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Abstract

Nonrenewable Resources, Strategic Behavior and the Hotelling Rule: An Experiment

by Roel van Veldhuizen and Joep Sonnemans*

This study uses the methods of experimental economics to investigate possible reasons for the lack of empirical support for the Hotelling rule for nonrenewable resources. We argue that as long as resource stocks are large enough, producers may choose to (partially) ignore the dynamic component of their production decision, shifting production to the present and focusing more on strategic behavior. We experimentally vary stock size in a nonrenewable resource duopoly setting and find that producers with large stocks indeed pay significantly less attention to variables related to dynamic optimization, and overproduce relative to the Hotelling rule.

Keywords: Laboratory experiment, nonrenewable resources, Hotelling rule, dynamic oligopoly

JEL classification: C90, Q30, L13

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1 Introduction

> Today those who plan for the future prosperity of their nation realize the extent to which other raw materials are essential to the general well-being, and for some of these we can see no adequate substitutes. Foremost among these most useful and least abundant (...) commodities stands mineral oil. (...) [Even] the most optimistic American may well ask himself, Where will my children and children's children get the oil? - George Otis Smith, National Geographic (1920)

Politicians, geologists and companies alike have been concerned with the depletion of nonrenewable resources for a long time. Indeed, George Otis Smith's words written some 90 years ago are surprisingly similar to comments made in recent years about coal depletion (e.g. Heinberg, 2007), phosphate depletion (e.g. Déry and Anderson, 2007) and oil depletion (e.g. Deffeyes, 2005). These concerns are rooted in the fear that if we continue to remain dependent on nonrenewable resources, we run the risk of economic collapse once these resources are no longer available. This has led to calls for governments to actively intervene and aid in the development of renewable alternatives. Indeed, former president Bill Clinton remarked in 2006 that "we may not have as much oil as we think, so we need to get in gear [and reduce oil dependence]" (Energy Bulletin, 2006), with then president George W. Bush going one step further by stating that the United States should "get off oil" (Mouawad, 2008).

However, economic theory suggests that the situation may not be quite so bad. Hotelling (1931) showed that in a perfectly competitive industry, nonrenewable resource producers will deplete the resource at the socially optimal rate. Moreover, in the presence of market power (Solow, 1974) or the presence of a constant severance tax (Heaps, 1985), the market will actually extract at a lower rate. To the extent that these factors are important, we should therefore be worried about nonrenewable resources being exhausted *too slowly*. In theory, the ideological successors of George Otis Smith can thus relax knowing that depletion–when it occurs–is likely to occur at the socially optimal time or later, provided that Hotelling's framework holds.

Yet how confident can we be that producers actually follow the Hotelling approach? Hotelling (1931) showed that in a perfectly competitive environment with zero marginal costs and constant demand (real) prices should grow at the rate of interest; a result which has become known as the *Hotelling rule*. More generally, prices may in fact grow at a larger or smaller rate depending on the assumptions, yet they should always grow in the long run.[1]

How well, then, does Hotelling's framework fit the real world? Figure 1 gives a time series of real crude oil prices since the 1860s. Clearly, there are occasional periods of increasing prices, yet prices have overall remained around the same level despite an enormous increase in production (Hall and Hall, 1984; Adelman, 2002). Moreover, this pattern is by no means unique to oil prices; figure 2 shows that (like crude oil) copper, zinc and iron ore prices have also not increased. More formally, in reviews of the empirical literature Krautkraemer (1998), Kronenberg (2008) and Livernois (2009) argue that empirical support for the Hotelling framework is very limited.[2]

Yet if the Hotelling framework is normatively the best way to approach the nonrenewable resource problem, this raises the question of what reason resource owners have had for not adopting it. In this article, we argue that the failure of the Hotelling rule may be the result of the multifacetedness of the nonrenewable resource problem. In particular, we argue that the nonrenewable resource problem consists

[1] In the short run they may temporarily decrease under some assumptions, for example if extraction costs are positive and decreasing over time. However, prolonged stretches of non-increasing resource prices are implausible; see the next section for more details.

[2] Empirical support is largely based on a small number of studies that have failed to reject one or more predictions implied by the Hotelling framework (e.g., (Miller and Upton, 1985; Stollery, 1985; Slade and Thille, 1997; Berck and Bentley, 1997; Chermak and Patrick, 2002)).

