

Competition and Resource Scarcity on a Nonrenewable Resource Market: An Experiment*

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Abstract

This study investigates strategic behavior in nonrenewable resource markets by means of an experiment. Essential characteristics of nonrenewable resource markets are (a) the fact that long run production is limited by a private resource constraint and (b) the presence of competition from similar firms. From the firms' perspective, the private resource constraint makes the problem dynamic, whereas the presence of other firms creates a possibility for strategic oligopoly behavior.

We experimentally examine the difference in behavior in three types of markets. In the first type of market, firms have enough resources left in order not to have to limit their production. In the second type of market, firms are somewhat constrained and in the third type of market the resource constraint is tightest. We hypothesize that the degree to which firms pay attention to either of the two aspects of the market is a function of the abundance of the resource. In particular, we hypothesize that strategic response behavior -where firms condition their production on the production of others- will be found more often in markets where usage of the resource is relatively unconstrained.

1 Introduction

From the 19th century American gold rushes to the 21st century quest for drilling rights on the North Pole, there has always been something special about nonrenewable resources. Nonrenewable resources share the characteristic that they cannot be replenished,¹ meaning that persistent use will eventually lead to physical or economic depletion (i.e. such that the remaining stock will not be worth extracting anymore). What's more, the extraction and use of non-renewable resources such as coal or oil sometimes seriously pollutes the environment.

Since nonrenewable resources are about scarcity, intergenerational equity and environmental externalities, it should perhaps not be surprising that they have become the subject

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[†]This is a preliminary working paper, so please do not quote. The newest version is available from the first author's website

¹Or at least not in any time span or at any rate that is relevant to humanity at the moment.

of study for economists as well. Hotelling (1931) laid the groundwork and the 1972 oil crisis did the rest to create a large and ever expanding literature describing the workings of natural resource markets.² However, so far none of the theoretical models have provided a good fit for real world data. This may in part be due to the complexity of the nonrenewable resource problem, which is dynamic because of the resource constraint. Indeed, the optimal rational solution would require rational expectations of not just today's interest rate, exploration possibilities, market demand, behavior of other firms etc, but also to make predictions for time periods in the possibly infinite future.

This is true especially for producer interactions. Many different models of competition on natural resource markets have been proposed, with none seemingly being able to capture all the features of natural resource markets. One reason for this is that fluctuations in producer output may not be due to strategic considerations, but may be the result of external factors (e.g. demand shifts) or internal factors (e.g. new oil wells being put into use) which can sometimes not be extracted from the data. Moreover, even if output changes are the result of strategic interactions, they may also be the result of revised expectations, which are also rarely available from real life data. Finally, even if a strategic pattern seems to emerge, it can sometimes be reconciled with multiple possible explanations.

These concerns can, however, be addressed using laboratory experiments. External and internal factors can be fixed experimentally, by controlling the demand specification. Expectations can be measured, such that revised expectations can be taken into account and be disentangled from strategic concerns. Different possible explanations can then be addressed by varying experimental conditions. This study is the first study to investigate the strategic behavior of producers on a natural resource markets in an experimental context.

In particular, we experimentally examine the difference in behavior in three types of markets. In the first type of market, firms have enough resources left in order not to have to limit their production. In the second type of market, firms are somewhat constrained and in the third type of market the resource constraint is tightest. We hypothesize that a relatively abundant resource stock makes firms focus on competition and interacting strategically with other firms. Once the resource stock has been sufficiently depleted, we hypothesize that firms will start to pay more attention to the resource constraint, leading to a larger focus on dynamically optimizing behavior and a smaller focus on competition behavior.

The paper is organized as follows. Section 2 gives presents the theoretical background of the experiment. Section 3 describes the motivation for this experiment and section 4 describes the experimental design. Section 5 gives the results, and section 7 will present a conclusion.

2 The Theoretical Framework

2.1 Hotelling and The Hotelling Rule

The field of natural resource economics owes much to Harold Hotelling (1931). In the spirit of an earlier work by Gray (1914), Hotelling set out the problem of a firm -in his case a mine owner- facing a limited stock of resources. Hotelling's work is notable for its novelty and its sheer scope: it addresses not just a new economic problem but also discusses many relevant extensions, including uncertainty, the possibility of exploration and market power. With this

²In this paper we shall use the terms 'nonrenewable resource market' and 'natural resource market' interchangeably. Note, however, that in other contexts the latter can also refer to renewable resources, such as wood or fish.

work he planted the seeds which allowed natural resource economics to blossom in such a spectacular fashion in the 1970s (see Devarajan and Fisher, 1981 for an early overview).

Hotelling starts his analysis by examining the problem of a resource-constrained firm in a fully competitive market. Firms in a competitive market face a trade-off between producing now and producing in the future. For the market to be in equilibrium, firms have to be indifferent between both possibilities. Producing now has the advantage that it will give immediate benefits plus interest income, whereas producing in the future will yield benefits at a later stage only. The only way to make firms indifferent is by making prices grow at the rate of interest. That way, producing one unit less now will mean a loss of today's price plus the interest over today's price, and this will be equal to the benefit of producing one unit more in the future. This result has become known as the *Hotelling Rule*.

The Hotelling Rule in its original form is valid only in a competitive environment with zero marginal costs. However, it can be generalized to other environments as well (see Krautkraemer, 1998, for an overview of some of these generalizations). In a more general form, it states that the *scarcity rent* should grow at the rate of interest. Here, the scarcity rent can be defined as the difference between the current market price and the market price that would result if the resource was abundant. It is also sometimes referred to as the *in situ value* of a resource, the marginal profit of a firm with respect to the resource or the user cost of the resource stock. The scarcity rent is equal to price only in the case of perfect competition and zero extraction costs, which is the case described by Hotelling. This follows from the definition of scarcity rent: in any perfectly competitive market with zero costs and abundant resources, market prices will be zero. Hence, the scarcity rent can be seen to be equal to the current market price.

Since Hotelling's seminal paper, the Hotelling rule has been tested empirically on numerous occasions. Early empirical studies indeed found a positive trend in resource prices over time (e.g. Barnett and Morse, 1963; or V. Kerry Smith, 1978). However, other studies have found insignificant or even negative trends (e.g. Slade, 1982).

2.2 The model

In this section, we will present the theoretical model that will form the basis framework for this experiment. For this purpose, we will consider a general model of a symmetric simultaneous-move oligopoly in the spirit of Loury (1986). In so doing we will try to stick to the original Hotelling set-up as much as possible. Hence, we will not consider possibilities of exploration, capital investments etc.

Let there be n symmetric producers indexed i , with equal profit function $\Pi(q_t^i)$, maximizing discounted profits with respect to quantity. Moreover, each producer faces a constraint that total production cannot exceed the total resource stock S_0^i . There is a (constant) common discount factor δ which is equal to $\frac{1}{1+r}$, with r being the market interest rate. Moreover, suppose that T is the maximum number of periods (which could be ∞). The problem is as follows:

$$\begin{aligned} & \max \sum_{t=0}^T \delta^t \Pi(q_t^i) \\ & \text{subject to } \sum_{t=0}^T q_t^i \leq S_0^i \end{aligned}$$

For this study, we will adopt a simple linear demand framework in order to keep the experiment as simple as possible for participants. In particular, let a be the choke price and b be the slope of the demand function, $Q = \sum q_i$ be the market quantity and $C(q_t^i)$ be the cost function. The individual profit function then becomes:

$$\Pi_t = (a - bQ_t)q_t^i - C(q_t^i)$$

To keep the set-up as simple as possible, let us furthermore assume that marginal costs are constant and (without further loss of generality) equal to zero. This yields the following Lagrangian:

$$L = \sum_{t=0}^{\infty} [\delta^t (a - bQ_t)q_t^i - \lambda^i q_t^i] + \lambda^i S_0^i$$

The solution to this Lagrangian depends on the assumptions that the firm makes about Q_t . Offerman, Potters and Sonnemans (2002) mention three benchmarks. In the Nash benchmark, all firms maximize expected total profits taking the production plans of other producers as given. Since all other players are assumed to be symmetric, we get $Q_t = b(n-1)q_t^n + bq_t^i$, where q_t^n is the expected quantity produced by the other firms. In the Collusive benchmark, firms maximize expected industry profits, which is equivalent to maximizing the own profit conditional on the other firms adopting the same production schedule. We then get $Q_t = bnq_t^i$. Finally, for the competitive or Walrasian benchmark, firms (mistakenly) believe that their production decision has no influence on market prices, which results in $Q_t = bnq_t^w$ (where q_t^w is the expected average quantity produced on the market). Plugging these expressions into the Lagrangian, taking the derivative with respect to q_t^i and q_0^i and by symmetry putting $q_t^i = q_t^w$ for the Competitive benchmark and $q_t^i = q_t^n$ for the Nash benchmark and re-arranging yields the following expression:

$$q_t^i = q_t^S - \frac{q_t^S - q_0^i}{\delta^t} \quad (1)$$

This is the Hotelling rule for quantities. Here, q^S is the static benchmark quantities, which are equal to the following expressions:

$$\begin{aligned} q_n^S &= \frac{a}{(n+1)b} \\ q_c^S &= \frac{a}{2nb} \\ q_w^S &= \frac{a}{nb} \end{aligned}$$

The second expression on the right of equation 1 (which is the scarcity rent) will always be positive. This term is exponentially increasing; as a result quantities will decrease exponentially (and prices will increase exponentially) with respect to the static equilibrium. Note that since $q_w^S > q_n^S > q_c^S$ for $n > 1$ quantities are decreasing fastest in the Competitive benchmark and slowest in the Collusive benchmark. This immediately implies that q_0 is highest for the Competitive benchmark and lowest for the Collusive benchmark. Thus, collusion actually

leads to slower extraction and greater conservation of the resource. Finally, note also that by the Kuhn-Tucker theorem (Kuhn and Tucker, 1951) the Hotelling rule only holds for periods with positive production levels.

