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# demand rationing in bertrand- edgeworth markets with fixed capacities: an experiment

by Martin Jacobs and Till Requate

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# Demand Rationing in Bertrand-Edgeworth Markets with Fixed Capacities: An Experiment

*Martin Jacobs<sup>\*</sup> and Till Requate<sup>§</sup>*

**Abstract.** This study is the first to investigate the effect of demand rationing in experimental Bertrand-Edgeworth markets with fixed exogenous capacities. It is found that prices and profits are significantly higher under proportional than under efficient demand rationing. Moreover, the amount of capacity available to each firm is varied. In accordance with earlier studies, prices and profits are significantly higher when capacities are lower. Those effects accord qualitatively with the Nash equilibrium predictions of the corresponding stage games. However, the Nash equilibrium concept does poorly at quantitative predictions. Prices are significantly higher than the Nash prediction in all treatments, irrespective of whether the Nash equilibrium is in mixed or in pure strategies. Profits are higher than the Nash prediction with high capacities, but may converge to the equilibrium prediction in the long run with low capacities. The data of individual price choices feature dynamic patterns that can potentially be explained by both Edgeworth price cycles and imitation of the price set by the competitor.

*JEL classification:* C72, C90, D43, L13.

*Key words:* Bertrand-Edgeworth, demand rationing, Edgeworth cycles, oligopoly, laboratory experiment.

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## 1. Introduction

Edgeworth's (1925) enhancements of Bertrand's (1883) price competition model tremendously complicate its game-theoretic solution. Specifically, the Nash equilibrium becomes contingent on the rule according to which demand is rationed. Compared to other market institutions, few experiments have so far been conducted to investigate price oligopoly with capacity constraints.

We follow the seminal experiment by Kruse et al. (1994) in that we consider price competition in markets with fixed, exogenously given capacity constraints. Our study, to the best of our knowledge, is the first to investigate the effect of demand rationing in such a setting. The two demand rationing rules most prominent in the literature are considered: proportional and efficient rationing. Moreover, we vary the amount of capacity available to each firm in the market.

We find that the seemingly minor change in demand rationing entails a significant effect. Prices and profits are higher with proportional than with efficient rationing. Furthermore, in accordance with earlier findings, lower capacities yield higher prices and profits. These effects are predicted qualitatively by the Nash equilibria for the single treatments. However, our data do not fit the Nash predictions quantitatively. This holds even for the treatment with low capacities and efficient rationing where the Nash equilibrium is in pure strategies. The empirical mean price is significantly higher than the expected mean price in Nash equilibrium in all treatments. Profits are significantly higher than the Nash predictions in the treatments with high capacities, but approach Nash predictions in the long run in the treatments with low capacities. Alternative, off-equilibrium concepts that may rationalize the empirical data are Edgeworth price cycles brought about by myopic best response pricing and imitation of the price set by the competitor in the past. Both of these concepts are able to partially explain empirical price choices; Edgeworth's myopic best response theory does somewhat better. A simultaneous test of the two alternative concepts is impeded by excessive collinearity. Therefore, a definite answer cannot be given to the question which of the two alternative concepts is the true driver of the dynamic pricing patterns in the data.

The remainder of this study is structured as follows. Sections 2 and 3 briefly review the theory and existing experimental evidence concerning Bertrand-Edgeworth markets with fixed capacities. Section 4 describes the market setting of our experiment, and section 5 presents the associated outcomes for prices and profits in benchmark situations. The

experimental procedures are explained in section 6. Section 7 states our hypotheses. Our experimental results are presented in section 8. Section 9 concludes.

## 2. Theoretical background

Bertrand's (1883) model of simultaneous price oligopoly yields the odd prediction that there will be perfect competition with marginal cost pricing and zero profits as soon as there are at least two firms in the market. That results from the assumption that each firm can produce any quantity at constant marginal costs. Edgeworth (1925) abandoned this assumption in order to receive a model with more realistic results. He assumed instead that firms' production capacities are constrained. The capacity constraints may be either exogenously given or endogenously imposed by introducing increasing marginal production costs, such that further production becomes unprofitable from some point.

While Edgeworth's modifications make the model more realistic, they also make it considerably more complicated. There is in general no Nash equilibrium in pure strategies. The existence of Nash equilibrium in mixed strategies in the Bertrand-Edgeworth setting has been proven only in the 1980s (Dixon, 1984; Dasgupta and Maskin, 1986; Maskin, 1986).

Equilibrium depends on how demand is rationed if firms choose different prices. Two assumptions about demand rationing are prominent in the literature: proportional and efficient rationing. Proportional rationing means that customers are served in random order, such that a fraction of randomly ordered customers, if any, is left for firms with higher prices. In contrast, under efficient rationing those customers with the highest willingness to pay are served first. Customers with a lower willingness to pay, if any, are then left for firms with higher prices. The quantity a firm is able to sell at a higher price will therefore be higher under proportional than under efficient rationing. Figure 1 illustrates the rationing rules graphically for a duopoly with linear total demand  $D(p) = 1000 - p$ . The bold line represents residual demand for firm 2 at varying prices  $p_2$ , given that firm 1 is willing to sell quantity  $q_1 = 300$  at price  $p_1 = 200$ . Whereas under proportional rationing the demand curve is rotated around the reservation price to obtain residual demand, it is shifted leftwards in parallel under efficient rationing.

- Figure 1 about here -

For several special cases of Bertrand-Edgeworth markets with exogenous capacity constraints the mixed-strategy Nash equilibrium has been characterized. Beckmann (1967) dealt with the symmetric duopoly with linear total demand under proportional demand rationing. The equilibrium for the otherwise same situation under efficient demand rationing

was described by Levitan and Shubik (1972). Vives (1986) generalized the analysis under efficient rationing to markets with more than two firms and non-linear demand (retaining the symmetry assumption). Osborne and Pitchik (1986) provided a generalization for the duopoly under efficient rationing to firms with asymmetric capacities and non-linear demand. Beckmann's results were corrected and generalized by Allen and Hellwig (1993) who provided a complete characterization of the equilibrium pricing strategies in the duopoly with proportional rationing and established uniqueness of equilibrium under weak conditions. More recently, Hirata (2009) and De Francesco and Salvadori (2010) analyzed the triopoly under efficient demand rationing. De Francesco and Salvadori (2013) established uniqueness of the equilibrium characterized by Vives and extended the analysis to some asymmetric capacity combinations.<sup>1</sup>

### **3. Related experiments**

Compared to the multitude of market experiments concerned with the standard models by Cournot and Bertrand, experiments in the more complex Bertrand-Edgeworth setting are still scarce. The first experimental investigation of Bertrand-Edgeworth markets with exogenous capacities is the seminal study by Kruse et al. (1994). They varied capacities and the amount of information firms have about cost and demand in symmetric oligopolies with four firms. An isoelastic demand function and proportional demand rationing were employed. The different capacity conditions gave rise to different mixed-strategy pricing Nash equilibria. Kruse et al. found that higher capacities led to lower prices while the variation of information did not entail a significant effect on prices. Subjects did not price according to the Nash equilibrium, but on average set higher prices. The dynamics of individual price choices can be explained by a partial adjustment to the myopic best response to the other firms' prices in the last period (as proposed by Edgeworth's price cycle theory).

Fonseca and Normann (2013) also found a negative effect of capacities on prices in a similar setting. Moreover, they conducted both duopoly and triopoly treatments and observed that prices in the latter are lower when total capacity in the market is held constant. Again, prices exceeded the equilibrium predictions. On the whole, Edgeworth's theory of myopic price adjustment rationalized the data better than the Nash equilibrium concept. In another study, Fonseca and Normann (2008) also considered asymmetric capacity distributions.

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<sup>1</sup> The analysis of a special case of the duopoly with linear demand and asymmetric capacities can also be found in the appendix of Levitan and Shubik (1972).

Asymmetry had a clear price-declining effect and even resulted in average prices below the Nash equilibrium prediction.

The finding that behavior according to the Nash equilibrium is too demanding in Bertrand-Edgeworth settings is corroborated by Heymann et al. (2014). They found that the pricing dynamics in their experiment can be explained by a simple heuristic: A subject raises her price by a certain increment as long as she does not fully utilize her capacity. In contrast, she lowers her price by that increment when she cannot sell up to her capacity.

This study is to our knowledge the first to investigate the effect of demand rationing in Bertrand-Edgeworth markets with exogenous capacities.<sup>2</sup> However, demand rationing has been varied in related experiments of price competition with convex costs (Kruse, 1993; Jacobs and Requate, 2016) and two-stage games of capacity-setting and subsequent pricing à la Kreps and Scheinkman (1983) (Lepore and Shafran, 2013; Jacobs, 2016). All those studies have found that, independently of the direction of the predicted effect, proportional demand rationing yields higher prices than efficient demand rationing.

#### 4. The market setting

We consider experimental duopoly markets where the two symmetric supplying firms offer a single homogenous good and compete in prices. Competition takes place repeatedly over several periods. In each period, firms are confronted with the linear market demand function  $D(p) = 1000 - p$ . Each firm can supply at most  $k$  units in each period; market capacity thus equals  $2k$ . Capacity per firm is one of the two treatment variables. In the high-cap treatments  $k = 500$  while in the low-cap treatments  $k = 300$ . For simplicity, production costs are set to zero, but the setting can easily be generalized to constant marginal costs up to the capacity constraint by appropriate rescaling. Any unsold capacity forfeits and cannot be transferred to the next period. For example, the setting may resemble competition between two retail firms which sell a perishable and are bound by long-term wholesale contracts, such that both quantity and unit price of their purchases are given and the accompanying costs are sunk.