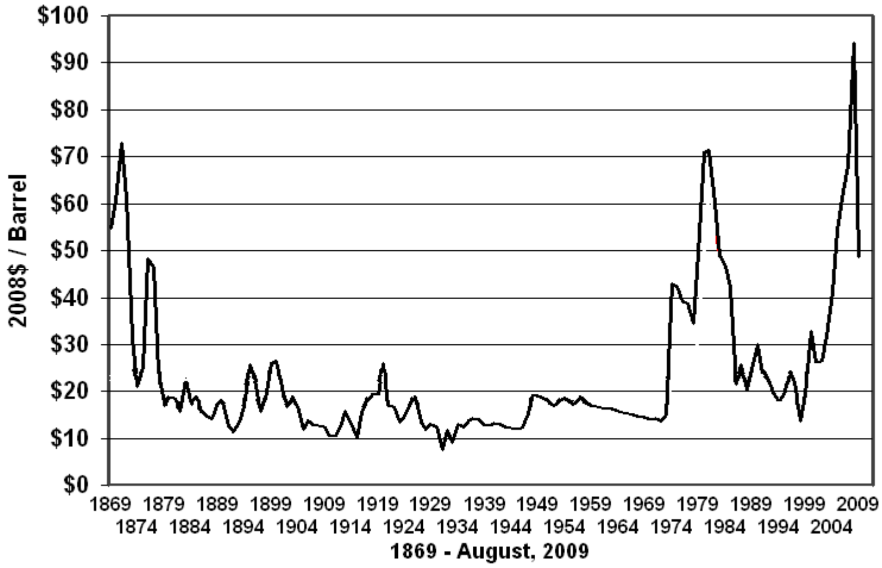


Figure 1: Crude Oil Prices (2008 Dollars)

Notes. This figure is adapted from "Oil Price History and Analysis (Updating)" by J.L. Williams, *http://www.wtrg.com/prices.htm*, 2009 (accessed April 22nd, 2010).

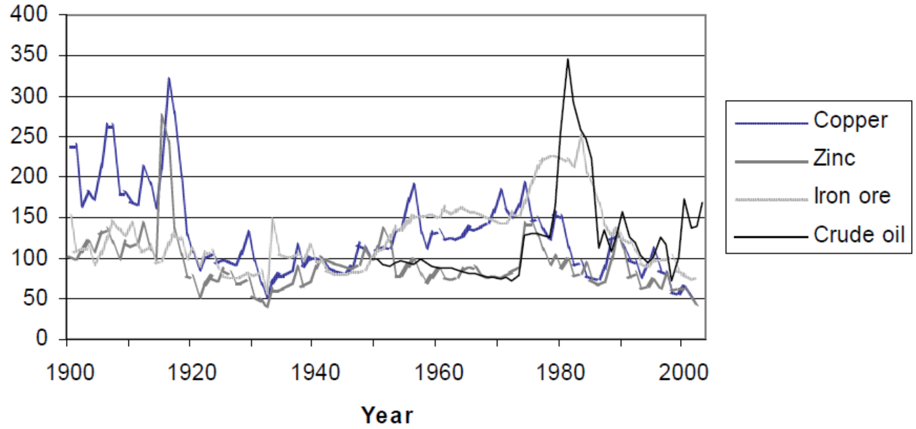


Figure 2: Resource Prices (1949 Dollars)

Notes. This figure is reprinted from "Should We Worry About The Failure Of The Hotelling Rule" by T. Kronenberg, 2008, *Journal of Economic Surveys, 22(4)*, 774-93.

of many different aspects (e.g. exploration, strategic behavior, technological developments, dynamic optimization, etc.) and that in practice producers may not be willing or able to take every aspect fully into account. Moreover we argue that the degree to which a nonrenewable resource producer pays attention to a given aspect of the resource problem depends on whether it can be feasibly included in the optimization problem, whether the benefits of including it outweigh the costs and whether the aspect is salient to the producer.