The Hotelling rules describe part of the optimal benchmark solutions. The two remaining steps are to find q_0 using the resource constraint and finally the optimal time of exhaustion³. This procedure, though mathematically straightforward, is quite tedious and thus omitted. However, figure x plots the benchmarks for the three treatments that will be used in this experiment.

As a final remark, it should be noted that use of the open-loop solution concept is not uncontroversial. In particular, open loop equilibria are not resistant to (small) mistakes and are subgame perfect only in some cases. As an alternative, some authors have suggested the use of the closed loop solution concept, which is subgame perfect and resistant to (small) mistakes. However, to our knowledge no general closed-loop framework for nonrenewable resource oligopolies has of yet been formulated. In particular, we know of only one attempt to do so for a specific case (Salo and Tahvonen, 2001), but this attempt itself is still controversial (see Pang, 2008). Thus we will stick to the open-loop benchmarks over the course of this paper. However, in our analysis we will deal with mistakes by recalculating the benchmarks conditional on the remaining stock in the current period.

3 Experimental Motivation

Thus, one of the main implications of the theoretical framework is that scarcity rents and thus resource prices should (exponentially) increase over time. However, this finding stands in stark contrast to the empirical reality. Indeed, although resource prices have sometimes increased for several consecutive years, in the long run resource prices have tended to remain constant or even decrease. For example, figure 1 (source: WTRG Economics(2009)) shows that real oil prices were actually lower in 1998 than in 1949. Moreover, a similar pattern holds for other nonrenewable resources such as zinc, iron ore and copper as figure 2 (source: Kronenberg (2006)) shows. Furthermore, the overall result seems to be the same if the analysis is extended to scarcity rents (see Krautkraemer(1998/2002) or Kronenberg(2006) for a review).

Several possible reasons for this discrepancy have been mentioned in the literature, which can be roughly divided into two categories. On the one hand, there are geological reasons, which include cost function specification, technological progress and exploration effects. In general, the idea is that the scarcity rent might fall over time as the result of decreasing costs or an unexpected increase in the resource stock. However, although these findings can explain decreasing resource prices over time in the short run, prices will have to start increasing in the long run (see Kronenberg (2006) for a more detailed explanation).

On the other hand, there might also be institutional reasons for the failure of the Hotelling rule to hold up empirically. Firstly, it might be that resource owners want to overstate their reserves in order to prevent a third party from developing a backstop technology or to increase the value of the firm (see e.g. Gerlagh and Liski, 2007). Since actions speak louder than words, the only credible way to do this would be to adopt the corresponding production schedule. Alternatively, uncertain property rights can also lead to high initial extraction rates and decreasing resource prices (e.g. Mead and Johanny, 1974). This may have been particularly relevant in the late 19th and early 20th century oil industry, when many oil extractors in

³The reader may have noticed that the solution procedure is essentially a backward-induction procedure.

Figure 1: Crude Oil Prices (2008 dollars)

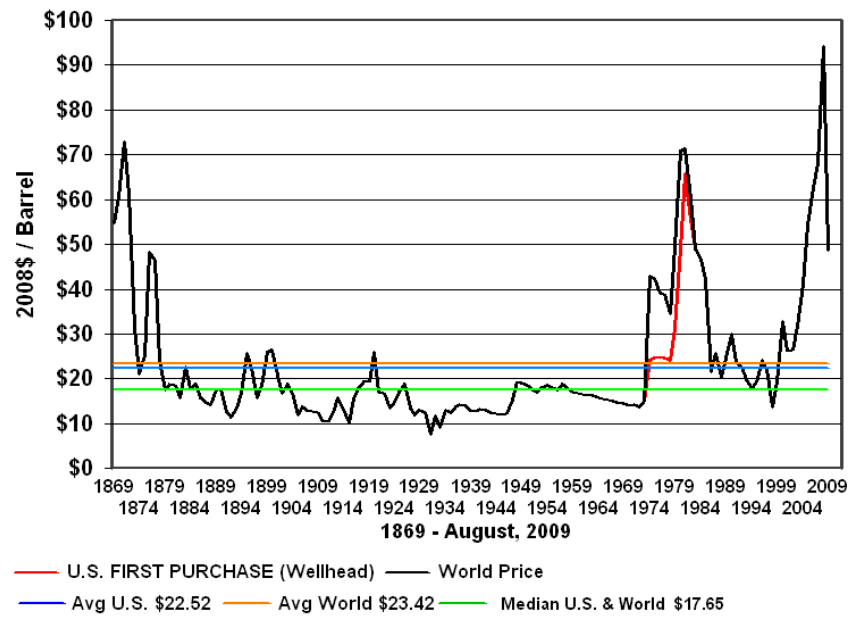
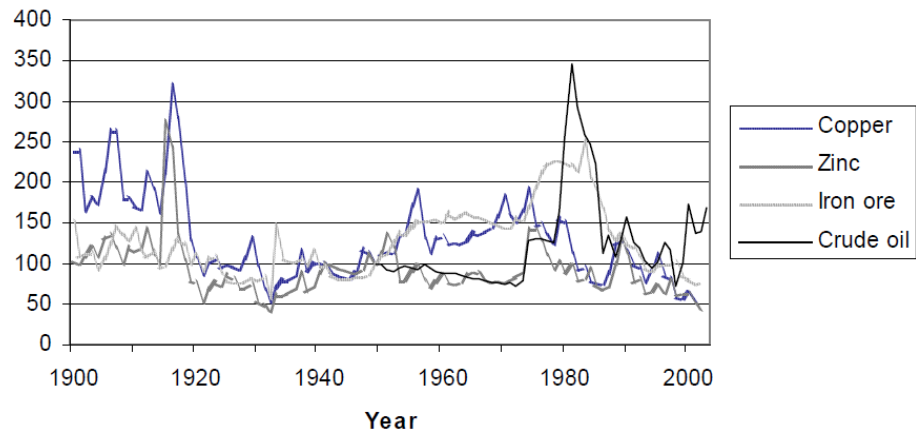


Figure 2: Resource prices (base=1949)



the US were tapping from the same oil field. It may also explain decreasing oil prices in situations where the resource extractor expects that there is a high likelihood of his resource to be confiscated in the future, as in the 1950s, 1960s and 1970s on the oil market. However, property rights are currently much better defined in the oil market whereas the prices still have not consistently increased. Moreover, property rights have been much better defined for other resources which have shown similar price patterns as in figure 2.

Thus, several explanations for the failure of the Hotelling rule have been proposed, some of which have been more successful than others. In this paper, we examine a different explanation. In particular, we argue that the nonrenewable resource problem has many different aspects. For example, a nonrenewable resource firm has to think about the plans of its competitors, the possibilities for further exploration, current demand elasticities in different countries etc. Crucially, the fact that the nonrenewable resource problem is a dynamic problem means that the firm has to do this not just for the current period but also for all future periods. Indeed, for a rational optimizing firm, changes in 2052 demand elasticities would require altering production levels in possibly all current and future time periods.

We think that the idea that real life nonrenewable resource firms may not always be willing or able to take all these aspects into account simultaneously for several reasons. Firstly, despite the enormous financial capabilities of some nonrenewable resource firms, it is unlikely that even a very rich nonrenewable resource owner has enough computational capacity to take all aspects (including e.g. exploration, forecasting future demand, competition, technological improvements etc) into account simultaneously. In fact, even including two aspects simultaneously might make the optimization problem intractable. For example, the economic literature has not yet been able to provide a subgame perfect (closed-loop) framework which can deal both with Cournot-Nash competition aspect and the dynamic optimization aspect⁴. Thus, nonrenewable resource firms have to make choices on what aspects of the decision problem they are going to pay most attention to.