The quantity a firm sells in a given period can be at most its capacity. Furthermore, the sales quantity  $q_i$  of firm  $i$  depends on the prices  $p_i$  and  $p_j$  the two firms choose and on the effective

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<sup>2</sup> Buchheit and Feltovich (2011) conducted a Bertrand-Edgeworth market experiment with exogenous capacity constraints and employed six different demand rationing schemes. However, demand rationing is not a treatment variable in their design. Rather, they investigated the effect of sunk fixed costs. In all their treatments, before each round one of the six rationing schemes is randomly determined to be effective in the next round. While Buchheit and Feltovich inform their subjects in the instructions which six rationing schemes can occur, subjects do not know the effective rationing scheme in the current round when they make their price choice.

demand rationing scheme, the second treatment variable. Under efficient demand rationing, it is given by

$$q_i^{eff}(p_i, p_j, k) = \begin{cases} \max\{0, \min\{1000 - p_i, k\}\} & p_i < p_j \\ \max\{0, \min\{500 - p_i/2, k\}\} & p_i = p_j \\ \max\{0, \min\{1000 - k - p_i, k\}\} & p_i > p_j \end{cases}$$

In case  $i$  has chosen a higher price than  $j$ , a different sales quantity for  $i$  results under proportional demand rationing:

$$q_i^{prop}(p_i, p_j, k) = \begin{cases} \max\{0, \min\{1000 - p_i, k\}\} & p_i < p_j \\ \max\{0, \min\{500 - p_i/2, k\}\} & p_i = p_j \\ \max\left\{0, \min\left\{\left(1000 - p_i\right)\left(1 - \frac{k}{1000 - p_j}\right), k\right\}\right\} & p_i > p_j \end{cases}$$

As there are no costs, firm  $i$ 's profit in a given period is equal to its revenue:  $\Pi_i(p_i, p_j, k) = p_i q_i(p_i, p_j, k)$ .

## 5. Benchmark outcomes

As benchmark cases we calculate the market outcome in our model under full competition as well as under full collusion. While those outcomes depend on the market capacity, they do not depend on the effective rationing scheme since both firms charge the same price in the benchmark settings.

The outcome under full competition is described graphically by the intersection of market supply and market demand in Figure 2. If there is enough capacity in the market to satisfy all demand, the competitive price is zero; otherwise the competitive price is given by the price at which market demand equals market capacity. Formally,  $p^{comp} = \max\{0, 1000 - 2k\}$ . The corresponding individual sales quantities and profits are  $q_i^{comp} = \min\{500, k\}$  and  $\Pi_i^{comp} = \max\{0, k(1000 - 2k)\}$ .

- Figure 2 about here -

Under full collusion, in case the market capacity is at least 500, both firms charge a price of 500 maximizing joint profit. Even higher prices occur if market capacity is smaller,  $p^{coll} = \max\{500, 1000 - 2k\}$ . Quantities and profits under full collusion are  $q_i^{coll} = \min\{250, k\}$

$$\text{and } \Pi_i^{coll} = \begin{cases} 125000 & k \geq 250 \\ k(1000 - 2k) & k < 250 \end{cases}$$



Another benchmark is the Nash equilibrium outcome of the stage game.<sup>3</sup> For the relatively simple case of duopoly with symmetric capacities we consider, for both proportional and efficient rationing Nash equilibrium has been characterized and its uniqueness has been proven. The analysis of the case with efficient demand rationing is due to Levitan and Shubik (1972).<sup>4</sup> For  $k \leq 1000/3$ , which is fulfilled in our low-cap condition, the Nash equilibrium is in pure strategies with  $p^{NE} = 1000 - 2k$  and  $\Pi_i^{NE} = k(1000 - 2k)$ . For  $k \geq 1000$ , price and profit in Nash equilibrium are zero. In the remaining interval,  $1000/3 < k < 1000$ , there is a Nash equilibrium in mixed strategies. For our high-cap treatment condition with  $k = 500$ , the cumulative distribution function (cdf) describing the mixed-strategy pricing Nash equilibrium is given by

$$\Phi^{high,eff}(p) = \begin{cases} 0 & p < 125 \\ \frac{500p - 62500}{p^2} & 125 \leq p < 250. \\ 1 & 250 \leq p \end{cases}$$

Under proportional demand rationing, we have  $p^{NE} = 1000 - 2k$  and  $\Pi_i^{NE} = k(1000 - 2k)$  for  $k \leq 250$  and again zero price and profit for  $k \geq 1000$ . Nash equilibrium is in mixed strategies in the capacity range  $250 < k < 1000$ , that is, in both our high-cap and in our low-cap condition. From the more general analysis by Allen and Hellwig (1993) it emerges that the cdf in our market setting is described by the integral equation

$$\Phi^{prop}(p) = \begin{cases} 0 & p < p_0 \\ 1 - p_0 k \sqrt{\frac{1000 - p}{2k - 1000 + p}} \int_p^{500} \frac{1000 - 2\pi}{\pi^2 (1000 - \pi)^{1.5} \sqrt{2k - 1000 + \pi}} d\pi & p_0 \leq p < 500, \\ 1 & 500 \leq p \end{cases}$$

where  $p_0$  is determined by the condition  $\Phi^{prop}(p_0) = 0$ . For the case  $k = 500$ , a closed-form solution is provided by Beckmann (1967),<sup>5</sup>

<sup>3</sup> In principle, since interaction takes place repeatedly over several periods, one may also expect supgame effects that lead to a more collusive conduct than predicted by the Nash equilibrium of the stage game. However, our experiment lasted for a given number of periods that was disclosed to the subjects *ex ante*. Thus, backward induction applies and the predictions for the stage game remain valid. Moreover, Kruse (1993) found that the stage-game Nash equilibrium can be a good predictor of behavior in a Bertrand-Edgeworth market experiment even if subjects are not informed about the number of periods to be played.

<sup>4</sup> Levitan and Shubik as well as Beckmann below dealt with the normalized demand function  $D(p) = 1 - p$ . The results presented here have been adapted to fit the demand function in our experiment.

<sup>5</sup> Beckmann considered the case of symmetric duopoly with linear market demand and provided closed-form solutions for any capacity. Yet, since he erroneously assumed  $(1000 - k)$  instead of 500 to be the upper limit of the integral, his results are invalid except for the case  $k = 500$ .

$$\Phi^{high,prop}(p) = \begin{cases} 0 & p < p_0 \\ 1 - \frac{p_0}{1000} \left( 1 - \frac{4}{3} \sqrt{\frac{1000-p}{p}} + \frac{1}{3} \left( \frac{1000-p}{p} \right)^2 \right) & p_0 \leq p < 500, \\ 1 & 500 \leq p \end{cases}$$

with  $p_0 \approx 171.773$ . For  $k = 300$ , we calculated the closed-form solution

$$\Phi^{low,prop}(p) = \begin{cases} 0 & p < p_0 \\ 1 - p_0 \frac{3}{10000} \sqrt{\frac{1000-p}{p-400}} \left[ \frac{-\sqrt{5}}{0.5^{1.5} 12} \left( \sqrt{0.5} + 2.25 \arctan\left(\frac{1}{\sqrt{8}}\right) \right) \right. \\ \left. + \frac{5^{3.5}}{3p \left(1 - \frac{p}{1000}\right)^{1.5}} \sqrt{\frac{1000-p}{5p-2000}} \left\{ 4 \sqrt{1 - \frac{p}{1000}} \left( \frac{7}{200000} p^2 - \frac{29}{1000} p + 6 \right) \right. \right. \\ \left. \left. - \frac{9}{1000} \left( \frac{p^2}{1000} - p \right) \sqrt{\frac{p}{100}} - 4 \arctan\left( \frac{4000 - 7p}{2\sqrt{2000 - 2p}\sqrt{5p - 2000}} \right) \right\} \right] & p_0 \leq p < 500 \\ 1 & 500 \leq p \end{cases},$$

with  $p_0 \approx 404.644$ .

- Figure 3 about here -

- Table 1 about here -

Figure 3 shows a plot of the Nash equilibrium cdf's for all four treatments. Given the cdf's, we can calculate the expected price and profit in Nash equilibrium. Table 1 summarizes the benchmark prices and profits for all treatments.<sup>6</sup>

## 6. Experimental procedures

Combining two capacity conditions with two rationing schemes, we obtained four different treatments. The treatments are named according to their capacity condition ("high" or "low") followed by their effective rationing scheme ("eff" for efficient or "prop" for proportional). Two sessions of each treatment were conducted at the economics experimental lab at Kiel University during April and May 2015. Due to no-shows of subjects, the number of markets

<sup>6</sup> Calculating expected prices and profits in the mixed-strategy Nash equilibria, we took into account that in our actual experimental setting price is not a continuous choice variable, but only integer prices were permissible. In order to discretize the setting, we took as probability that an integer price  $p^*$  is chosen the value of the cdf at this price minus the value of the cdf at  $(p^* - 1)$ , i.e.  $prob(p^*) = \Phi(p^*) - \Phi(p^* - 1)$ . The stated expected prices and profits as well as the accompanying standard deviations therefore differ slightly from the results with continuous pricing.

per treatment varies between 10 and 14. 96 subjects from all fields of study participated in the experiment;<sup>7</sup> each subject took part only once.