Indeed, many nonrenewable resource owners may not have sufficient computational capacity to take every aspect into account for all future periods. In fact, even including more than one aspect into a single model has proven very difficult.[3] Moreover even if a nonrenewable resource producer did have the ability to include all aspects of the nonrenewable resource problem in its decision making process, it might not be beneficial for her to do so from a cost-benefit perspective. For example, making accurate predictions about market demand in 15 or 20 years is likely to be quite costly, whilst a transient change would have a negligible effect on present-day extraction rates. In addition not all aspects of the nonrenewable resource problem may be equally salient to a producer. For example, the manager of a resource firm may not be directly concerned with long-run profits if she expects to retire long before the date of exhaustion has been reached.[4]

Although in principle there are many possible aspects to consider, in this article we will focus on the two aspects that are in our opinion the most crucial parts of the nonrenewable resource problem. The first key aspect of the nonrenewable resource problem is that producers always have to take into account that their current extraction decision is going to affect future extraction possibilities. This is a necessary characteristic of the Hotelling framework and a necessary condition for the Hotelling rule to hold; we will refer to it as the dynamic optimization aspect. The less attention producers pay to the dynamic optimization aspect, the further away from the Hotelling rule their production path will be.

The other key element of most real-life incarnations of the nonrenewable resource problem is that multiple producers are active on the market, leading to the possibility of strategic behavior with respect to other producers. In this context, strategic behavior entails making accurate predictions about the production levels of other firms and (best) responding accordingly. Most non-renewable resources have multiple active producers, which has led to a large number of papers focusing on strategic behavior on nonrenewable resource markets (see Newbery, 1981; Lewis and Schmalensee, 1980; Groot, Withagen, and De Zeeuw, 2003; Loury, 1986; Smith, 2005; among others). Strategic behavior can have a large impact on immediate profits, most notably for large producers who have the ability to substantially affect market prices. The less attention producers pay to the strategic behavior aspect, the less they update their production decision on the basis of the production decision of other producers.

We argue that the degree to which nonrenewable resource producers pay attention to a given aspect of the resource problem depends on the size or longevity of their resource stock. In particular, the larger the resource stock is, the less (more) attention a producer will pay to dynamic optimization (strategic behavior). Indeed, for a large stock producer the date of exhaustion is still far in the future, which may make it computationally difficult to stick to a dynamically optimal time path for all periods, whereas the benefits of doing so may not outweigh the costs in any case. On the other hand, it will be relatively profitable to behave strategically with respect to other producers and perhaps even create a cooperative agreement. Similarly, the date of exhaustion for a small stock producer is more imminent, making it more beneficial, computationally easier and more salient to take the imminent exhaustion into account. Since most nonrenewable resource producers in practice still have a large remaining stock (Shafiee and

[3]See e.g. Groot, Withagen, and De Zeeuw (2003) for a discussion of some of the difficulties associated with incorporating both dynamic optimization and strategic behavior into a single model.

[4]Pindyck (1981) and Farrow (1985) and Spiro (2012) give evidence that resource firms may ignore some aspects of the resource problem in practice. Cairns (1986) argues that mining firms may ignore the dynamic optimization aspect in the Nickel industry.

Topal, 2009; Sorrell et al., 2010), we should thus expect them to focus more on strategic behavior than on dynamic optimization, leading to overproduction with respect to the Hotelling rule.

Ideally, it would be possible to investigate the relationship between stock size and the applicability of the Hotelling framework using field data. However, using field data to investigate this relationship might be problematic for several reasons. One problem is that field data may be biased (a well-known example is OPEC 'proven reserve' data).[5] Field data may also be unavailable altogether (especially marginal cost data; Krautkraemer, 1998) or may simply be very noisy (e.g. because of unobserved demand shifts, small changes in technology etc., see e.g. Griffin, 1985). Moreover, even if good data are available, it may be hard to compare large stock and small stock producers, since they are likely to differ on more than just the stock dimension.[6] Also, any observed production differences may be the result of changes in factors outside the model of interest (such as government interventions, oil booms on the stock market, see e.g. Hamilton, 2009) which might not be extractable from the data or otherwise may not be easily incorporated into a dynamic model. Moreover, output changes may be the result of revised expectations, which are also rarely available from field data.[7]

These data concerns can, however, be addressed using laboratory experiments. In a controlled laboratory environment, it is possible to exclude factors outside the model as well as possible biases or noise by keeping the environment fixed between sessions. Expectations can also be obtained, such that revised expectations can be taken into account and be disentangled from strategic concerns. Indeed, the field of experimental economics has a large tradition of experiments in oligopoly.[8]

We run an experiment in which two producers with a limited stock of nonrenewable resources are paired on a nonrenewable resource market. In this way the experimental setting allows for strategic behavior and dynamic optimization whilst abstracting away from other aspects of the decision problem. To our knowledge, this is the first study to investigate producer behavior in a nonrenewable resource market in a laboratory experiment.

