training. Subjects participated in four training sessions in which they were introduced first to oral and then to computerized double auction markets. Subjects then participated in a truncated oral version of the experimental market, in which they received shares and coupons in the form of slips of paper and in which they manually optimized coupon use over time. Finally, each subject participated in two short training markets using the experimental software. In November an additional thirty-two subjects were recruited for training from the McMaster University student population. These subjects participated in training sessions comparable to the July sessions. A total of 55 subjects participated in the sessions analysed in this paper. Subjects typically participated in from 2 to 5 experimental sessions. The results from twenty-four experimental sessions are reported here. The twelve uncertainty sessions were conducted after the twelve certainty sessions had been run.[12] Sessions lasted between two and three hours. Subjects were paid five Canadian dollars (C$) per session for arriving on time in addition to their earnings from the experiment. The latter ranged from C$5.32 to C$45.09 with a mean of C$21.55 per session.

Benchmarks

We assess market performance under four headings: system efficiency, trading volumes, price signals, and price stability. In general the point of reference is the coupon allocation that would minimize system abatement costs given the constraints imposed in any given treatment.

Because the effective number of coupons available is less under uncertainty than in the case of certain control over emissions, minimum system abatement cost varies in the two cases.

We define twelve benchmarks for assessing system efficiency and prices (see Tables III and IV). The *command-and-control benchmarks* (CCC, CCU_S, and CCU_M) represent the performance of the market if neither trading nor banking occurs. In the certainty case all coupons are used by the subjects to whom they are issued in the period when they are received. The uncertainty benchmarks (CCU_S and CCU_M) adjust for the effective reduction in coupons available after the realization of random gross emissions. The *system optimum* command-and-control uncertainty benchmark (CCU_S) presumes that firms will allocate all their available coupons to production every period. The *market equilibrium* command-and-control uncertainty benchmark (CCU_M) assumes that firms face the same penalty structure under command-and-control that they do under the various banking and trading regimes. In this case, the high penalty for coupon deficits would induce risk-averse or risk-neutral firms to hold one coupon in reserve at the production decision phase against the possibility of a bad draw in the production result phase, reducing coupon use and raising system abatement cost.[13]

The *banking-only benchmarks* (BOC, BOU_S and BOU_M) represent system abatement costs when subjects may bank but not trade their coupons. In the case of certainty, firm types A and B use eight coupons each period while firm-types C and D use four. The system optimum uncertainty benchmark, BOU_S, adjusts for the effective reduction in coupons and the market equilibrium uncertainty benchmark, BOU_M, adjusts for incentives to hoard, as in the command-and-control case.

The *trading-only benchmarks* (TOC, TOU_S and TOU_M) represent system abatement costs when subjects may trade coupons but not bank them. System optimum and market equilibrium benchmarks are defined as in the earlier cases. Finally, the *banking and trading benchmarks* (BTC, BTU_S and BTU_M) represent performance if subjects are both bank and trade optimally. Table III summarizes system abatement costs and potential gains from trading and banking for each of the benchmarks. Table IV reports the corresponding prices.

The data of Table III can be used to define several efficiency measures. The most obvious, *gross efficiency*, is the observed reduction in system abatement costs expressed as a percentage of the maximum reduction, that is the difference between the BTC and CCC benchmarks. This measure unfairly penalizes the uncertainty sessions, however, since the realized random errors in our experiment effectively reduced the total stock of coupons by one per period, and hence increased the minimum achievable system abatement cost. Consequently we define *net efficiency* to be the actual gains from trade measured from the CCC or CCU benchmark as appropriate, expressed as a percentage of the potential gains computed using the BTC or BTU benchmarks as appropriate. System optimum and market equilbrium variants of the net efficiency measure are defined using the appropriate benchmarks. Formulas for all efficiency concepts appear as notes to Table VI.

Note that the trading-only benchmarks (TOC, $TOU_{S,}$ and TOU_M) for net efficiency are 79.8%, 79.7%, and 62.3% respectively. This reflects the fact that the initial, unequal allocation of total coupons over the twelve periods of the experiment does not minimize system abatement cost. Using the net efficiency measure to compare trading-only with banking-and-trading treatments will confound the effect of banking as a set of institutional rules with banking as a device allowing an efficient redistribution of coupons over time. To focus on the institution of banking we also make use of *adjusted net efficiency* indices for both the system cost-minimizing and market equilibrium concepts. These are defined as the cost savings achieved as a percentage of the maximum achievable savings, namely the TOC and TOU savings for no banking and the BTC and BTU savings for banking treatments. The benchmark value of these indices is, of course, always 100%.