At the beginning of each session, subjects were randomly allocated to computer terminals in the lab. They received printed instructions that provided full information about the market setting, but were not told any of the benchmark outcomes mentioned in the last section.<sup>8</sup> After reading, the key features from the instructions were repeated by the experimenter in a short presentation. Then the actual experiment started which was computerized using the z-tree software (Fischbacher, 2007). Subjects first played three unpaid trial rounds, then were re-matched and played 20 paid rounds in fixed groups. The number of rounds to be played was common knowledge. In each round, each subject had to decide on her sales price. Integers from 0 to 1000 were admissible prices. Buyers were simulated by the computer. Throughout the experiment, subjects could use a profit calculator implemented in the software. The profit calculator returned a subject's sales quantity and profit when two hypothetical sales prices were entered. After each round, subjects were informed about the prices chosen in that round and about their resulting own sales quantity and profit. In the end, subjects were paid the sum of their earnings from all paid rounds at a predefined exchange rate.<sup>9</sup> Payments were made in private. An average session took about 80 minutes, including time for instructions and payment. The average payment per subject amounted to 16.1 Euro.

## 7. Hypotheses

Taking into account the benchmark outcomes from section 5 and the results of the related experiments mentioned in section 3, we set up hypotheses about the experimental outcome. The first two hypotheses concern the effects of the two treatment variables.

**Hypothesis 1:** Prices and profits will be higher in the low-cap than in the high-cap condition.

**Hypothesis 2:** Prices and profits will be higher with proportional than with efficient demand rationing.

The hypotheses follow from the Nash equilibrium predictions stated in Table 1. Moreover, evidence from the experiments by Kruse et al. (1994) and Fonseca and Normann (2013) supports Hypothesis 1. The effect of demand rationing has not yet been investigated experimentally in the market setting we employ, but support for Hypothesis 2 stems from the

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<sup>7</sup> The hroot software package (Bock et al., 2014) was used for subject recruitment.

<sup>8</sup> Instructions for a sample treatment are included in Appendix A.

<sup>9</sup> The exchange rate was 1 Euro per 120,000 experimental currency units (ECU) in the high-cap treatments and 1 Euro per 150,000 ECU in the low-cap treatments.

experiments by Kruse (1993) and Jacobs and Requate (2016) which consider the closely related setting of price competition with convex production costs.

While the first two hypotheses are only qualitative, the Nash equilibrium predictions allow us to set up also quantitative hypotheses. Assuming behavior in accordance with Nash equilibrium, we formulate the next two hypotheses:

**Hypothesis 3:** The distribution of individual price choices in each treatment will follow the probability distribution predicted by the respective Nash equilibrium.

**Hypothesis 4:** The mean price and profit in each treatment will equal the expected mean price and profit in the respective Nash equilibrium.

As it is quite demanding to expect that the experimental data will fit the Nash prediction even in their distributions, we take Hypothesis 4 as an alternative to test a somewhat weaker accordance of the data with Nash equilibrium theory. However, the studies by Kruse et al. (1994) and Fonseca and Normann (2013) support neither of the two hypotheses. They found that pricing within the same market across periods is not independent as the Nash predictions purport. Instead, they observed dynamic pricing patterns that can be explained by Edgeworth's off-equilibrium theory of price cycles which come about when subjects myopically optimize taking past prices as fixed. Hence, our next hypothesis:

**Hypothesis 5:** Individual price choices will follow a myopic best response rationale as purported by Edgeworth's price cycling theory.

Yet, as investigated in Jacobs and Requate (2016) for Bertrand-Edgeworth markets with convex costs, still another possible behavioral pattern is that subjects just imitate past prices of their competitor:

**Hypothesis 6:** Individual price choices will be based on imitation of the other firm's price observed in the last round.

We thus have two opposing hypotheses of off-equilibrium behavior that provide alternatives to the Nash predictions.

## 8. Results

We divide the presentation of our results into two parts. Hypotheses 1 and 2 are concerned with how the market outcome is affected by variations of the treatment variables in the experiment. We therefore use data aggregated on the market level to evaluate those hypotheses. Hypotheses 3 to 6, in contrast, pertain to individual price choices and the resulting individual profits. Consequently, data on the individual level have to be considered for an assessment.

## 8.1 *Market performance*

As measures to assess market performance, we use the market price and the average profit per firm in a market. The market price is the quantity-weighted average of the prices the single firms in a given market and period set; it equals total revenue divided by total sales quantity in a given market and period. The average profit per firm equals the total profit realized in a given market and period divided by two, the number of firms in each market. Thus, for both price and profit we have one observation per market and period.

- Figure 4 about here -

- Figure 5 about here -

- Table 2 about here -

Aggregating data from different markets in the same treatment, Figures 4 and 5 illustrate how prices and profits develop throughout the experiment in the different treatments.<sup>10</sup> Table 2 presents the corresponding numbers, combining data from several periods for conciseness. The graphical impression from Figures 4 and 5 supports Hypotheses 1 and 2. Prices and profits are considerably higher in the low-cap than in the high-cap treatments. Whereas the effect of demand rationing is somewhat less sizable, the results appear clear-cut also in this respect. Holding capacity constant and comparing the data points in Figures 4 and 5 pairwise, we find that prices and profits are almost always higher under proportional than under efficient rationing. The only exception to this can be found in the first four periods where in the high-cap condition the market price is somewhat higher under efficient than under proportional rationing.

For a formal statistical analysis, we compare market prices and profits between two treatments within single periods with nonparametric Mann-Whitney tests. For conciseness, we restrict our attention to the data from the second half of the experiment (periods 11 to 20). The implications of our results do not change if all periods are considered. For each treatment variable, two pairwise treatment comparisons apply: To investigate the effect of capacity, data from treatment "high, eff" ("high, prop") are compared to data from "low, eff" ("low, prop"). The effect of the rationing scheme is examined by comparing data from "high, eff" ("low, eff") to data from "high, prop" ("low, prop"). That is, for both prices and profits we conduct 20 significance tests per treatment variable (2 pairwise treatment comparisons multiplied by 10 periods).

- Table 3 about here -

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<sup>10</sup> Figures showing the development of market prices within single markets can be found in Appendix B.

The test results are summarized in Table 3. The results concerning the effect of capacity are as clear-cut as they can be: Every single test result is significant at the one percent level.<sup>11</sup> Both prices and profits are significantly higher in the low-cap than in the high-cap condition. We also find a consistently significant effect of the rationing scheme although the results are somewhat less powerful. Comparing prices in the two high-cap treatments, the effect of rationing becomes significant in period 12 and remains significant thereafter. In the low-cap treatments there is a significant effect in all periods. The same pattern holds for the profit data. Hence, Hypotheses 1 and 2 are strongly supported, and we conclude:

**Result 1:** Prices and profits are significantly higher in the low-cap than in the high-cap condition.

**Result 2:** Prices and profits are significantly higher with proportional than with efficient demand rationing.

## 8.2 *Individual-level data*

As the Nash equilibrium makes predictions about individual pricing, we examine our data on the individual level in order to test the accordance of our subjects' behavior with the Nash equilibrium prediction. Hypothesis 3 purports that the distribution of individual prices in each treatment will follow the respective Nash distribution. Figure 6 for each treatment plots the cdf of empirical price choices against the predicted cdf. It can be seen that the empirical cdf's almost entirely lie to the right of the predicted cdf's. That is, subjects largely choose higher prices than predicted. Kolmogorov-Smirnov tests allow us to clearly reject Hypothesis 3. In each treatment, the maximum difference between the values of the empirical and the predicted cdf is at least 0.43. The accompanying probability that the empirical and the predicted price distribution are identical is smaller than  $10^{-80}$  in each case. If one assumes that subjects need some incentivized trials to learn optimal pricing behavior and hence considers only the price choices from period 11 onwards for the empirical cdf's, the test results remain strongly significant.

**Result 3:** The distribution of individual price choices does not follow the probability distribution predicted by the respective Nash equilibrium.

- Figure 6 about here -

However, it still can be that some qualities of the Nash equilibrium predictions are contained in the empirical data. We first test for each treatment whether the empirical mean price equals the predicted mean in Nash equilibrium. As mentioned in the above paragraph,

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<sup>11</sup> All  $p$ -values refer to two-tailed tests.

from Figure 6 it appears that higher prices than predicted are chosen. That impression is confirmed by the test results. The null hypothesis of equal means can be rejected at the one percent level for each treatment ( $t$ -tests). This still holds if only price choices from periods 11 to 20 are included. The test results are visualized in Figure 7. Figure 7 for each treatment shows the 99 percent confidence interval of the empirical mean price (from all periods) together with the Nash equilibrium prediction. The result that prices are higher than the Nash equilibrium prediction is in accordance with the findings in Kruse et al. (1994) and in Fonseca and Normann (2013). Moreover, it can be seen that the difference between the empirical mean price and its Nash prediction is larger in the high-cap treatments, which confirms another observation by Fonseca and Normann.

- Figure 7 about here -

At first sight, it appears especially noteworthy that pricing behavior significantly deviates from the Nash prediction even in the "low, eff" treatment where the Nash equilibrium is in pure strategies and pricing according to that equilibrium promises fairly high profits. Yet, while the chosen prices are significantly higher than the Nash equilibrium prediction, subjects may have little incentive to price exactly according to the Nash equilibrium when the payoff function is flat. This pertains especially to our low-cap treatments where the (expected) profits in all benchmark outcomes are close to each other (recall Table 1). Therefore, we also compare realized profits to their equilibrium predictions. For the two high-cap treatments, the test results are clear. Profits are significantly higher than the Nash prediction, no matter whether one considers all periods or only periods 11 to 20 (all  $p$ 's  $< 0.01$ ,  $t$ -tests). The results for the low-cap treatments are somewhat ambiguous. In the "low, eff" treatment, profits are significantly *lower* than predicted by the Nash equilibrium if data from all periods are included ( $p < 0.01$ ). However, if one includes only the data from periods 11 to 20, profits are not significantly different from the Nash equilibrium profit ( $p = 0.45$ ). It may be that learning takes place in the first periods of the experiment and subjects adjust their pricing behavior towards the Nash equilibrium, such that profits then converge towards the equilibrium level. Due to the flatness of the payoff function, this can lead to a situation where prices are still significantly different from the benchmark, but profits are not. In the "low, prop" treatment, profits are higher than the Nash prediction. The difference is weakly significant ( $p < 0.1$ ) for both periods 1 to 20 and periods 11 to 20.