Secondly and relatedly, even if nonrenewable resource firms did have the ability to include many or even all aspects of the nonrenewable resource problem in their decision making process, it might not be beneficial to do so from a cost-benefit perspective. For example, making accurate predictions about the elasticity of demand in 15 or 20 years is likely to be quite costly, since making a good prediction would mean for instance taking into account the expected availability of a backstop technology in the future, which in turn depends on the expected rate of technological progress in this area etc. At the same time, even a sizable change in the expected demand elasticity in 15 or 20 years might not affect the optimal current extraction rate very much. Thus, in many cases the benefits of acquiring information about certain aspects of the nonrenewable resource problem and then incorporating these into the model might not be worth the costs.

Finally, some aspect of the decision problem might be more salient to the decision makers than others. In particular, nonrenewable resource producers might be somewhat myopic. For example, a firm manager who is about to retire might not care so much about exploration or the future of demand elasticities. Similarly, an oil-rich country might have accumulated so many assets in the future that its oil reserves pale in comparison; making it unnecessary to think about the future very much. Thus, myopia might induce oil producers to pay more attention to current period aspects of the optimization problem, such as competition, rather

⁴As previously mentioned, the exception here is Salo and Tahvonen (2001). However, Pang (2008) casts some serious doubts on the validity of their analysis.

than future aspects, such as exploration.

Thus, the degree to which a nonrenewable resource producer pays attention to a given aspect might depend on if it is feasible to include it in the optimization problem, if in doing so the benefits of inclusion outweigh the costs and if the aspect is salient to the producer. For this paper, we use a model that has only two aspects to it. Firstly, there is a DYNAMIC OPTIMIZATION aspect. In other words, the producers always have to take into account that producing a higher quantity now is going to affect future production possibilities (as is in principle the case for all nonrenewable resource firms). For another, we allow for the presence of Cournot COMPETITION between producers. Although the exact market form of many nonrenewable resource markets is disputed⁵, an important fact of most non-renewable resource markets is that multiple producers are active on the market. Thus, in our model producers may focus more on dynamic optimization or competition depending on the producer's situation.

In particular, we argue that the degree to which producers focus on either competition or dynamic optimization depends crucially on the size of the remaining private resource pool. Consider for example a producer who has a very large (close to infinite) stock remaining. Since this large stock will allow him to remain active on the market for many periods even for very high production levels, he is unlikely to be worried about exhaustion⁶. As a result, he should focus more on the competition aspect and less on dynamic optimization.

Now consider a producer who has a very small stock remaining (close to zero). As a consequence, he will exhaust his stock sometime in the immediate future; thus he knows that he will not be active on the market very long. As a consequence, it will become important to him to pay attention to allocating his resource optimally over time. As a result, he should focus more on the dynamic optimization aspect and less on the competition aspect.

Although these are just two examples, we propose that this idea holds more generally. In particular, we propose that the higher the resource stock, the more attention producers will pay to competition. We propose that this line of reasoning can be a way to explain the failure of the Hotelling rule. Specifically, most non-renewable resources, though decreasing in stock, are still relatively abundant. For example, oil (the first fuel resource to be exhausted) is currently estimated to be exhausted on October 22nd, 2047 (EEP, 2010). Since this is still relatively far in the future, oil producers might not care so much about allocating their remaining resource over time; instead they should be focused on other aspects, including competition. Indeed the presence of OPEC is testament to the need that the big oil producers still feel the need to curtail competition.

This hypothesis could be investigated empirically in at least two ways. One way would be to collect data on the structure of a nonrenewable resource market (including e.g. remaining stock sizes, extraction costs etc) for a number of time periods, compute the optimal extraction paths and see if these paths deviate in ways that are in line with this hypothesis. Alternatively, it would be possible to use proxies for dynamic optimization behavior and competition behavior and see if variation in these proxy variables can be explained by changing stock sizes.

However, an empirical study would face two related problems. On the one hand, an

⁵This is true in particular for the oil market, where many several forms have been proposed, including perfect competition, cournot oligopoly and cartel-versus-fringe.

⁶This could be either because exhaustion is not salient, because the costs of including the possibility for exhaustion in his optimization problem outweigh the benefits or because the firm lacks the means to include all aspects (or all three aspects).

empirical study would require making many simplifying assumptions, some of which may be hard to justify and can influence the results substantially. For example, there is still considerable disagreement on the market form of the oil market. On the other hand, data availability tends to be quite limited⁷. For example, there tends to be little data on extraction costs and there are some suspicions over the publicized oil reserve estimates. Data may also be noisy due to for example regime changes, demand shocks or wars which cannot always be extracted from data.

This is true also for data on the competition behavior of producers. Many different models have been proposed, with none seemingly being able to capture all the features of natural resource markets. One reason for this is that fluctuations in producer output may not be due to competition considerations, but may be the result of external factors (e.g. demand shifts) or internal factors (e.g. new oil wells being put into use) which can sometimes not be extracted from the data. Moreover, even if output changes are the result of competition, they may also be the result of revised expectations, which are also rarely available from real life data. Finally, even if a competition pattern seems to emerge, it can sometimes be reconciled with multiple possible explanations.

These concerns can, however, be addressed using laboratory experiments. External and internal factors can be fixed experimentally, for example by using a constant demand specification. Expectations can be measured, such that revised expectations can be taken into account and be disentangled from strategic concerns. Different possible explanations can then be addressed by varying experimental conditions. This study will present a first attempt to investigate the strategic behavior of producers on a natural resource markets in an experimental context.

In particular, we run three treatments. In treatment LOW, firms have only a limited available stock. Specifically, in the LOW treatment, the static collusive benchmark (which is the most conservative of the three benchmarks) can be maintained for only one period. In treatment HIGH, firms have a somewhat higher stock; as a result the static collusive benchmark can be maintained for up to five periods. Finally, we include a treatment (treatment FULL) where firms are not limited by resource scarcity at all. Thus, in this treatment all static benchmarks can be maintained indefinitely. Table 1 states the parameters corresponding to the three treatments.

We propose that the experimentally induced variation in stock levels results in a shift of relative focus between competition and dynamic optimization. Looking first at dynamic optimization, we expect firms in treatment LOW to pay most attention to dynamic optimization. In particular, firms in the LOW treatment should be more likely to condition their production decision on their remaining resource stock as well as the remaining resource stock of the other firm. Moreover, firms in the FULL treatment should not worry about dynamic optimization at all. This leads to the following hypothesis:

Hypothesis 1: The higher their resource stock, the less attention firms pay to the dynamic optimization aspect.

1a: Firms in treatment LOW are more likely than firms in treatments HIGH and FULL to condition their production decision on their own stock and the stock of the other firm.

⁷Indeed, this may partly explain why there is still considerable disagreement on the market form of the oil market.

1b: Firms in treatment FULL do not condition their production decision on their own stock and the other firm’s stock at all.

Moreover, changing the salience of the dynamic optimization aspect could also affect firm behavior in another way. In particular, a firm who pays no heed to the dynamic optimization aspect cannot produce according to any of the dynamic benchmarks. Instead, we propose that such a firm should produce according to one of the static benchmarks. In general, the less attention a firm pays to the dynamic optimization aspect, the more his production decision should move towards the static benchmarks. In other words, such a firm should exhaust a higher share of his resource in any period. Since the competitive equilibrium has the highest extraction rates, we arrive at the following sub-hypothesis⁸:

1c: Firms in treatment HIGH should be more competitive than in treatment LOW.

For the competition aspect, a similar line of reasoning holds. In particular, the higher the resource stock, the more attention firms will pay to the competition aspect. As a result, the higher the resource stock, the more likely it is that a firm’s production decision will be based on what he expects the other firm to produce. As a result, we expect firms in treatment FULL to be most likely to condition their production decision on what they expect the other firm to produce; we also expect firms in the HIGH treatment to be more likely to do so than firms in the LOW treatment. This leads to the following hypothesis:

Hypothesis 2: the higher their resource stock, the more attention firms pay to the competition aspect.

2a: Firms in the FULL treatment are most likely to condition their production decision on what they expect the other firm to produce.

2b: Firms in the HIGH treatment are more likely to condition their production decision on what they expect the other firm to produce than firms in the LOW treatment.

4 Experimental Design

In the experiment, each participant represented a firm with a limited amount of resources to be allocated over a total of 6 time periods (along the lines of the model of section 2). Moreover, participants were paired so that there are always two active firms on the experimental market. In every time period, each participant decided how much of his resource to extract in the current period and how much to save for the remaining periods. As soon as both participants on the market had made their decision, they moved on to the next period, where both participants received feedback on the production of the other firm, the ensuing market price and their own profits (including what those profits would be worth including interest payments)⁹.