We experimentally vary stock size and find that in the large stock treatment extraction rates are persistently above the Nash-Hotelling level, whereas in the small stock treatment they are never higher than the Nash-Hotelling level in any period. As a consequence, the Hotelling rule is almost perfectly observed in the small stock treatment, whereas in the large stock treatment it is persistently violated through overproduction. Moreover, when we investigate what aspects of the decision problem producers pay attention to, we find that producers with small stocks pay significantly more attention to variables related to dynamic optimization, although the evidence for strategic behavior is not so clear-cut.

In the next section, we will review Hotelling's work as well as several previous attempts at explaining the failure of the Hotelling rule. In section 3 we formulate the model that forms the basis of the experiment, which brings us to the hypotheses for the experiment in section 4. In section 5, we then go over the design of the experiment before we show the results in section 6. Finally, section 7 provides a short discussion of the results.

[5] In particular, since OPEC production quotas became based on proven reserves in the early 1980s, the official estimates of some OPEC states (including Saudi Arabia, UAE, Iran and Iraq) have shown suspiciously large upward jumps in reserve levels. For example, the UAE's proven reserve increased by nearly 200% from 1985 to 1986 (BP, 2010). See Gerlagh and Liski (2011) for a theoretical model that provides one explanation why it may be optimal to overstate reserves.

[6] Also, small stock nonrenewable resource markets are quite hard to find, since in most cases resource pools are still projected to be sufficient for several decades.

[7] See Farrow (1985) or Chermak and Patrick (2002) for a more detailed discussion of difficulties associated with testing the Hotelling framework using field data.

[8] See for example Huck, Normann, and Oechssler (1999, 2004); Abbink and Brandts (2008, 2009); Apesteguia, Huck, and Oechssler (2007); Apesteguia et al. (2010); Rassenti, Reynolds, Smith, and Szidarovszky (2000) or see Engel (2010) or Potters and Suetens (2013) for an overview of the literature. See also Chermak and Krause (2002); Fischer, Irlenbusch, and Sadrieh (2004); Sadrieh (2003); Brown, Chua, and Camerer (2009) for experiments on dynamic optimization tasks.

2 Literature Review

The origins of the field of nonrenewable resource economics can be traced back to Harold Hotelling (1931). In the spirit of an earlier work by Gray (1914), Hotelling sets out the problem of a firm –in his case the owner of a mine[9]– facing a limited stock of resources. Hotelling's work is notable for its novelty and for its sheer scope: it addresses not just a then new economic problem but also discusses many relevant extensions, including uncertainty, the possibility of exploration and market power.[10]

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 extracting their resource in the present and extracting it at some future date. For the market to be in equilibrium and to prevent arbitrage opportunities, firms have to be indifferent about when to extract their resource. Hotelling shows that in a competitive environment with zero marginal costs, the only way to keep resource owners indifferent between extracting in the present and extracting in the future is for resource prices to grow at the rate of interest. That way, extracting a marginal unit in the present results in a marginal profit of today's price plus the interest over today's price, and this is equal to the benefit of extracting a marginal unit in the future. This result has become known as the *Hotelling rule*.

The Hotelling rule in its original form assumes a competitive environment with zero marginal costs. However, it can be generalized to other environments as well. In a more general form, the Hotelling rule states that the *scarcity rent* should grow at the rate of interest. The scarcity rent represents the excess return that producers get to compensate them for exhausting their resource. The scarcity rent is thus equal to the difference between the equilibrium price on a nonrenewable resource market and the equilibrium price on the same market if the resource had been abundant. It is also sometimes referred to as the in situ value, (marginal) user cost or shadow price of the resource. Examples of generalized Hotelling rules are presented in studies which allow for exploration possibilities or technical innovation (Pindyck, 1978, 1980; Arrow and Chang, 1978), allow producers to have non-profit maximizing motives (Mead, 1979) and allow the market to be less than fully competitive (Newbery, 1981; Loury, 1986; Polasky, 1992; Salo and Tahvonen, 2001; Groot, Withagen, and De Zeeuw, 2003).