A further benchmark is the minimum number of trades required to achieve maximum available abatement cost savings under each of our experimental treatments. These are reported in Table V. In the baseline treatment of no banking and no share trading a minimum of 224 trades is required to obtain the maximum achievable cost saving. This falls to as few as sixteen share trades and eight coupon trades when both share trading and banking are permitted.[14]

Predictions

Our goal is to testbed institutions rather than to test theories, consequently our working hypotheses are based primarily on past experience. We have the following predictions.

Prediction 1: *In the baseline treatment (NB/NS/NU) prices should converge quickly to TOC levels and adjusted net efficiency should be close to unity.*

Because the baseline treatment of no banking, no tradable shares, and no uncertainty is essentially a conventional multiple-unit double auction, we expect that prices will converge fairly rapidly to the *TOC* benchmarks of L$14 and L$123 - L$136 and that net efficiency will be close to the *TOC* benchmark of 79.8 percent.

Prediction 2: *Uncertainty in emissions should raise coupon inventories, reduce trading volumes and reduce system optimum net efficiency. There should be a high variance in reconcilation market prices when no banking is permitted.*

Introducing uncertainty in emissions will expose subjects to penalties if they are caught with a coupon deficit. We predict that this will lead to higher inventories of coupons, a reluctance to trade, and reduced system optimum net efficiency compared with the baseline. The market equilibrium net efficiency concept incorporates predicted hoarding and should not be reduced. On the basis of the Caltech experiments [5,6] we predict more price instability and reduced efficiency (relative to the baseline of *NB/NS/NU*) in the *NB/NS/U* and *NB/S/U* treatments. We expect these effects to be less pronounced in the banking treatment.

Prediction 3: *Banking should reduce or eliminate the spread between early and late coupon prices, should eliminate volatile prices in the reconciliation period, and should increase net efficiency but not adjusted net efficiency.*

Banking allows subjects to equate the marginal valuation of their coupons over time. If the final allocation is efficient the final prices should reflect the BTC and BTU benchmarks. When banking is allowed, the demand for reconciliation coupons can be met from other agents' coupon inventories, so there is likely to be competition in the market for coupons and prices will more closely conform to sellers' opportunity costs than to the extremely high marginal valuation of a trader who is short of coupons. This should eliminate the price instability predicted for reconciliation markets when no banking is allowed. Banking should increase net efficiency both because it allows for intertemporal substitution of coupons and because it discourages hoarding. There is no need to withhold additional coupons as a reserve against a bad production result if the agent is already planning to bank some coupons for future use. Since neither of these effects affect adjusted net efficiency we do not expect the latter to be increased by banking.

Prediction 4: *Share trading should reduce trading volumes and slightly increase both net and adjusted net efficiency. Coupon prices should not be affected.*

Trading shares can substitute for plans to trade coupons later in a session. If shares are traded, fewer coupon trades will be necessary. In an environment with a complete set of futures markets for coupons, tradable shares would be redundant and would have no role in improving efficiency. Because the laboratory institution has no futures markets, however, share trading may play a role in reducing uncertainty about the terms of future exchanges. This may allow more accuracy in banking and allocation decisions, increasing net and adjusted net efficiency.

RESULTS

Summary statistics for efficiency, trading volume, prices and coupon use are reported in Tables VI to X. Table VI reports mean efficiency and trading volumes by treatment. Mean adjusted net efficiency (system optimum) across all sessions is 87.90%. The B/NS/NU results appear anomalously low. The individual sessions in this cell yielded efficiencies of 29.54%, 52.14%, and 74.39%.[15] The first two observations, the lowest across all sessions, may be associated with one particular subject who by chance was assigned to both sessions and who was observed to concentrate on small trading gains rather than the redemption value of her coupons. Below, we will report results both including and excluding these outlying sessions.

We also ran regressions of adjusted net efficiency (system optimum) and trading volume on all treatment variables, an experience index, and their interactions.[16] The experience index was introduced to control for the subject pool's increasing familiarity with the overall structure of the experiment. We sought an index that would be strictly increasing and concave in each participant's experience. A convenient form is

$$x = \frac{1}{8}\sum_{i=1}^{8} \ln(c_i)$$

where x is the experience index and c_i is the number of sessions in which subject i had participated, including the current one. The index simplifies to the log of the number of sessions if all subjects are equally experienced.

Our observations are summarized in the following results.

Result 1: *The baseline treatment exhibits high efficiency and trading volumes are close to benchmark levels, but prices converge only slowly to the TOC prices.*

Table VI shows that adjusted net efficiency for the baseline treatment is 93.79%. Almost all the available gains from coupon trading are realized. The actual number of coupons traded, 211, was remarkably close to the benchmark minimum of 224. The pattern of price convergence is shown in Figure 2. In two of three cases, prices at the end of the first four periods were relatively close to the NB/NU benchmark of 14. In all three sessions prices rose after the fourth period. Only in the third of the three sessions was there a rapid shift to the new equilibrium price in periods five to twelve.