⁸Of course, it is also possible to directly test if firms produce closer to the static benchmarks in the HIGH treatment than in the LOW treatment. However, this would be true by construction, since firms in the LOW treatment cannot produce as much as in the HIGH treatment. They can, however, produce more or less close to the dynamic competitive equilibrium.

⁹An example of a decision screen is given in Appendix A.

Table 1: Experimental Time Line

Prologue 1:	<u>Nonrenewable Resource Monopoly</u>		
	1. Introduction & Check up Questions		
	2. Practice		
	3. Paid-out Round		
Prologue 2:	<u>Renewable Resource Oligopoly</u>		
	1. Introduction & Check up Questions		
	2. 3 Paid-out Rounds		
Main:	<u>Nonrenewable Resource Oligopoly</u>		
	1. Introduction & Check up Questions		
	2. 10 Paid-out Rounds		
	<u>Treatments</u>		
	LOW	HIGH	FULL
Stock	170	480	∞
a	372	372	372
b	1	1	1
Interest Rate	10%	10%	10%

After the sixth period, participants were informed of their total income, which was calculated by adding profits and interest incomes from all periods and subtracting a fixed cost. Once all participants in all other groups were done as well, they moved on to the next round, where they had to go through the same set-up again. In every round, participants were matched to a different participant in their matching group (which was between size 6 and 10). Thus, participants could never face the same person twice in succession. Moreover participants were never told the identity of the other participant.

The parameters of the decision problem depended in part on the respective treatment (LOW, HIGH or FULL). The parameters used in the three treatments (LOW, HIGH and FULL) are given in table 1. The most important parameters is resource stock, since it is the focus of our hypotheses. In the LOW treatment resources were meant to be relatively scarce whilst still requiring Nash participants to preserve some of their stock until the final period. This is important, since a lower stock would have reduced the effective number of strategic periods, reducing the chances of a rapport being established by both firms on the market. In the HIGH treatment, we made resources more abundant, whilst at the same time keeping them at a level that was low enough not to reduce any of the dynamic equilibria to the static equilibria (which would have happened at a stock of 558). This is important, since it ensured that any profit-maximizing participant would be resource-constrained even in the collusive (low-production) benchmark. Finally, in treatment FULL resources were not limited in any way. This way the results of the other two treatments could be compared to a static oligopoly benchmark which has commonly been used in the experimental literature before (see e.g. Offerman et al, 2002).

We tried to keep the other parameters the same between treatments. For example, the demand curves identical in all treatments; moreover the three benchmarks are not obvious

numbers even in the FULL treatment¹⁰. We introduced a fixed cost to increase the difference in earnings between the three benchmarks and thus provide a greater reward for a well thought-out production scheme. However, we had to adjust both fixed costs and the conversion rate of experimental points to euros to create similar incentives in all treatments. We decided to implement discounting by means of an interest rate rather than a stochastic ending mechanism, as is sometimes done. Explicitly incorporating an interest rate avoids issues of risk aversion, the gambler’s fallacy (see e.g. Terrel, 1994) and keeps all rounds comparable (same number of periods)¹¹, whilst also staying close to the theoretical framework.

However, we realized that the nonrenewable resource situation might be quite challenging for participants. Hence we tried to keep the experimental set-up as simple as possible by limiting the number of periods to six and the number of competitors to one¹². Moreover, all participants had access to an on-screen calculator which allowed them to compute profits including interest income for any production level of themselves and the other firm.

Moreover, before going to the nonrenewable resource oligopoly set-up, participants also went through a preparatory phase (or prologue) of the experiment. The prologue lasted for approximately one hour and consisted of two phases: nonrenewable resource *monopoly* and *renewable* resource oligopoly. Each of these aspects reflects one of the two main aspects of the nonrenewable resource problem. Indeed the main purpose of the prologue was to allow participants to get to know the nonrenewable resource problem in a stepwise way. As a bonus, it also allowed us to compare behavior in the prologue to behavior in the main part of the experiment.

Participants first went through the nonrenewable resource monopoly phase. Since there were no other firms to worry about, this part of the prologue allowed participants to learn about the dynamic optimization aspect without having to worry about competition. All participants first received a set of instructions and check-up questions (all instructions, questions and questionnaires are reprinted in appendix B). Once every participant had finished these, they could practice for 15 minutes, during which they could go through as many rounds of the monopoly set-up as they liked¹³. Thus, they had the time to check many possible production paths; as a result we expected most to get to know at least the basic rule of dynamic optimization in a nonrenewable resource context (which is to produce more at the beginning than at the end). After practice, they had to go through one more round which was paid out at the end of the experiment. All in all, this part took approximately 35-40 minutes.

The next phase of the prologue consisted of a renewable resource (or static) oligopoly. Since participants were no longer resource constrained, they no longer had to worry about dynamic optimization. Instead, the focus of phase two was on learning how to deal with the presence of another firm on the market. In particular, we hoped that phase two would teach participants that it tends to be good for the own firm to increase production in a given period, but that it will decrease the profits of the other firm on the market. At the beginning of this phase, participants received a new set of instructions and questions. Participants then went through three rounds of this set-up, facing a different participant (from the same matching group) in every round. All three rounds were paid out at the end of the experiment. In total,

¹⁰Indeed, the static benchmarks were 93, 124 and 186 respectively.

¹¹Brown, Flinn and Schotter (2009) suggest that both mechanism may yield very similar results in any case.

¹²Indeed, we had previously run a pilot where we had 10 periods and 2 competitors and found that many participants took a very long time to make a decision.

¹³On average, they went through 26 practice rounds, with a minimum of 10 and a maximum of 53.

phase two lasted for approximately half an hour.

After finishing the prologue, participants then went on to the main part of the experiment, which is also the basis for most of the analysis presented in the next section. They received a final set of instructions and questions and then had to go through ten rounds of the nonrenewable resource oligopoly set-up. In total, the main part of the experiment lasted for approximately 65 minutes.

After finishing the last round of the main part, participants received an overview of their earnings over the whole experiment (including a show-up fee of seven euros and their earnings for expectations, see below). They were then asked to fill out a questionnaire, which consisted of two parts. Firstly, participants were asked to answer some background questions as well as questions relating to the way they played in the experiment. Secondly, subjects were asked to fill out the shortened version of the Stanford Time Perspective Inventory (STPI, see D'Alessio et al, 2003). This questionnaire consists of three subscales measuring future orientation and two kinds of present orientation (hedonistic and fatalistic). We are most interested in the former subscale, which we will occasionally call on in the next section.

One final thing to note is that in all even rounds we also requested participants to indicate how much they expected the other firm to extract in the current period. Indeed, to test if participants are indeed more likely to condition their production decision on what they expect the other firm to produce (as hypothesis 2 suggests), a measure of expectations is required. A big advantage of experiments is that expectations can be elicited directly, such that a very direct measure of expectations becomes available.

However, elicited expectations are not uncontroversial in the literature. In particular, they might suffer from a false consensus or reciprocity effect (see e.g. Croson, 2000). In this case, this means that participants might base their expectation of the other firm's production on their own production level. Since we are interested in the opposite effect, this means that we will have to correct for possible reverse causality when investigating firm interactions by means of expectations. In particular, we will use a two stage least-squared approach. Moreover, another problem with elicited expectations is that the elicitation procedure itself may change behavior in a round (see e.g. Gächter and Renner, 2006). However, since we only elicited expectations in even rounds, we will be able to put this idea to the test by comparing behavior in even and odd rounds.

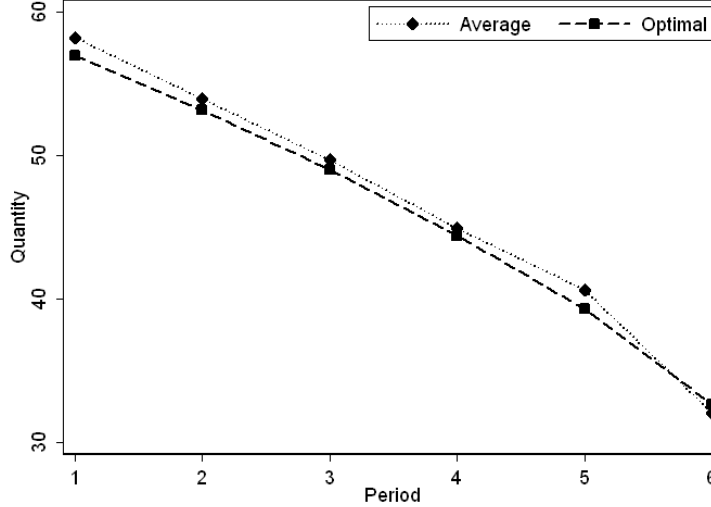
At the end of the experiment one expectation was randomly picked to be paid out. For this purpose, we asked one randomly picked subject to come forward and roll a die to determine the round and period that would be paid out. The pay-off was determined using a linear scoring rule, where a unit deviation from the actual value would reduce earnings by 20 cents, from a maximum of five to a minimum of zero euros.