These results indicate that we cannot generally exclude *ex ante* that there are dynamic patterns which lead to long-run convergence to Nash equilibrium prices and profits. In order

to investigate such possible dynamics, we set up two regressions. The first regression equation has the form

$$p_{i,t} = \sum_{j=1}^4 \left( \beta_j TD_j \frac{1}{t} + \gamma_j TD_j \right) + \varepsilon_{i,t}.$$

The endogenous variable  $p_{i,t}$  is the individual price chosen by subject  $i$  in period  $t$ .  $TD_j$ ,  $j = 1, \dots, 4$ , is a set of treatment dummy variables. In the first summand in the brackets on the right hand side of the equation, the treatment dummies are interacted with the inverse of the period,  $1/t$ . The  $\beta_j$  coefficients hence account for treatment-specific time trends. The  $\gamma_j$  coefficients measure the long-run price convergence level in treatment  $j$ . An analogous regression equation is set up for profits. In the second equation the endogenous variable is the profit subject  $i$  realizes in period  $t$ ; the right hand side of the equation remains unchanged.

- Table 4 about here -

GLS estimations are performed to account for possible autocorrelation and heteroskedasticity of prices set by the same subject in different periods. The regression results are presented in Table 4.<sup>12</sup> The  $\beta$  coefficient estimates in the first regression indicate that there is a significant downward time trend for prices in three of the four treatments. The price decline over time is most pronounced in the "high, eff" treatment. In the "high, prop" treatment there is no observable time trend in prices. The picture is more diverse in the second regression concerning the profit data. For the two high-cap treatments, we find a downward time trend as for prices, but the effect is not significant. In the two low-cap treatments, in contrast, profits increase over time. The time trend is significant only in the treatment with efficient rationing.

The estimates of the  $\gamma$  coefficients allow us to test whether prices and profits converge to their Nash equilibrium levels in the long run ( $t$ -tests). We find that the price convergence levels are significantly higher than the Nash equilibrium predictions in all treatments. Whereas the result is significant at the one percent level in the three other treatments, we observe only weak significance at the ten percent level in the "low, eff" treatment. One can speculate that this is due to the fact that the Nash equilibrium for this treatment is in pure strategies and the equilibrium price of 400 has some attraction. Indeed, the exact equilibrium

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<sup>12</sup> We also ran an extended version of the two regressions which included individual characteristics of the subject (age, gender, and field of study) as exogenous variables. While these characteristics have no significant effect on price choices, there are two significant, albeit small, effects on realized profits: Females earn about 4,500 ECU less per round than males ( $p < 0.01$ ,  $t$ -test), and subjects who study economics or a related subject earn about 3,600 ECU more per round than subjects with other fields of study ( $p < 0.05$ ).



price accounts for 34 percent of all price choices in the treatment. In periods 11 to 20, the share is even higher; we then observe 44 percent exact Nash equilibrium price choices.

The profit convergence levels are significantly higher than the Nash equilibrium predictions at the one percent level in the two high-cap treatments. In contrast, we cannot reject equality of the convergence levels to equilibrium profits in the low-cap treatments ( $p = 0.75$  in "low, eff",  $p = 0.26$  in "low, prop"). Moreover, for the "low, prop" treatment we can neither reject equality to the benchmark profit under full collusion ( $p = 0.44$ ).<sup>13</sup>

On the whole, we have found very limited support for Hypothesis 4. Prices are considerably higher than the Nash equilibrium predictions and do not converge to equilibrium levels either. As to profits, these conclusions hold only for the high-cap treatments. In the treatments with low capacities, however, profits are close to their equilibrium predictions in the long run.

**Result 4:** With high capacities, the mean price and profit are higher than the expected mean price and profit in the respective Nash equilibrium. With low capacities, the mean price is higher than the expected mean price in the respective Nash equilibrium, but the mean profit converges to a level close to the expected Nash equilibrium profit.

Having found that the Nash equilibrium concept has little explaining power for our empirical data, we turn to the alternative off-equilibrium concepts formulated in Hypotheses 5 and 6. In order to investigate the presence of myopic best response pricing or price imitation in our data, we estimate the regression equation

$$p_{i,t} - p_{i,t-1} = \alpha + \beta(BR_i(p_{j,t-1}) - p_{i,t-1}) + \gamma(p_{j,t-1} - p_{i,t-1}) + \varepsilon_{i,t}.$$

The endogenous variable  $p_{i,t} - p_{i,t-1}$  is the change of subject  $i$ 's price choice compared to her choice in the last period.  $BR_i(p_{j,t-1})$  is the best response price of subject  $i$  to the price set by subject  $j$ , the other subject in the same market, in the last period. The  $\beta$  coefficient thus measures the share of adaptation to the best response price. In case each subject in each period sets the price which is the best response to the price she has observed in the last period, i.e.  $p_{i,t} = BR_i(p_{j,t-1})$ , we have perfect myopic best response pricing as Edgeworth's theory suggests. The  $\beta$  then takes a value of one. Imitation is included as an additional explaining factor. The  $\gamma$  coefficient measures the share by which subject  $i$  adapts her price choice in period  $t$  to the price chosen by subject  $j$  in period  $t - 1$ . The  $\gamma$  takes a value of one if each subject in each period mimics the price the other subject in the market has set one period before.

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<sup>13</sup> In the three other treatments, the profit convergence levels are smaller than the collusive benchmark profit at least at the five percent level. Price convergence levels are significantly smaller than the collusive benchmark price at the one percent level in all four treatments.

The regression model originates from Kruse et al. (1994), but has been enlarged to consider also imitation, such that Hypotheses 5 and 6 can be tested against each other. A similar approach is pursued in Jacobs and Requate (2016). The results from those studies indicate that one should not expect that one of the two factors completely explains empirical pricing patterns. Coefficient estimates have not been close to one for either factor. Instead, it has been observed that, depending on the exact experimental setting, only one of the factors or both factors can have a significant impact, but in any case adjustment has been only partial.<sup>14</sup> That is, we expect that either both the  $\beta$  and the  $\gamma$  coefficient or only one of them will be significant, and that any significant coefficient will be positive, but smaller than one.

Note that our specification includes both adaptation to subject  $j$ 's price and adaptation to the best response price, which, in turn, is a function of subject  $j$ 's price. In all treatments, there is some price interval in which the best response is to underbid subject  $j$ 's price by one ECU, the smallest admissible increment. Collinearity may therefore be a serious issue with this specification. As a consequence, we consider two more regressions with a restricted version of the model in which either of the two factors is dropped, i.e. we let either  $\beta = 0$  or  $\gamma = 0$ .

- Table 5 about here -

Table 5 presents the regression results. Specification (1) allows for both myopic best response and imitation effects. Whereas the  $\beta$  coefficient is significant and lies between zero and one as expected, the  $\gamma$  coefficient is significantly *negative*. This would mean that subjects react to other prices with counter-adaptation, i.e. if a subject observes that the other firm in her market has set a lower price than her, she would raise her price, and vice versa. Such a behavioral pattern does not appear to make any sense. In synopsis with regressions (2) and (3), the results of regression (1) appear as an artifact of overfitting due to excessive collinearity in our data. The bivariate correlation coefficient between the two factors is as high as 0.965; the corresponding variance inflation factors of the two coefficients in regression (1) are around 15, which indicates considerable collinearity. If only one factor is included in the estimation, the respective coefficient is roughly equal to the sum of the two coefficients in regression (1),<sup>15</sup> i.e. the joint effect of the two factors in regression (1) can be reproduced in the more parsimonious specifications (2) and (3). Comparing specifications (2) and (3), the best response pricing rationale supposed in regression (3) explains a higher share of the

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<sup>14</sup> The Figures in Appendix B show price fluctuations in some markets, but a more or less monotone price decline in others. Note that in the "low, eff" treatment Edgeworth's myopic best response rationale does not predict price cycles either since there is a Nash equilibrium in pure strategies.

<sup>15</sup> Letting subscripts denote the regression from which a coefficient estimate originates, we can reject the null hypothesis  $\beta_1 + \gamma_1 = \gamma_2$  ( $p < 0.01$ ,  $t$ -test), but we cannot reject that  $\beta_1 + \gamma_1 = \beta_3$  ( $p = 0.77$ ).

variance in the data than price imitation in regression (2). The difference between models (1) and (3) in the share of explained variance is negligible; thus, specification (3) appears to provide the best fit to the data.<sup>16</sup>

As to our Hypotheses 5 and 6, our conclusions have to remain reluctant. After all, the pricing patterns in our data can be explained by either myopic best response behavior or imitation (or a mixture of both). Although Edgeworth's myopic best response rationale fits the data better if only one explaining factor is considered, it does not follow that an imitation effect is absent since the two factors are highly collinear. In regressions (2) and (3), an effect caused by the omitted factor can add to the coefficient of the contained factor. Model (1) which considers both myopic best response and imitation simultaneously suffers from overfitting, such that the effects of the two factors cannot be disentangled.