Many of these generalizations were created to provide an explanation for the lack of empirical support for the original Hotelling (1931) rule. It is possible for a generalized Hotelling rule to imply non-increasing prices under certain conditions. Intuitively, in any Hotelling-type model prices are pushed upwards over time by increasing scarcity rents. For a model to be consistent with non-increasing prices, there thus needs to be an alternative force that provides enough downward pressure on prices to compensate the upward pressure created by the increasing scarcity rents. Previous work has suggested several mechanisms through which non-increasing prices can occur within a generalized Hotelling rule.

Firstly, including *exploration possibilities* can lead to a U-shaped price pattern if there are *stock effects* in the cost function (Pindyck, 1978). That is, newly found resource stocks may be cheaper to extract, which means that marginal cost decreases may more than match increasing scarcity concerns, leading to decreasing prices. Relatedly, *technological developments* can also lead to decreasing marginal costs and (non-increasing or) decreasing price patterns in the short to medium run (Slade, 1982). In both cases price decreases are the result of marginal costs decreases which more than match scarcity rent increases. However, since marginal costs are bounded from below, prices will eventually have to start rising. Thus, either exploration possibilities or technological developments can only explain non-increasing resource prices in the short run; in the long run they imply a U-shaped price pattern. However, there is little evidence for a long-run U-shaped price pattern for any nonrenewable resource.[11]

[9] In this article, we shall use the terms firms, producers and resource owners interchangeably.

[10] See Devarajan and Fisher, 1981 for an early overview of the impact of Hotelling's work on the field.

[11] A notable exception is formed by oil prices from 1870 to 1978. Indeed Slade (1982) finds a U-shaped time pattern for this time period. However, prices have since fallen back to World War II levels. Thus her results may no longer be

It is also possible for non-increasing prices to occur for *strategic reasons*. For example, if price is taken as a signal of resource abundance, it may be beneficial for resource owners to keep prices artificially low to prevent a third party from developing a renewable alternative (Gerlagh and Liski, 2011). However, their model with discounting predicts increasing prices in the short run and falling prices in the long run, which seems hard to reconcile with current price data. Alternatively, non-increasing prices can also be caused by *insecure property rights*. This applies for example to the early history of American oil drilling, when property rights applied to land parcels and not oil fields, meaning that there were often multiple pumpjacks extracting oil from the same field.[12] More recently, it also applied to the Middle East oil fields of the 1960s and 1970s, when the big American oil firms correctly anticipated that their resources would be confiscated in the near future (Mead, 1979). Yet although property rights may explain non-increasing prices for some resources in some periods, they have been quite well defined for other resources and other time periods and there, too, prices have rarely consistently increased.

There are several more extensions of the Hotelling set-up which allow prices to be non-increasing, including capacity constraints and stochastic exploration (see Krautkraemer's 1998, Gaudet's 2007 or Livernois' 2009 survey of the literature for more details). Each of these mechanisms could explain the empirically observed pattern of non-increasing resource prices in the short run. At the same time, scarcity rents should still be increasing even in the short run.[13] However, studies examining (constructed estimates of) scarcity rents have also failed to consistently reveal increasing trends (Farrow, 1985; Halvorsen and Smith, 1991; Cairns and Davis, 1998). For example, Farrow (1985) gives a case where scarcity rents actually seem to decrease over time.

What all these extensions have in common is that they attempt to reverse the implications of the basic Hotelling rule (i.e. find a model that predicts decreasing prices instead of increasing prices) while keeping the main assumption –firms dynamically optimize profits over a long time horizon– intact. However, following Pindyck (1981) and Cairns (1986) we argue that in fact the assumption that firms dynamically optimize profits over a long time horizon –though normatively appealing– may not be descriptively accurate. Indeed, as Adelman (2002) and Hamilton (2009) argue, another way to interpret historical data on oil prices is to say that "oil prices historically hav[e] been influenced little or none at all by the issue of exhaustability" (Hamilton, 2009). First, however, we will derive the Hotelling model that forms the benchmark for the remainder of the article.

3 Theoretical Framework

We generalize the Hotelling set-up by allowing for market power in the Cournot sense. This way, the model allows for both dynamic optimization and strategic behavior. Other than allowing for market power, we stick to the original Hotelling set-up as much as possible. Hence, we abstract away from possibilities of exploration, capital investments et cetera.