5 Experimental Results

In this section, we first examine production dynamics at the aggregate level. We then investigate if performance in the main part of the experiment is correlated to performance in the preceding stages. We subsequently look at strategic dynamics in the third part of the experiment after which we look further into the differences between the HIGH and LOW treatments.

This experiment was run in February 2010 at the University of Amsterdam's CREED laboratory. In total, there were 8 sessions (2 for FULL and 3 for HIGH and LOW) in

Figure 3: Monopoly Quantities



which a total of 186 subjects took part (50 for FULL, 72 for HIGH, 64 for LOW). On average, participants earned 27.51 euros. Each participant was asked to take a seat at a randomly assigned computer desk. Subjects were told that instructions would be given on-screen, although the experimenters would be available for questions if necessary.

5.1 Aggregate Production Dynamics

The main purpose of this study is to investigate if the relative salience of competition and dynamic optimization varies as a function of stock size. For this purpose, we use data from the prologue to investigate if participants had at least a reasonable understanding of both these aspects separately. In particular, for the dynamic optimization aspect participants should at the very least understand that their extraction rate should be nonincreasing over time; for the competition aspect they should understand that a quantity increase in general increases the profit of the own firm but decreases the quantity of the other firm.

In phase one of the prologue, participants were able to learn about the principle of dynamic optimization in a nonrenewable resource monopoly. Optimality dictates that quantities should be monotonically nonincreasing over time. This is indeed the case for 91% of our participants (or 170/186). Moreover, 89% (165/186) displayed a significant negative time trend. Furthermore, 86% (160/186) earned a higher income than they would have earned with a constant production schedule¹⁴. In fact, the median participant was within 5 cents of the maximum (theoretical) pay-off.

This suggests that, on average, participants were well able to approximate the optimal time path. Figure 3 shows that this was indeed the case. However, participants show a small but significant tendency to exhaust the resource prematurely: on average participants extract 1.83% more than the optimal quantity in the first five periods ($t(929)=2.939$, $P=0.002$). This echoes the findings of Brown, Chua and Camerer (2009) who find that in a savings experiment, participants tend to save too little. However, participants seem to understand that the optimal

¹⁴Id est, they earned more than they would have earned if they had produced 47,47,47,47,46,46

Figure 4: Oligopoly Quantities

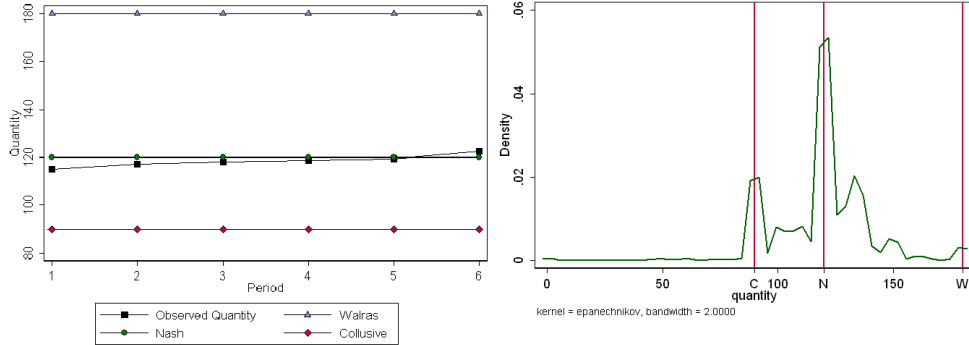


Table 2: Prologue Competition Behavior

	Dependent Variable: Quantity in period t
Other firm quantity in $t - 1$	.1411 (.0318)***
Quantity in $t - 1$	.2091 (.0417)***
Observations	2790(186)
Adj. R-Squared	.2137

Clustered Standard Errors in parentheses

* significant at 10%; ** significant at 5%; *** significant at 1%

production path of a dynamic nonrenewable resource game involves decreasing production levels over time.

In phase two of the prologue, participants had the possibility to learn about competition behavior. To investigate if there is evidence that participants pay attention to the competition aspect in this phase, we investigate participants' production function. For this purpose, we estimate a time and individual fixed effects regression of quantity in period t on quantity in $t - 1$, other firm quantity in $t - 1$ ¹⁵. Along the lines of hypothesis 2, there is evidence of competition behavior if participants condition their production decision on what they expect the other firm to produce. Table 2 documents the results of this regression. On average, participants increase their production if their rival had previously produced a high quantity. Moreover, this effect is significant despite using only an indirect proxy.

Figure 4 plots average quantities for each period (in the left panel) as well as the distribution of quantities over all periods (in the right panel). As the left panel shows, participants were on average a little below the Nash equilibrium in the first 5 periods and displayed an end-game effect in the final period. As the right panel shows, however, there is also quite a bit of heterogeneity. In particular, there is also a mode at the collusive equilibrium as well as at 135, which is the Nash response to a collusive opponent. As a consequence, there is also

¹⁵Since elicited expectations were not available in the prologue, we proxy for expectations using last period's other firm quantity. This will be a good proxy if participants base their expectations on what the other firm produced in the previous period; we will see in the main part that this is indeed what they do.

quite a bit of heterogeneity in earnings, with participants who face a competitive opponent or who are overly competitive themselves even managing to get negative earnings. On the whole, behavior is not unlike what is commonly observed in oligopoly experiments (see for example Engel, 2007 for an overview).

Thus, there is strong evidence that most participants achieved a good level of understanding of both the competition and the dynamic optimization aspect individually. Since the main part of the experiment mixes both aspects, behavior in the prologue might be somewhat correlated to prologue behavior. Moreover, if hypotheses 1 and 2 are correct, the degree to which this is true might depend on the treatment. In particular, behavior in the LOW treatment should be most correlated to behavior in the monopoly phase of the prologue, whereas behavior in the FULL treatment should be most correlated to the renewable resource oligopoly phase.

To test this idea we compute correlation coefficients between behavior in the main part and key elements of behavior from the prologue. Table 3 shows that participants with a high difference between first and sixth period quantity in phase one of the prologue also had a high difference between first and sixth period quantity in the main part, but only in treatment LOW¹⁶. Similarly, participants who started aggressively in every round of phase two of the prologue also started aggressively in the main part, but only in treatment FULL. Moreover, participants who were successful in the first (second) part of the prologue were also more successful in the LOW (FULL) treatment in terms of income¹⁷. Thus there seems to be evidence that both behavior and success in the main part are correlated to behavior and success in the prologue, but only for LOW for phase one and for FULL for phase two.

Finally, it is also possible that some participants did better in part III because they were more future-oriented. The final row of table 3 contains correlation coefficients between the future orientation subscale of the STPI questionnaire and income in the main part. The results indicate that participants who were more future oriented did better in treatment LOW, but not in the other treatments. However, the coefficient is quite small; a one standard deviation increase on future orientation only raised income by approximately 2% in the LOW treatment. Moreover, there might be a reverse causality effects because the questionnaire was administered after the experiment.

5.2 Main Part Aggregate Behavior

Figures 5, 6 and 7 present an overview of aggregate production dynamics in the third part of the experiment. For every period we plot the average production quantity over all rounds and individuals plus the three theoretical symmetric benchmarks.¹⁸ For the FULL treatment, the equilibria are the same in all periods; for the other two treatments, the equilibrium is

¹⁶The results are identical if we use the differential between the highest and lowest quantity instead.

¹⁷In comparing the second phase we correlate overall income in phase two to overall income in the main part. However, for phase one there are three complications: (a) participants in part III could improve their time allocation of resources from the other firm in the first round, (b) because of practice almost all participants were able to do well in phase one of the prologue and (c) phase one earnings were heavily skewed to the left. As such we use only the first round of the main part and correlate income of part III to a dummy variable which is equal to one only if the participant managed to run a profit in at least one of his first three practice rounds. This was true for 57% of all subjects. If we instead use overall phase one income (but still use a dummy to combat skewness), the results are similar but no longer significant at conventional levels.

¹⁸These symmetric benchmarks assume that participants on average predict that the other firm is going to produce the same quantity as themselves. A closer look at the data shows that this assumption is reasonable, since average predictions are indeed very close to average behavior. We refer to the appendix for more details.