**Results 5 and 6:** The data contain dynamic pricing patterns that can be explained by both myopic best response pricing and imitation. The effects of the two explaining factors cannot be disentangled due to the high collinearity between the factors. Confining the analysis to one factor, myopic best response pricing explains the data better than imitation.

Nevertheless, the comparison of the results from regressions (2) and (3) lets us conjecture that Edgeworthian myopic best response pricing is the prevailing factor.<sup>17</sup> This is corroborated by the result by Jacobs and Requate (2016) that imitation becomes important only in triopolies where finding the best response is more complex whereas best response pricing is the prime driving factor in duopolies.

## 9. Conclusion

This study adds to the so far quite limited evidence of pricing behavior in experimental Bertrand-Edgeworth markets. It is the first to investigate the effect of demand rationing in Bertrand-Edgeworth markets with fixed exogenous capacities. The second treatment variable besides the demand rationing scheme is the amount of exogenous capacity per firm.

We find that both treatment variables entail significant and sizable effects on prices and profits. Prices and profits are higher with proportional than with efficient demand rationing and with low than with high capacities. This accords qualitatively with the Nash equilibrium

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<sup>16</sup> We could not find any treatment-specific effects. Substituting the respective exogenous variable in regressions (2) and (3) by interactions of this variable with dummy variables for all treatments does not improve the fit of the regressions. Neither can the hypothesis be rejected that all four treatment-specific coefficients are equal ( $p = 0.22$  and  $p = 0.67$ , respectively,  $F$ -tests).

<sup>17</sup> If one applies the procedure suggested by Kruskal (1987) and Lipovetsky and Conklin (2001) to attribute shares of explained variance to the factors, myopic best response pricing accounts for 15 percentage points and price imitation for 12 percentage points of the total  $R^2$  of 0.27. The procedure is analogous to the calculation of the Shapley value in cooperative games.

predictions. However, the quantitative Nash predictions are not reflected by the data. Mean prices are significantly higher than the equilibrium level. This holds even when the Nash equilibrium predicts pure-strategy pricing. The gap between predicted and observed prices is more pronounced with high capacities. As to profits, empirical profits significantly exceed the equilibrium level with high capacities, but converge to the equilibrium level with low capacities.

Two alternatives to the Nash equilibrium concept are considered: Edgeworth's theory of myopic best response pricing that leads to price cycles and simple imitation of the competitor's price in the last period. Considered separately, each alternative is able to explain individual pricing dynamics partially, where Edgeworth's concept does somewhat better than simple imitation. A simultaneous analysis of the two alternative off-equilibrium concepts is inhibited by the tremendous collinearity between them. Therefore, we cannot say whether myopic best response behavior or imitation is the underlying driver of individual pricing. This shortcoming suggests that further research is needed in order to disentangle the different effects. Although collinearity between myopic best response pricing and price imitation is to some degree an inherent feature of Bertrand-Edgeworth markets since for some prices it is the best response to just underbid them, a suitable parameterization might trigger more price choices outside the price range where underbidding is the myopic best response and thus allow for a clear discrimination between Edgeworth cycles and imitation.

## Appendix A

English translation of the written instructions in treatment "high, eff".

Welcome to the Laboratory for Economic Experiments at Kiel University.

You are about to participate in an economic experiment where you will have to make some decisions. You can also earn some money. The amount of money will depend on both your own decisions and the decisions of the other participants in the experiment.

Please read these instructions carefully. If after reading there are any questions, please raise your hand. An experimenter will approach you and answer your questions in private. Please do not communicate with other participants during the experiment.

All participants receive the same instructions.

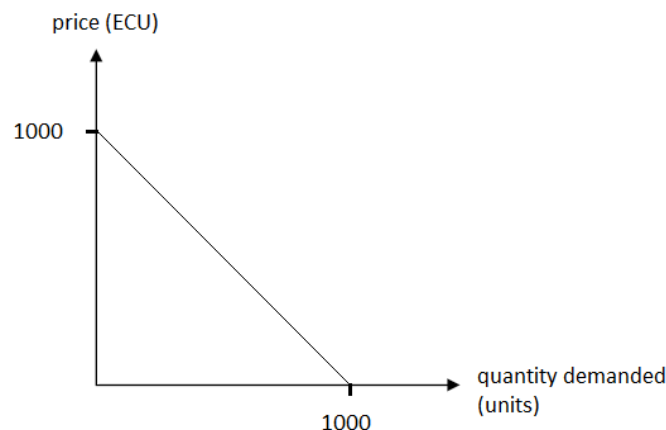
In this experiment you represent a **firm** which sells a single good. On a market you **compete with one other firm** being represented by one of the other participants. Both firms sell the same good.

The experiment consists of **20 periods**. At the beginning of the experiment, the participants will be randomly matched into groups of two. The other member of your group will be your competitor. The grouping will be fixed throughout the experiment.

In each period you and the other firm must simultaneously and independently **decide on the price** at which to offer the good on the market. All **integers from 0 up to 1000** are **admissible** prices.

Throughout the experiment, all money amounts will be accounted in **Experimental Currency Units (ECU)**. Your total profit will be paid off to you after the experiment at an **exchange rate of 120,000 ECU/Euro**, i.e. for each 120,000 ECU earned in the experiment you will receive 1 Euro.

The demand side of the market will be simulated by the computer and will be identical in all periods. There are many different potential customers with different willingnesses to pay for the good. A sale will come about if the offer price is no higher than a customer's maximum willingness to pay. At a price of 0 ECU there will be a total demand for 1000 units on the market. With a price increase by 1 ECU, demand is reduced by 1 unit. At a price of 1000 ECU no one will be ready to buy the good. Here is a graphical representation of this relationship:



Customers will first try to purchase the good from the firm offering at a lower price. Those customers with the highest willingness to pay will be served first. In case one firm does not meet its whole demand, the remaining demand will be left for the other firm that offers the good at a higher price. If both firms choose the same price, demand will be divided equally among them.

Each firm can sell up to 500 units of the good in each period. Firms do not incur any costs for those units. In case a firm cannot sell all 500 units in a given period, the units that could not be sold will forfeit and cannot be transferred to the next period.

Your **profit** (in ECU) per period equals the offer **price chosen by you multiplied by your sales quantity**. Your profit thus depends on the offer prices chosen for this period by you and the other firm.

To get a general idea of your sales quantities and profits resulting from different price combinations, you may use the "**profit calculator**". Simply enter two hypothetical prices (one for each firm) and click on "Calculate". Then your resulting sales quantity and profit will be displayed. You may use the profit calculator throughout the whole experiment.

Moreover, after each period a screen with a "**history**" will inform you about the outcomes so far. For all past periods the "history" shows the prices chosen by the two firms, your resulting sales quantity, your resulting profit per period, and your total profit over all previous periods so far.

The following two screenshots illustrate the use of the profit calculator and the history:

Here you can enter two hypothetical prices and have the results calculated.

Here you can enter and submit your price choice for the current period.

My price	Other price	My sales quantity	My profit
400	399	300.0	40000.0
400	400	300.0	120000.0
399	400	500.0	199500.0
499	400	1.0	-99.0

The results of the profit calculator are displayed here.

Your total profit so far is displayed here.

The results of the last period are displayed here.

Period	My price	Other price	My sales quantity	My profit
-2	0	0	0.0	0.0
-1	0	0	0.0	0.0
0	0	0	0.0	0.0
1	450	354	50.0	22500.0
2	554	350	0.0	0.0
3	299	444	500.0	149500.0

This is the history showing the outcomes of all past periods. Zeros are displayed for trial periods.

To practice there will be **three trial periods** before the actual periods start. The procedures in the trial periods are the same as in the actual periods described above, but the outcomes of the trial periods will not add to your total profit or payoff. After the trial periods, the participants will be randomly re-matched into new groups. The

new groups will stay fixed throughout all actual periods of the experiment. The profit calculator will be available to you during both trial and actual periods. The history, however, will not be displayed after trial periods and will only contain the data of the actual periods.

Your **total profit** is the **sum of your profits in the single periods** of the experiment (not including the trial periods).

Your total profit will be **paid to you** after the experiment at the above-mentioned exchange rate. None of the other participants will come to know your profit, and neither will you come to know the profit of any other participant. Furthermore, no participant will come to know with whom he or she interacted during the experiment.

If you click on the "Continue" button on your screen, some statements will appear to check whether all participants have understood the instructions. Please decide whether those statements are right or wrong. As soon as all participants will have evaluated the statements correctly, the first trial period will start.

If there are any questions concerning the experimental procedures, please raise your hand. Enjoy the experiment!

## **Appendix B**

Evolution of market prices in single markets.

- Figure B1 here -

- Figure B2 here -

- Figure B3 here -

- Figure B4 here -

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## Tables and figures

	Full Competition	Full Collusion	Nash Equilibrium
high, eff	$p^{comp} = 0$	$p^{coll} = 500$	$E(p^{NE}) = 153.929$ $\sigma_p = 24.570$
	$\Pi_i^{comp} = 0$	$\Pi_i^{coll} = 125000$	$E(\Pi_i^{NE}) = 62667.833$ $\sigma_\Pi = 9518.569$
high, prop	$p^{comp} = 0$	$p^{coll} = 500$	$E(p^{NE}) = 233.779$ $\sigma_p = 58.378$
	$\Pi_i^{comp} = 0$	$\Pi_i^{coll} = 125000$	$E(\Pi_i^{NE}) = 86017.658$ $\sigma_\Pi = 20128.786$
low, eff	$p^{comp} = 400$	$p^{coll} = 500$	$p^{NE} = 400$
	$\Pi_i^{comp} = 120000$	$\Pi_i^{coll} = 125000$	$\Pi_i^{NE} = 120000$
low, prop	$p^{comp} = 400$	$p^{coll} = 500$	$E(p^{NE}) = 416.933$ $\sigma_p = 14.655$
	$\Pi_i^{comp} = 120000$	$\Pi_i^{coll} = 125000$	$E(\Pi_i^{NE}) = 121433.871$ $\sigma_\Pi = 2223.262$

Table 1: Benchmark outcomes.