Let there thus be N symmetric producers indexed i with a per-period profit function $\Pi(q_t^i, Q_t)$ that depends on the producer's quantity of the resource sold in period t (q_t^i) as well as the market quantity sold in period t ($Q_t = \sum_{j=1}^N q_t^j$). Moreover, each producer i faces a resource constraint which limits total production over all periods to be no larger than an initial private resource stock S_0^i. There is a common discount factor δ which is equal to $\frac{1}{1+r}$, where $r > 0$ is the market interest rate.

A first thing to note about this setup is that we use a discrete time rather than a continuous time

applicable if price data are extended beyond the 1970s.

[12] This led Smith (1920) to lament "the waste of capital and labor under conditions of competitive drilling".

[13] An important exception to this point are possible stock degradation effects. Indeed, if extraction costs increase sufficiently strongly as the resource stock gets depleted, it is possible for scarcity rents to decrease over time, whilst prices would then be increasing (Livernois and Martin, 2001). However, this pattern is inconsistent with the empirically observed pattern of non-increasing prices.

framework. Although a continuous time framework is more commonplace in the literature, a discrete time framework fits in better with the experiment. To keep the experiment as simple as possible for participants, we also adopt a linear demand framework with a the choke price and b the slope of the demand function. We also assume that marginal costs are constant and (without further loss of generality) equal to zero. We then get the following specification for the profit function:

$$\Pi(q_t^i, Q_t) = (a - bQ_t)q_t^i$$

Producers maximize the sum of discounted profits subject to the resource constraint. The solution to the producer problem depends on the assumptions that the producer makes about the market quantity Q_t. Offerman, Potters, and Sonnemans (2002) mention three benchmarks, which differ only in the degree to which individual producers think they can influence the market quantity Q_t. For the Nash equilibrium benchmark, producers assume that they can only influence their own production strategies; they treat the production strategies of other producers as given. In the second benchmark (Collusion) producers maximize joint profits. Finally, for the Walras (or competitive) benchmark, producers (mistakenly) believe that no firm has the ability to influence the market price and hence the market quantity (i.e. producers assume that $Q_t \perp q_t^i \; \forall i$).

Of the three benchmarks, the Collusive and Walras benchmarks are essentially individual optimization problems, since in both cases producers assume that there are no other parties on the market that can influence their profits. Thus, both the Collusive problem and the Walras problem can be solved using calculus of variations. Letting $0 < T \leq \infty$ be the maximum number of periods and dropping the superscript i for ease of notation, the Lagrangian becomes:

$$L = \sum_{t=0}^{T} \delta^t (a - bQ_t)q_t - \lambda(\sum_{t=0}^{T} q_t - S_0)$$

Here, λ is the Lagrange multiplier of the resource constraint. $Q_t = Nq_t$ for the Collusive benchmark and $Q_t = Nq_t^W$ for the Walras benchmark, where q_t^W is the average quantity on the Walrasian market. Plugging these expressions for Q_t into the Lagrangian, taking the derivative with respect to q_t and q_0, and then by symmetry putting $q_t = q_t^W$ for the Walras benchmark yields the following expression:

$$q_t \quad \geq \quad q_U^k - \frac{q_U^k - q_0}{\delta^t} \text{ with } q_U^C = \frac{a}{2Nb} \text{ and } q_U^W = \frac{a}{Nb} \tag{1}$$

This is the Hotelling rule for Walrasian or Collusive symmetric oligopolies expressed in terms of quantities. Here, q_U^k is the unconstrained or static benchmark quantity, which differs depending on the benchmark that is adopted; it is equal to the quantity that would be produced in the absence of resource scarcity, see below. By summing over all firms, equation 1 can also be rewritten in terms of prices:

$$p_t \quad \leq \quad p_U^k + \frac{p_0 - p_U^k}{\delta^t} \text{ with } p_U^C = \frac{a}{2} \text{ and } p_U^W = 0 \tag{2}$$

The two remaining steps are to use the resource constraint to find the optimal q_0 (or equivalently p_0) and the optimal time of exhaustion t^*. This procedure, though mathematically straightforward, is somewhat tedious and thus omitted. Turning our attention back to equation 2, the first term on the right is the unconstrained benchmark price. The difference between the actual market price and the unconstrained market price is made up by the second term on the right ($\frac{p_0 - p_U^k}{\delta^t}$) which is the scarcity rent of the resource.