Table 3: Comparing Prologue and Main Part

	LOW	HIGH	FULL
Dependent Variable: main part income			
Phase 1 income	5940 (2274)**	2463 (1554.26)	-5418.816 (3512.527)
Phase 2 income	.0029 (.0041)	.0044 (.0184)	.0843 (.0328)**
Dependent Variable: main part dispersion			
Phase 1 dispersion	.6469 (.2121)***	.1589 (.3823)	.1574 (.2328)
Dependent Variable: main part first period quantity			
Phase 2 first period quantity	-.0365 (.2227)	.0930 (.1180)	.7784 (.1388)***
Observations	64	72	50

Standard errors in parentheses

* significant at 10%; ** significant at 5%; *** significant at 1%

Figure 5: Quantities: LOW

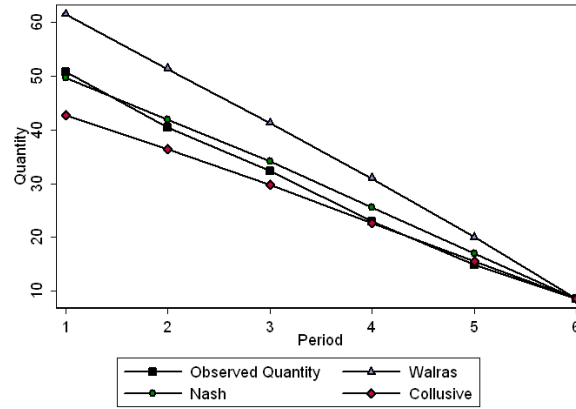


Figure 6: Quantities: HIGH

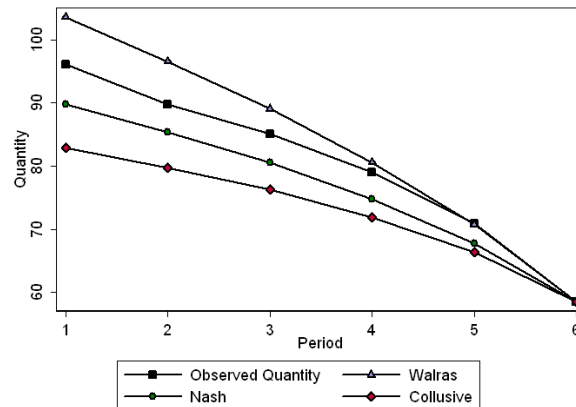
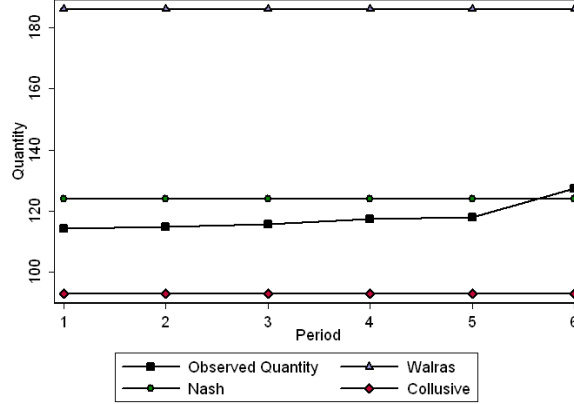


Figure 7: Quantities: FULL



calculated for every period conditional on the remaining stock. In table 4 we then use two-sided t-tests to compare the observed quantity with the (conditional) benchmarks¹⁹.

Participant behavior is quite different between treatments. For the LOW treatment, participants produce close to the Nash quantities in the first two periods, but subsequently start to produce less, reaching the collusive equilibrium in periods 4 and 5. For the HIGH treatment, participants are initially between the Nash equilibrium and the Walras equilibrium but eventually increase to reach the Walras equilibrium in periods 4 and 5. As such, participants in the HIGH treatment appear to be more competitive than participants in the LOW treatment. This is in line with hypothesis 1c, which predicted that participants would pay more attention to the dynamic optimization aspect in the HIGH treatment. As a consequence, they should produce closer to the static equilibria, leading to a more competitive overall outcome. Finally, in the FULL treatment participants produce almost identically to part II, with quantities being slightly lower than Nash in the first 5 periods and slightly higher in period 6.

So far we have looked primarily at aggregated results (over all participants). We can extend the analysis to the individual level also for the first period of every round. In this period, participants will not know what quantity the other firm is going to play, and thus the initial period quantity will be a reflection of the strategy they intend to pursue through subsequent rounds as well²⁰. Figures 8 to 10 show the smoothed distribution of first period quantities. One thing that stands out is that there seems to be substantial heterogeneity in all treatments. Secondly, the distribution of initial strategies is clearly bimodal in the FULL treatment (with modes at Nash and collusion), whereas it seems to be more or less unimodal

¹⁹Conditional benchmark quantities are computed by computing the theoretical quantity conditional on the currently remaining resource stock (rather than the theoretically remaining resource stock, as in the original benchmark).

²⁰Doing a similar analysis for subsequent periods would also have been informative. However, it is very difficult to get an accurate estimate of the type of equilibrium someone is playing from period 2 onwards, since the optimal Nash, collusive or Walrasian strategy depends not just on the own stock and the period, but also on the other firm's situation. This includes not just the other's stock, but also his past and expected future production levels. These are not all available from the data; moreover it was very hard for participants to learn the equilibria after period 1, since it would only rarely happen that the other firm had the same stock in the same period in two separate rounds. Hence we restrict ourselves to first period behavior on the individual level.

Table 4: Main Part Benchmarks

LOW treatment (N=640)					
Period	Average Quantity	Std. Error	Nash	Collusive	Walras
1	50.85	1.096164	49.6054	42.7123***	61.5139***
2	40.375	1.160814	41.9620	36.3506**	51.3631***
3	32.32969	.6690444	34.1002**	29.8186***	41.291***
4	22.9875	.574621	25.6451***	22.7418	30.974***
5	14.83594	.962235	17.0751***	15.599	20.0275***
HIGH treatment (N=720)					
Period	Quantity	Std. Error	Nash	Collusive	Walras
1	96.10833	1.843001	89.7837**	82.8906***	103.5697***
2	89.72222	.9698938	85.3261***	79.7147***	96.5488***
3	85.15139	1.034977	80.5114***	76.2298***	89.0746***
4	79.05556	.7835841	74.7607***	71.8574***	80.5674
5	70.97639	1.246042	67.7917**	66.3155***	70.744
FULL treatment (N=500)					
Period	Quantity	Std. Error	Nash	Collusive	Walras
1	114.388	4.050146	124*	93***	186***
2	114.756	4.275151	124*	93***	186***
3	115.846	4.586625	124	93***	186***
4	117.430	4.94513	124	93***	186***
5	117.926	3.995107	124	93***	186***
6	127.532	2.418835	124	93***	186***

Standard errors are clustered by participant ID. Note that we have omitted period 6 from the LOW and HIGH treatment since in this period all equilibria are trivially equal to full exhaustion.

* significant at 10%; ** significant at 5%; *** significant at 1%

Figure 8: First Period: LOW

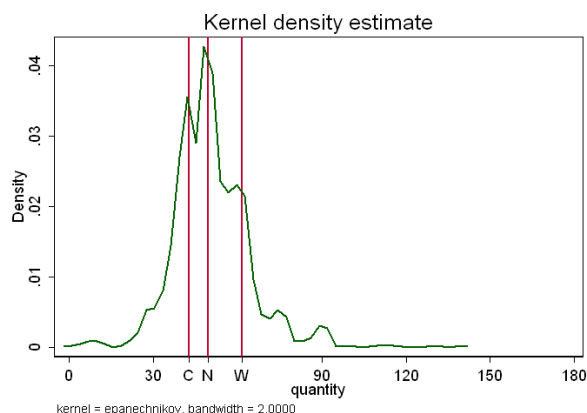


Figure 9: First Period: HIGH

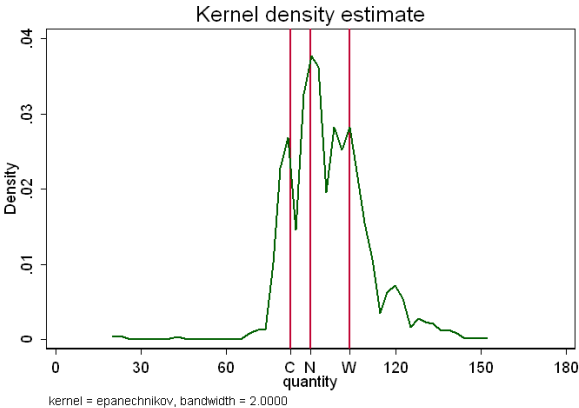


Figure 10: First Period: FULL

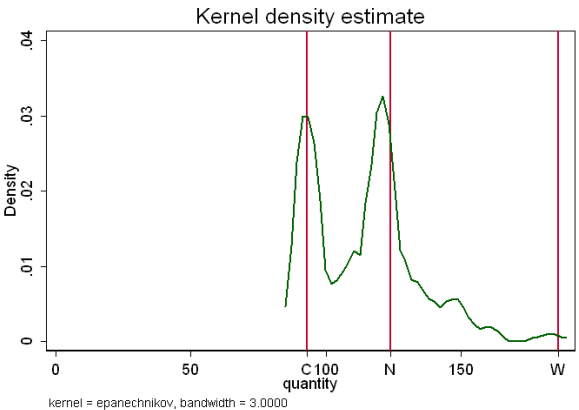
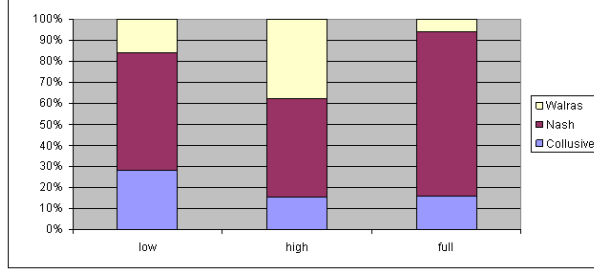