Result 2: *Uncertainty in emissions*

a. leads to price spikes and price instability in the reconciliation market when banking is not permitted,

b. does not affect trading volumes,

c. increases coupon inventories when there is no share trading, and

d. does not reduce system optimum net efficiency.

The summary data in Tables VIII and IX indicate that coupon prices in the reconciliation market for NB/NS/U and the NB/S/U sessions are highly variable and generally much greater than coupon prices in the primary market. Contrary to our expectations, introducing uncertainty in emissions did not significantly affect trading volumes. Table VI shows that trading volumes actually increased in a number of cases and regression analysis confirms that uncertainty has no significant effect.[17] Mean coupon balances after period four were 62.67 and 115.33 in the no-shares certainty and no-shares uncertainty treatments respectively, while they were 86.33 and 81.67 in the corresponding share treatments.[18]

Mean net efficiency and mean adjusted net efficiency are higher under uncertainty than under certainty in all four contrasts shown in Table VI (NB/NS/NU vs. NB/NS/U, etc). This is particularly true of the market equilibrium measure in the no-banking treatments (121.99 and 129.20 for no-shares and shares respectively). Regression analysis shows that uncertainty has a positive and statistically significant effect on both net and system optimum adjusted net efficiency when all sessions are included, but that the impact, while still positive, is not statistically significant when the outlying sessions are excluded.[19] We conclude that there is no evidence to suggest that uncertainty reduced the net efficiency of the coupon markets.

Result 3: *Banking coupons*

a. greatly reduces the standard deviation of reconciliation prices,

b. greatly reduces the rise in prices when coupon dividends are reduced,

c. tends to increase coupon trading volumes,

d. significantly increases net efficiency, and

e. significantly reduces adjusted net efficiency.

Table IX provides dramatic evidence that banking reduces the variation in reconciliation prices. The standard deviation drops sharply when banking is introduced. Only one price spike was apparent in all of the six banking sessions. An example of how banking affects reconciliation prices is captured by two sessions reported in Figure 3. We tested the significance of this effect by computing the standard deviation of reconciliation prices in each of the early (periods 1-4) and late (periods 5-12) stages of each session. The standard deviations in the banking sessions are significantly lower.[20,21]

Coupon price averages reported in Table VIII for the banking sessions show no tendency to change significantly after period 4 when the coupon dividend falls. Coupon prices in the banking, no-share sessions did not conform well to the BTC and BTU benchmarks. In particular, the prices in the two outlying sessions in the B/NS/NU treatment never really depart from the early stage TO benchmark of 14. As noted above, this behaviour may have been caused by one particular subject. We tested the significance of the smoothing effect of banking by computing the absolute value of the change in mean coupon price between early and late stages for each session. We then regressed this change on all treatment variables and their interactions. The impact of shares and uncertainty was insignificant, however the effect of banking was to reduce the spread between early and late prices by an average of 65 lab dollars. The effect is statistically significant ($F_{4,16}$ = 47.01, p = 0.000).

Regression analysis shows that trading volumes were somewhat higher in the banking sessions than in the no-banking sessions. When the two outlying sessions are excluded, introduction of banking increases trading volumes by about 28 coupons per session. The effect is marginally significant ($F_{5,12}$ = 3.080, p = 0.061).

Inspection of Table VI suggests that net efficiencies are higher and adjusted net efficiencies are lower under the banking treatments, except for the B/NS/NU case. The effect is most pronounced for the market equilibrium efficiency concepts in the uncertainty cases. Regression analysis confirms the significance of these effects. When outliers are excluded, banking increases system optimum net efficiency by about 9 percentage points but reduces system optimum adjusted net efficiency by almost 10 percentage points. The effects are statistically significant ($F_{5,12}$ = 4.52, p = 0.015 and $F_{5,12}$ = 3.68, p = 0.038 respectively).

Result 4: *Tradable shares lead to*

a. significantly lower trading volumes in the primary coupon market,

b. more stable primary coupon prices, and

c. significantly higher efficiencies.

Inspection of Table VI shows that share trading dramatically reduces the volume of trading in the primary coupon market. Regression analysis controlling for experience confirms the effect.is significant ($F_{5,12}$ = 23.36, p = 0.000, excluding outliers). Data summarized in Table VIII show the introduction of share trading significantly reduces the standard deviation of coupon prices in both early and late stages (one-tailed exact randomization test, p=0.001).