<b>Panel A: Market Prices</b>			
<i>periods</i>	<i>1-20</i>	<i>1-10</i>	<i>11-20</i>
high, eff	259.007 (77.847) [232.878]	285.382 (82.528) [277.292]	232.633 (62.864) [211.335]
high, prop	289.050 (65.447) [276.611]	295.967 (68.715) [284.716]	282.133 (61.495) [269.512]
low, eff	419.820 (30.444) [416.076]	421.907 (38.118) [423.053]	417.732 (20.009) [411.957]
low, prop	461.447 (36.394) [462.162]	464.901 (39.530) [467.435]	457.994 (32.798) [453.909]

<b>Panel B: Average Profits per Firm</b>			
<i>periods</i>	<i>1-20</i>	<i>1-10</i>	<i>11-20</i>
high, eff	88,409.2 (16,266.9) [85,039.750]	92,330.6 (16,813.2) [93,119.750]	84,487.8 (14,746.8) [80,836.000]
high, prop	99,673.1 (11,865.9) [98,871.325]	101,233.6 (12,955.0) [101,379.125]	98,112.6 (10,485.6) [95,987.100]
low, eff	117,270.9 (8,461.3) [120,000.000]	114,864.8 (11,255.9) [119,077.000]	119,677.1 (2,337.4) [120,000.000]
low, prop	122,772.4 (3,648.2) [123,680.325]	122,336.0 (4,632.4) [123,648.475]	123,208.7 (2,215.7) [123,708.525]

Standard errors in parentheses. Medians in square brackets.

*Table 2:* Market prices (Panel A) and profits (Panel B): Summary statistics.

<b>Panel A: Market Prices</b>				
	<i>significance test results</i>			
	$p < 0.01$	$0.01 \leq p < 0.05$	$0.05 \leq p < 0.1$	$p \geq 0.1$
<i>effect of capacity</i>				
"high, eff" vs. "low, eff"	10/10	0/10	0/10	0/10
"high, prop" vs. "low, prop"	10/10	0/10	0/10	0/10
<i>effect of the rationing scheme</i>				
"high, eff" vs. "high, prop"	2/10	5/10	2/10	1/10
"low, eff" vs. "low, prop"	6/10	4/10	0/10	0/10

<b>Panel B: Average Profits per Firm</b>				
	<i>significance test results</i>			
	$p < 0.01$	$0.01 \leq p < 0.05$	$0.05 \leq p < 0.1$	$p \geq 0.1$
<i>effect of capacity</i>				
"high, eff" vs. "low, eff"	10/10	0/10	0/10	0/10
"high, prop" vs. "low, prop"	10/10	0/10	0/10	0/10
<i>effect of the rationing scheme</i>				
"high, eff" vs. "high, prop"	5/10	4/10	0/10	1/10
"low, eff" vs. "low, prop"	10/10	0/10	0/10	0/10

Pairwise comparison of treatments in periods 11 to 20. Frequencies of results of two-tailed Mann-Whitney tests. Table entries in the first three columns indicate the number of cases in which the null hypothesis of equal medians is rejected at the displayed significance level in favor of the alternative hypothesis that the median is higher in the second treatment.

*Table 3:* Market prices (Panel A) and profits (Panel B): Results of significance tests for treatment effects.

Dependent Variable	Individual Price	Individual Profit
	(1)	(2)
$\beta_{high,eff}$	195.341*** (19.044)	8,139.560 (7,688.602)
$\beta_{high,prop}$	25.340 (19.763)	11,187.087 (7,978.840)
$\beta_{low,eff}$	42.505** (21.485)	-18,185.939** (8,673.913)
$\beta_{low,prop}$	43.652* (22.534)	-2,014.018 (9,097.277)
$\gamma_{high,eff}$	229.562*** (7.007)	83,319.644*** (1,591.999)
$\gamma_{high,prop}$	301.549*** (7.271)	96,701.571*** (1,652.096)
$\gamma_{low,eff}$	415.193*** (7.905)	120,575.874*** (1,796.017)
$\gamma_{low,prop}$	453.817*** (8.290)	123,536.027*** (1,883.679)
Observations	1,920	1,920
Adjusted R <sup>2</sup>	0.258	0.181

GLS regressions with clustered errors on the individual level. Clustered standard errors in parentheses. \*\*\*, \*\*, and \* denote significance at the 1, 5, and 10 percent level.

Table 4: Convergence of individual prices and profits: Regression results.

Dependent Variable	$p_{i,t} - p_{i,t-1}$		
	(1)	(2)	(3)
Restriction	None	$\beta = 0$	$\gamma = 0$
$\alpha$	-1.659 (1.912)	-5.026*** (1.921)	-2.605 (1.883)
$\beta$	0.713*** (0.076)		0.513*** (0.020)
$\gamma$	-0.194*** (0.072)	0.451*** (0.019)	
Observations	1,824	1,824	1,824
Adjusted R <sup>2</sup>	0.272	0.238	0.270

OLS regressions. Standard errors in parentheses. \*\*\*, \*\*, and \* denote significance at the 1, 5, and 10 percent level.

Table 5: Best response pricing and imitation: Regression results.

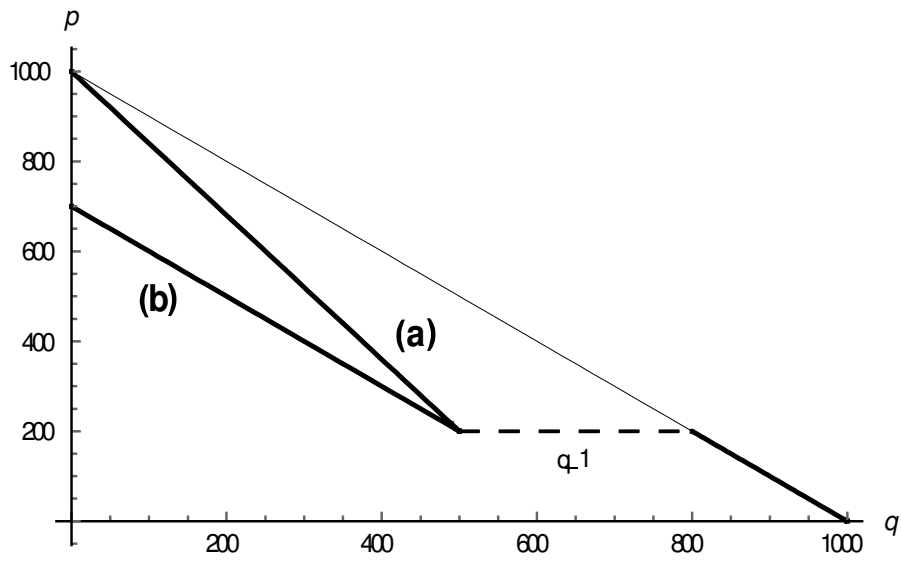


Figure 1: Proportional (a) and efficient (b) demand rationing.

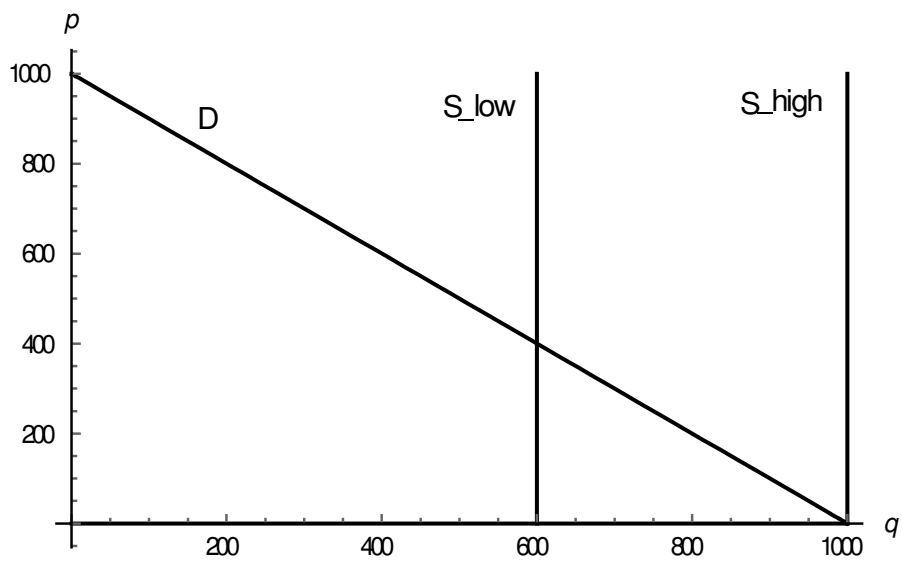


Figure 2: Market supply and market demand.