This term is positive and exponentially increasing; as a result prices will increase exponentially with respect to the unconstrained benchmark.

Solving for the Nash equilibrium requires the use of dynamic game theory (see Başar and Olsder, 1999). Salo and Tahvonen (2001) solve for the Nash equilibrium for a continuous and infinite time framework with a continuous action space. However, the setup we use in the experiment is simpler to analyze because it uses a finite time horizon, a discrete time framework and integer production quantities. This allows us to solve for the Nash equilibrium numerically using a recursive procedure.[14] Figure 3 shows the benchmark price and quantity levels for one of the parameter combinations used in the experiment (for treatment HIGH). The figure shows that prices are increasing at the highest rate in the Walras benchmark and at the lowest rate in the Collusive benchmark. This implies that p_0 is lowest for the Walras benchmark and highest for the Collusive benchmark.[15]

It is important to note that for figure 3 we assumed that producers stick to each benchmark perfectly. However, both in the experiment and in real life it is possible that producers make mistakes or switch between benchmarks after period 1. To allow for these possibilities, we also calculated the Nash, Collusive and Walras strategies for every possible state of the market (i.e. every possible period/stock combination); these are the benchmarks we compare our results to in the results section.

Finally, in what follows we will sometimes refer to unconstrained or static benchmarks. The unconstrained benchmark quantities are the quantities that would be adopted by producers with abundant resources (and by producers who fully ignored the dynamic component of their production decision). The market quantities Q_t are equal to $\frac{N}{N+1}\frac{a}{b}$, $\frac{1}{2}\frac{a}{b}$ and $\frac{a}{b}$ for Nash, Collusion and Walras respectively. From equation 1 it is easy to see that unconstrained benchmarks always encompass larger production levels (and thus lower prices) than their dynamic counterparts.

4 Hypotheses

In previous sections we saw that the Hotelling rule does not seem to describe the data very well. In this article, we argue that the lack of empirical support for the Hotelling is due to producers not paying sufficient attention to the dynamic consequences of their production decision when their resource stocks are large. By contrast, when their resource stocks are small, we expect them to follow the Hotelling rule much more closely. Moreover, we expect producers with smaller stocks to pay less attention to strategic behavior concerns.

To test this line of reasoning, we ran a laboratory experiment of a non-renewable resource duopoly along the lines of the model of the previous section (with N equal to 2). There were two treatments. In treatment LOW, producers' resource stock was relatively small. In particular, the unconstrained collusive quantity –which is the smallest of the three unconstrained benchmark quantities– could be maintained for only one period. By contrast, in treatment HIGH, firms had a larger stock; as a result the unconstrained collusive benchmark could be maintained for up to five periods. Table 1 gives an overview of the parameters corresponding to the two treatments.[16]

We propose that producers in treatment HIGH focus less on the dynamic consequences of their production decision than producers in treatment LOW. This should be immediately visible in market

[14] In the terminology of Başar and Olsder, 1999, we are solving for the feedback Nash equilibrium. Since the producer problem in the experiment is a ladder-nested multi-act feedback game, the numerical procedure we use for the feedback Nash equilibrium is the one described by Başar and Olsder (1999) on page 119-121.

[15] Since high prices and low production levels go together, collusion actually leads to slower extraction and greater conservation of the resource. This point was also noted by Solow, 1974, who argued that "if a conservationist is someone who would like to see resources conserved beyond the pace that competition would adopt, then the monopolist is the conservationists friend. No doubt they would both be surprised to know it." (Solow, 1974, p. 5)

[16] Besides stock there were two other parameters which differed between treatments. These were fixed costs and the conversion rate of experimental points to Euros. They were changed to create similar incentives in all treatments; they did not affect any of the benchmarks in any way.