Inspection of Table VI suggests that shares have a positive effect on efficiency. This is confirmed by regression results which indicate that introducing share trading raises system optimum adjusted net efficiency by about nine percentage points, even when the outlying sessions are excluded. The effect is strongly significant ($F_{5,12}$ = 5.320, p = 0.001)

DISCUSSION

Unlike experiments designed to test specific predictions, ours has been an exercise in testbedding. We wished to observe the performance of a proposed market institution under closely controlled changes in institutional arrangements in the hope of validating and improving upon the proposed design. In this light, Result 1 is perhaps the most important. We have shown that emissions trading plans can be implemented in a double auction laboratory environment and that they display a high degree of efficiency under a wide range of institutional choices. Despite the relative complexity of our procedure, we have achieved higher levels of efficiency than reported by Franciosi, Isaac, Pingry and Reynolds [11] and by Cronshaw and Brown Kruse [7]. We attribute this partially to the more intensive training our subjects received and partly to assistance of the planner and wizard in guiding bidding and production decisions.[22] Both factors should reassure proponents of tradable emission permit plans that good results can be achieved when agents are well trained, well informed and have the requisite decision support.

Our results on banking and uncertainty (Results 3 and 4) confirm a finding by Carlson and Sholtz that emissions trading plans may experience severe price instability when control over emissions is imperfect and no provision is made for intertemporal substitution of emissions. The Carlson and Sholtz finding is based on a single pair of laboratory sessions; our result demonstrates that their finding is replicable under more frequent repetitions and a wider variety of institutional arrangements. Since control of emissions will usually be less than perfect, the result itself provides strong support for including some form of banking or intertemporal substitution in the design of emissions trading programs.

Banking has been shown to have a strong, positive impact on the net efficiency of emissions trading markets. Banking affects efficiency for at least three reasons. First, it raises the potential gain by allowing firms to mitigate the distorting effect of an intertemporally suboptimal initial allocation of coupons. Second, it reduces the incentive to hoard coupons to avoid penalties for coupon deficits, because there is no need to hoard additional coupons as a reserve against a bad production result if the agent is already planning to bank some coupons for future use. This also raises potential gains. Finally, banking may affect the efficiency of the competitve institution itself, by complicating the decision-making environment. Our results show that the net effect of these three influences is definitely positive.

In contrast, our *adjusted* net efficiency results suggest that the third effect of banking may be negative. Subjects achieve a lower fraction of the higher potential gains from trade when banking is present than when it is absent. This may be due to the increased complexity of the banking environment. Result 3c, that banking increases trading volumes, provides some support for this conjecture. An increase in volume probably reflect subjects' attempts to increase profit by speculation and arbitrage. This might have reduced the adjusted net efficiency of the market. Note, however, that the banking and experience interaction is significantly positive for both net and (system optimal) adjusted net efficiency, with or without outliers, suggesting that subjects experienced in the environment may benefit from banking ($t > 1.875$, $p < 0.05$ with at least 10 degrees of freedom on a one-tail test). In any case, any loss in adjusted net efficiency is more than compensated by banking's increasing the potential gains from trade.

Our results on share trading (Result 4) are quite remarkable. While most policy discussions of emissions trading plans envisage the development of futures markets in coupons, no previously reported laboratory experiments have implemented any form of trading future entitlements to coupons. We have shown that the introduction of shares improves the performance of the market even though it reduces trading volume. The gain in efficiency may be due to a reduction in the noise of price signals which accompanies a reduction of intramarginal trades. Our results suggest that formal trading of future entitlements to discharge permits may improve both the price revealing and efficiency properties of emissions trading plans.

More generally, our results suggest that although emissions trading markets are quite complex, high efficiencies can be obtained provided participants are well trained and supported by software that reduces the computational complexity of the market. They provide demonstrable support for emissions trading programs in comparison with other forms of regulation. This conclusion should be qualified, however, by noting that the high efficiencies are obtained in a double auction environment, a market institution known to be highly efficient in other applications. The efficiency properties of emissions trading programs might be compromised by using alternative market institutions, such as private negotiation.

The experiment reported here represents only part of a continuing program of laboratory research into the properties of emissions trading markets. We plan to investigate systematically the effect of thin markets, large firms, and opportunities for strategic behaviour on the performance of these markets. We believe our results demonstrate the value of laboratory research in testbedding alternative designs for new economic institutions. Any practical innovation, such as emissions trading, requires many specific design decisions. Rather than choosing among these on the basis of *a priori* reasoning, testing the proposed design in a laboratory setting is entirely practical. Although extrapolation of laboratory results to the field is always difficult, these laboratory results offer useful guidance to policy makers engaged in the design of emissions trading programs.

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