Figure 11: First Period: FULL



in the LOW (between collusion and Nash) and HIGH (at Nash) treatment. Thirdly, there are spikes at the collusive and Nash benchmarks in all treatments, but there is a spike at Walras only in the FULL treatment, in line with hypothesis 1c²¹. Figure 11 shows that most participants in all treatments were close to the Nash strategy. However, significantly more participants were close to the Walras strategy in the HIGH treatment at the 5% level. Of the other differences, only the difference in the number of collusive players between HIGH and LOW is significant at the 10% level.

Thus, the evidence so far seems to be that subjects produce most competitively in HIGH and least competitively in LOW, with FULL falling somewhere in between. To some extent these differences are also apparent in earnings levels. To compare earnings levels, we cannot use raw earnings, since these are not adjusted for different fixed costs. Hence, we compare a weighted earnings average where $Y_{av} = \frac{Y - Y_w}{Y_c - Y_w}$, where Y_w is the theoretical Walras profit, Y_c is the theoretical collusive profit and Y is actual income. By this measure, normalized average earnings are .542 for LOW .201 for HIGH. The difference between these two is significant ($z(64,72)=3.649$, $p=.0003$). For FULL the respective number is .899; however this number cannot be compared to the other two treatments since the meaning of Walras changes substantially in the presence of nonrenewable resources. Alternatively, we can also compare the same measure but then with Nash and Collusive. The results in that case are essentially the same: -6.70 for HIGH, -1.72 for LOW and .09 for FULL, with all differences being significant (L vs H: $z(64,72)=6.422$, $p=.0000$).

In summary, participants on average produce close to the Nash benchmark in all treatments. However, participants were somewhat more collusive in the LOW treatment and somewhat more competitive in the HIGH treatment, which is in line with hypothesis 1c. Moreover, this effect is reflected by average earnings. Moreover, there is substantial heterogeneity between participants, with most participants in all groups playing close to the Nash quantity. In the next section we will look a bit further into hypotheses 1 and 2 using a regression framework.

5.3 Competition Behavior

In previous sections we have focused on differences between overall behavioral patterns, mostly in terms of benchmarks. In this section, we will use a fixed effects regression framework to examine hypotheses one and two. That is, we will examine to what degree participants base their production decision on stock levels (hypothesis 1) and what they expect the other firm

²¹Remember also that these graphs represent first period quantities only, whereas from table 4 we know that participants on average actually become more competitive in later periods.

to do (hypothesis 2). A regression framework is necessary, since the reasons for producing can only indirectly be inferred. For example, suppose that we observe that a participant who expects the other firm to produce a high amount responds by producing a high amount himself as well. One interpretation of this could be that he responds to the decision of the other firm, and thus is responding strategically. However, it could also be that this is a participant who always produces a high quantity. Or it could be that the participant is in period 1, where average quantities are higher than in later periods in LOW and HIGH. Or it could be that the participant and the other firm have a relatively large stock left, which means he should both produce a high quantity and expect the other firm to do similarly.

To filter out these alternative explanations we use the following panel data regression:

$$Q_{it} = \beta * EQ_{jt} + \gamma_1 * S_{it} + \gamma_2 * S_{jt} + \gamma_3 * Q_{i,t-1} + \gamma_4 * T_{it} + \delta_i + \epsilon_t$$

Firstly, the regression includes time fixed effects (γ_3) and individual fixed effects (δ_i) to correct for systematic differences between people and periods. We saw possible evidence of period-specific production differences in some of the graphs above, whereas individual differences are likely to occur if some participants persistently produce more aggressively than others. The two stock variables (S) reflect dynamic optimization behavior since in the dynamic benchmarks a firm's production decision should be an increasing function of the own resource stock and a decreasing function of the other firm's resource stock. Moreover, lagged quantity is included to allow participants to base their decisions on past observations. The final variable (EQ_{jt}) is the expected quantity produced by the other firm, which is the strategic interaction variable²². Note that we apply the same regression to all treatments, including FULL. To keep the regressions between treatments as comparable we replace the stock variables with a measure of cumulative extraction. The implications of this measure are the same (the more the participant has previously produced, the lower the score on the measure) and hence we shall keep referring to it as stock.

Because of possible reverse causality issues, we will not use expectations directly. Instead, we use an instrumental variable approach, where we instrument the current prediction using last period's prediction and last period's other firm quantity. Last period's prediction meets the two criteria for a valid instrument since it (a) affects the current prediction and (b) does not affect the current production decision directly and vice versa. Last period's other firm quantity (a) also affects the current prediction and (b) is unlikely to affect current production directly. Note, however, that while this approach allows us to correct for the endogeneity problem in expectations, it does not correct for the possibility that merely eliciting expectations will affect behavior.

5.3.1 Results

Table 5 displays the results of the regression for all treatments. When it comes to the prediction variable (Prediction in t), the results are in the direction predicted by hypothesis 2a: participants are more likely to condition their behavior on what they expect the other

²²The included variables contain all the information that participants had on their decision screen, except for information about what happened in periods before the last period. We did not include more periods since an analysis with lagged variables can only be done in periods where these variables are actually available. With lags of length one, this means that only the first period needs to be discarded, whereas longer lag lengths require later periods to be discarded as well.

Table 5: Strategic Behavior: Instrumental Variables

	Dependent Variable: Quantity in t					
	LOW		HIGH		FULL	
	Coeff.	Std Err.	Coeff.	Std Err.	Coeff.	Std Err.
Prediction in t	.2426	.0595***	.1552	.0641**	.3793	.1195***
Stock in t	4380	.0410***	.287	.0323***	-.0268	.0319
Quantity in $t - 1$	.3294	.0599***	.5439	.0616***	.2741	.0603***
Other firm stock in t	-.0738	.0225***	-.0075	.0101	.0001	.0301
Observations	1280(64)		1440(72)		1000(50)	
R-Squared	.7417		.4941		.6252	

Clustered Standard Errors in parentheses

* significant at 10%; ** significant at 5%; *** significant at 1%

firm to do in the FULL treatment. However, the effect is somewhat stronger for the LOW treatment than for the HIGH treatment, contrary to hypothesis 2b. The result that in the LOW treatment participants seem to respond more to others might seem somewhat puzzling; we will see that this effect is reversed in rounds where expectations are not demanded. At the same time, the differences between treatments are not significant at conventional levels.

However, the strategy coefficient reflects an average only; averages do not tell us if a low coefficient is (a) caused by more people responding negatively (as a Nash strategy would predict), (b) fewer people responding positively or (c) all participants responding less. To investigate this issue, we run a regression similar to table 5 for every individual; we do not use IV here since at the individual level too few data points are available to get reliable results. We then count the number of participants who have a positive and a negative coefficient for expectations respectively.

The results (table 6) reveal a very similar pattern to the results of the previous section. A larger share of participants responds to their expectation either negatively or positively in the FULL treatment compared to the other two treatments, with participants responding slightly more in LOW than in HIGH overall. Indeed, this difference is significant for LOW versus FULL ($z(112)=-2.78$, $p<.01$, Mann-Whitney) and for HIGH versus FULL ($z(122)=-3.44$, $P<.01$), but not for LOW versus HIGH ($z(136)=.72$, $p>.1$). Interestingly, the number of participants who have a negative coefficient for expectations is higher in FULL than in any of the other two treatments. Indeed if we sum the number of participants with a positive coefficient and subtract the number of participants with a negative coefficient and divide by the total number of participants (as in the final column of table 6) we get almost the same coefficients as in table 5 above.