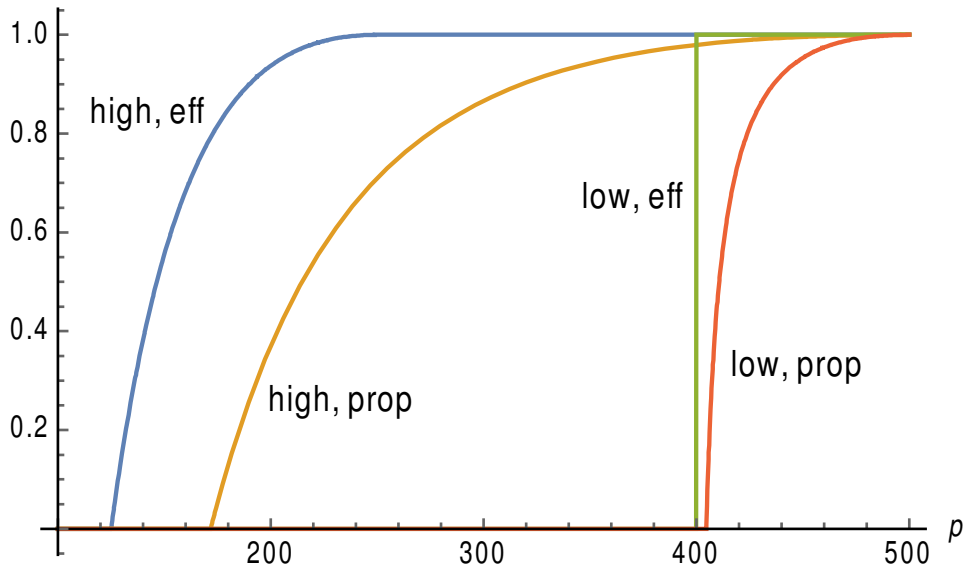


Figure 3: Cumulative distribution functions of the pricing Nash equilibria.

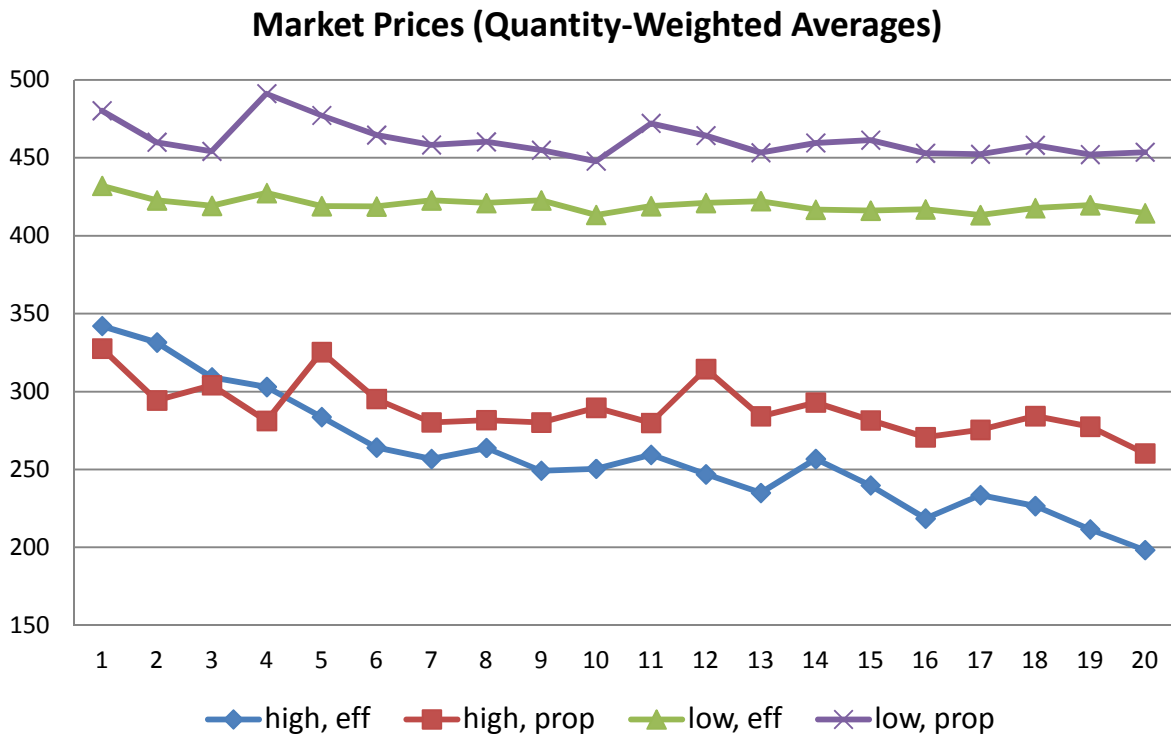


Figure 4: Series of market prices.

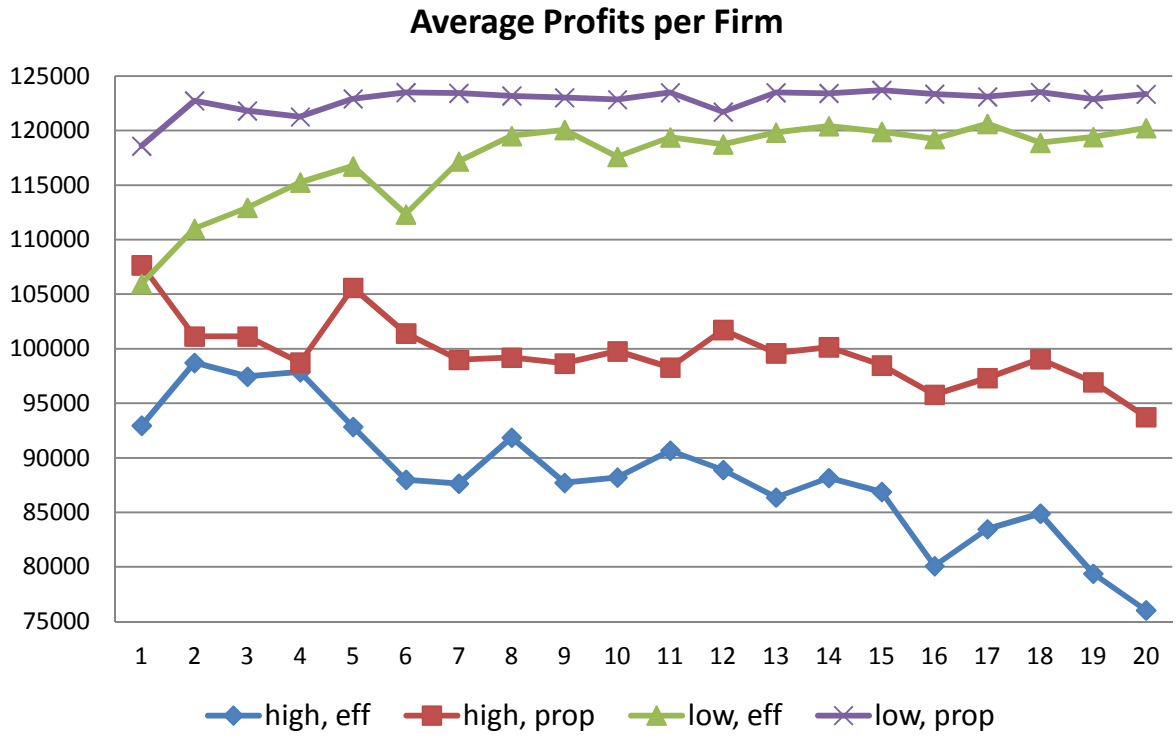


Figure 5: Series of average profits per firm.

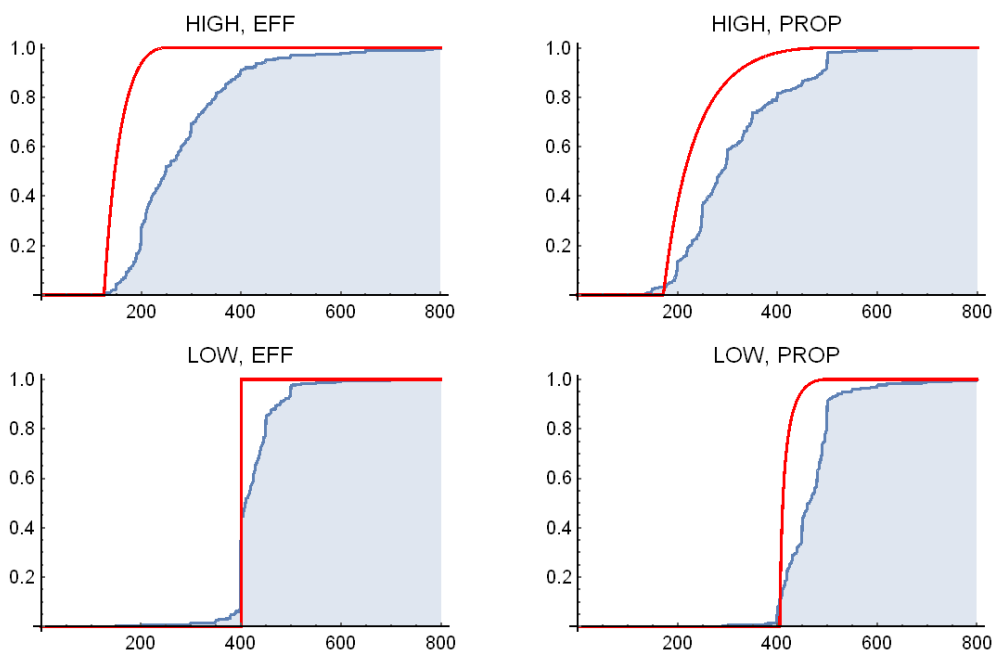
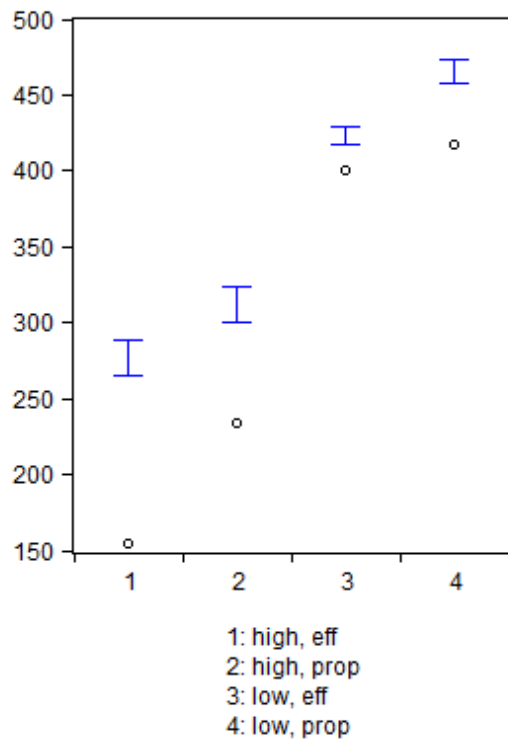


Figure 6: Empirical cumulative distribution functions (blue) and Nash equilibrium predictions (red).