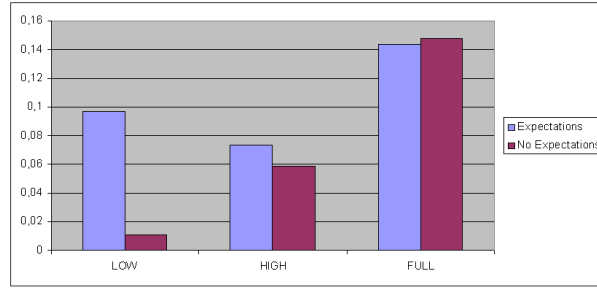
When it comes to the variables of hypothesis 1, participants condition their production decision on their own stock in the LOW and HIGH treatment but not in the FULL treatment, as expected. Moreover, the t-value for stock is much higher for the LOW and the difference in coefficients is significant at the 1% level. Participants in the LOW treatment also adjust their production upwards if the other firm has a lower stock. This is what dynamically optimal best response behavior would predict for both LOW and HIGH, but it is altogether absent from the HIGH treatment. This suggests that participants were more focused on the dynamic consequences of the other firm's behavior in the LOW treatment. Indeed the difference in coefficients is significant at the 1% level. Both findings are in line with hypothesis 1.

Table 6: Strategic Behavior: Individual Level

	Negative	Positive	Overall	Normalized
LOW	1(1.6%)	16 (25%)	17 (26.6%)	.2344
HIGH	2(2.8%)	13 (18.1%)	15 (20.9%)	.1528
FULL	5(10%)	21 (42%)	26 (52%)	.3200

Counts the number of people with a significant coefficient in a regression of quantity on expectation, lagged quantity, stock, other firm stock and time dummies

Figure 12: Responsiveness: Expectations versus No Expectations



Finally, there is a strong correlation between past and current production levels in all treatments. Thus, someone who produced a relatively high quantity in the last period is more likely to do so also in the current period. Moreover, this effect is particularly strong for the HIGH treatment²³. Although this effect is not of direct interest to the main hypotheses, participants were more likely to stick to what they were doing in the last period in the HIGH treatment.

In sum, firms that have a higher stock indeed pay less attention to the dynamic optimization aspect, as predicted by hypothesis 1. In particular, we found that firms in treatment LOW were more likely to condition their production decision on the stock of the other firm (1a) and were less likely to produce competitively (1c) than firms in the HIGH treatment. As expected there was no indication of any dynamic behavior in the FULL treatment (1b). For the hypothesis that firms with a high resource stock pay more attention to the competition aspect (hypothesis 2), the results were somewhat mixed. On the one hand we did find that participants were more likely to condition their production decision on what they expected the other firm to produce in treatment FULL than in other treatments (1a), although this difference was significant only at the individual level. On the other hand, firms in the HIGH treatment were actually somewhat less likely to condition their behavior on what they expect the other to produce than firms in the LOW treatment, although this difference was never significant.

5.4 Re-examining Expectations

So far we have looked only at rounds where participants were asked for expectations, primarily because we used the expectations variable in most of the analyses run above. However, there is a possibility that participants in the lab may respond differently to a decision problem if they are explicitly asked for their expectations. To see if this is the case, we repeat the

²³The difference between HIGH and the other two treatments is significant at $p < .05$

Table 7: Interactions (Expectations vs no Expectations rounds)

	Dependent Variable: Quantity in t					
	LOW		HIGH		FULL	
	Coeff.	Std Err.	Coeff.	Std Err.	Coeff.	Std Err.
With Expectations						
Other firm quantity in $t - 1$	.0971	.0234***	.0732	.0465	.1439	.0534***
Stock in t	.4450	.0413***	.2995	.0332***	-.0043	.0307
Quantity in $t - 1$	.3656	.0607***	.5640	.0585***	.3593	.0617***
Other firm stock in t	-.0003	.0154	.0110	.0129	-.0503	.0209**
Observations	1280(64)		1440(72)		2000(50)	
R-Squared	.7224		.4462		.5824	
Without Expectations						
Other firm quantity in $t - 1$	.0110	.0314	.0590	.0369	.1480	.0564**
Stock in t	.4103	.0315***	.3306	.0429***	-.0527	.0303*
Quantity in $t - 1$	.3901	.0523***	.3947	.0729***	.1696	.0754***
Other firm stock in t	-.0009	.0135	.0040	.0172	-.0310	.0264**
Observations	1280(64)		1440(72)		2000(50)	
R-Squared	.7405		.4253		.5095	

Clustered Standard Errors in parentheses

* significant at 10%; ** significant at 5%; *** significant at 1%

Table 8: Strategic Behavior: Individual Level

	Negative	Positive	Overall	Normalized
With Expectations				
LOW	2 (3.1%)	7 (10.9%)	9 (14.1%)	.078125
HIGH	1 (1.4%)	7 (9.7%)	8 (11.1%)	.083333333
FULL	4 (8%)	14 (28%)	18 (36%)	.2
Without Expectations				
LOW	3 (4.7%)	2 (3.13%)	5 (7.8%)	-.015625
HIGH	5(6.9%)	6 (8.3%)	11 (15.3%)	.013888889
FULL	2 (4%)	8 (16%)	10 (20%)	.1200

Counts the number of people with a significant coefficient in a regression of quantity on lagged other firm quantity, lagged quantity, stock, other firm stock and time dummies

analysis of the previous section separately for rounds where expectations are not asked and rounds where they are asked. However, since the expectation variable is not present in the former case, we replace the expectation variable by last period's other firm quantity, which was previously used as an instrument for expectations.

Table 7 gives the results for rounds with and without expectations for all treatments separately. For treatments HIGH and FULL, the coefficients for last period's other firm quantity are very similar, though somewhat less precise. However, for the LOW treatment, decreases from 0.097 to 0.011. Moreover, this difference is significant at the 5% level ($t(57)=2.21$, $p<.05$). The results are displayed graphically in figure 12.

Table 8 gives the results of the analysis done at the individual level. In the LOW treatment fewer participants respond both in general and positively. A similar story also holds for the FULL and HIGH treatment; this might explain why the aggregate coefficient was measured less accurately than in rounds with predictions. Thus these findings seem to largely support the findings at the aggregate level.

Thus, what we see at both the aggregate and the individual level is that in the LOW treatment, participants seem to respond less to others if they are not asked for their expectations. At first glance, this might seem to be a puzzling finding. However, recall that by hypotheses one and two we expected the degree to which participants paid attention to either dynamic optimization or competition would be a function of remaining stock size. However, it may be that the degree to which participants pay attention to each of these aspects also changes as the result of the expectation elicitation procedure. In particular, this line of reasoning suggests that asking for expectations shifts the focus of the participants towards the other firm, since it forces them to make predictions on what the other firm is going to do. As a result, they are more focused on responding to the other firm in rounds where they are asked for expectations. This is indeed what we find in particular for the LOW treatment.

6 Conclusion and Discussion

In conclusion, we have presented a first investigation of the nonrenewable resource problem in an experimental context. In particular, we investigated if the degree to which firms pay attention to either the dynamic optimization aspect or the competition aspect is a function of remaining stock size. Indeed, we hypothesized that firms would pay more attention to dynamic optimization when they had a low stock remaining; they would pay more attention to competition if they had a relatively high stock left over. The results suggests that this is indeed the case. In particular, firms with a low resource stock indeed paid more attention to the dynamic optimization aspect than either firms with a high stock or firms with no resource scarcity. Moreover, firms with no resource scarcity paid most attention to the competition aspect, although there were no significant differences between low stock and high stock firms.

These results suggest first of all that nonrenewable resource firms only start paying attention to optimally saving their resource stock once their resource has become relatively scarce. As a consequence, as long as resources are still relatively abundant, firms will produce a too large quantity, leading to a quickened exhaustion of the resource pool. This is in line with the failing of the Hotelling rule: firms may simply have had too many resources left to bother taking the eventual exhaustion of the resource into account.

Secondly, the results suggest that the nonrenewable resource framework, though difficult, can be implemented in a laboratory experiment. This creates the possibility to also investi-

gate other characteristics of nonrenewable resource markets in an experimental context. For example, it would be possible to investigate different market forms (such as leader-follower), allow for explicit communication between firms or investigate different production control mechanisms and see which one is most effective. At the same time, care should be taken to ensure that the experiment does not become too complicated for participants, as this will introduce more noise into the data, which could make it harder to extrapolate meaningful results from the data.

Thirdly, we saw that eliciting expectations may indeed have an impact on the way participants behave in the experiment. In particular, participants were more likely to condition their production on the other firm's behavior in rounds where expectations were requested in the LOW treatment. At the same time, possible reverse causality or false consensus issues can be addressed using a two stage least squares procedure.

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