*Figure 7:* 99 percent confidence intervals of empirical mean prices and Nash equilibrium predictions (circles).

TREATMENT HIGH, EFF: MEAN MARKET PRICES IN SINGLE MARKETS

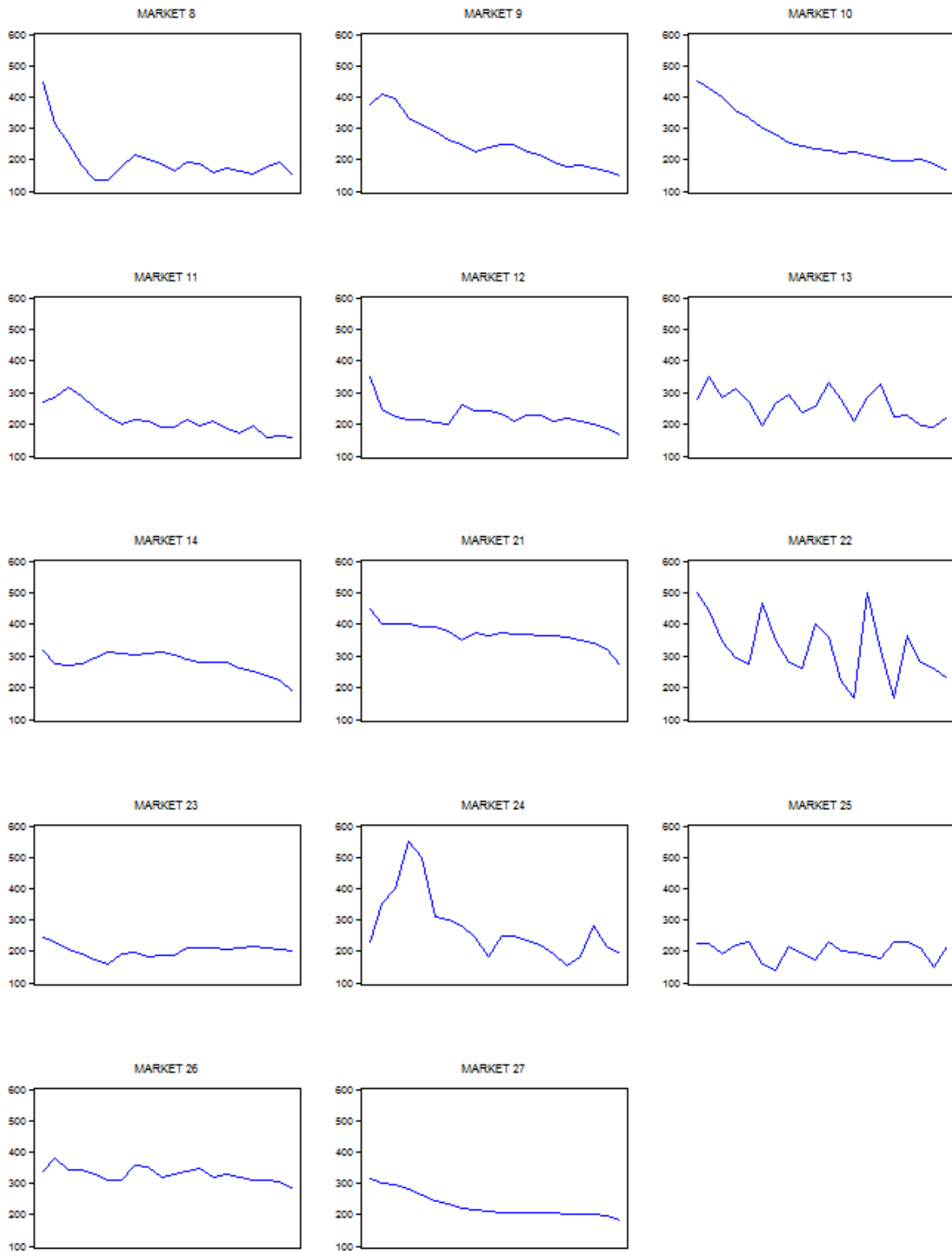


Figure B1: Development of market prices within single markets: treatment "high, eff".

TREATMENT HIGH, PROP: MEAN MARKET PRICES IN SINGLE MARKETS



Figure B2: Development of market prices within single markets: treatment "high, prop".

TREATMENT LOW, EFF: MEAN MARKET PRICES IN SINGLE MARKETS

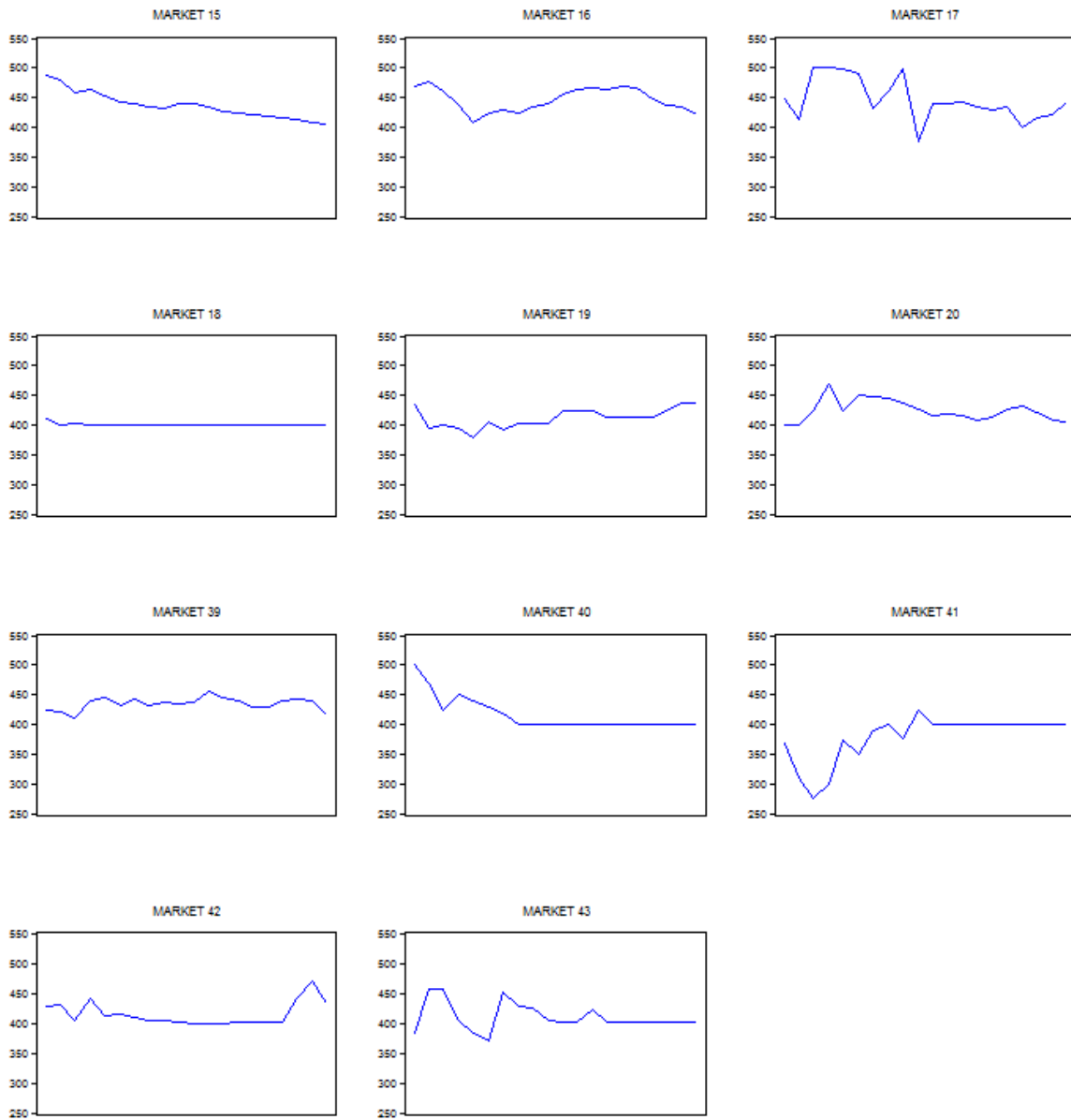


Figure B3: Development of market prices within single markets: treatment "low, eff".



Figure B4: Development of market prices within single markets: treatment "low, prop".