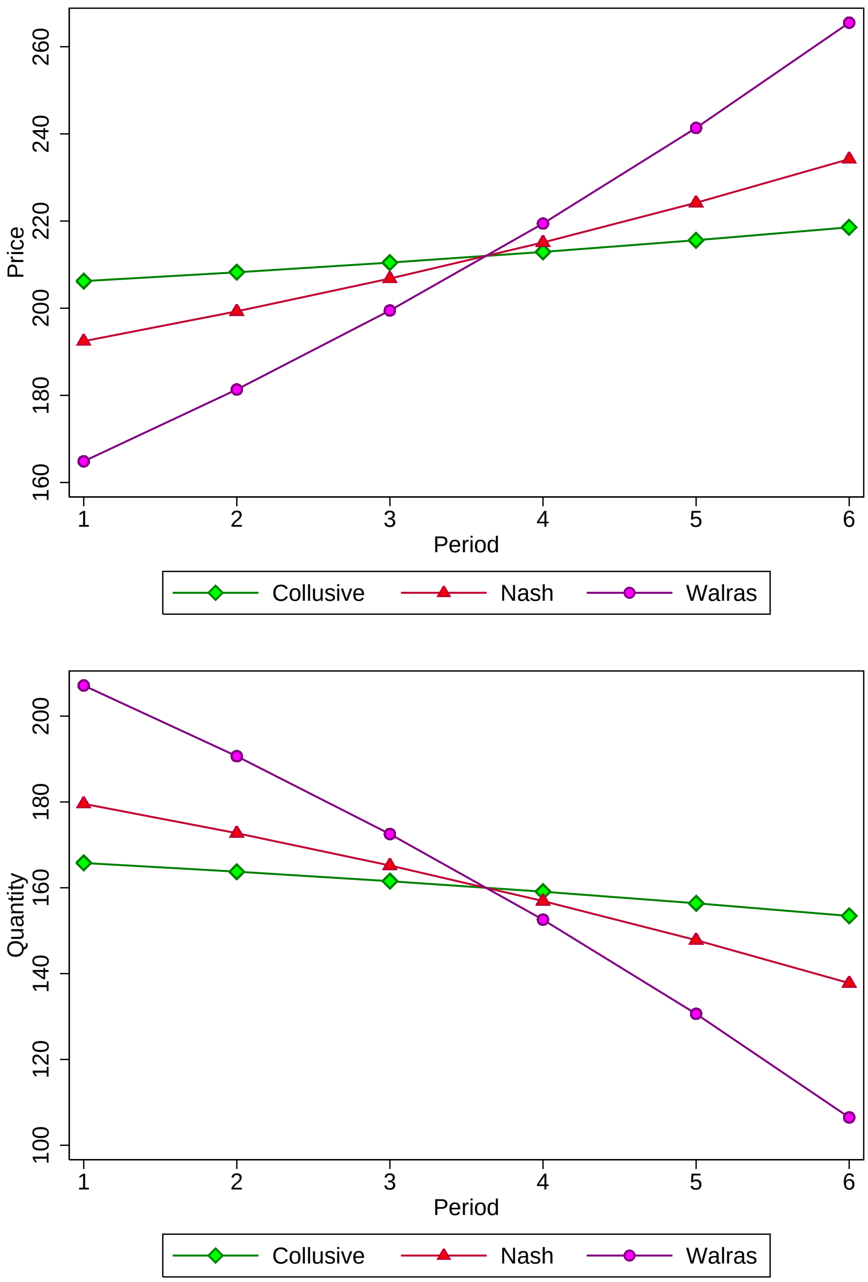


Figure 3: Benchmark Prices and Quantities

Notes. This figure plots the symmetric benchmark market prices and quantities for treatment HIGH of the experiment for all periods.

Table 1: Experimental Parameters

	Parameters			
	PROLOGUE		MAIN PART	
	Prologue 1	Prologue 2	LOW	HIGH
Stock	280	∞	170	480
a	372	360	372	372
b	2	1	1	1
Interest Rate	10%	10%	10%	10%
Periods	6	6	6	6
Producers	1	2	2	2

production levels. Producers who take the dynamic consequences of their production into account should (on average) produce the Nash-Hotelling benchmark quantity. However, producers who care insufficiently about these dynamic consequences will overproduce and extract more than the Nash-Hotelling quantity. By extrapolating this line of reasoning to market quantities, this leads to the following hypothesis:

Hypothesis 1: Markets in treatment HIGH are more likely to overproduce relative to the Nash-Hotelling benchmark than markets in treatment LOW. Analogously, scarcity rents are more likely to be below the Nash-Hotelling benchmark in the LOW treatment than in treatment HIGH.

Secondly, we investigate whether producers in treatment HIGH indeed pay less attention to dynamic optimization by directly estimating what aspects of the decision problem producers take into account in their production function. A dynamically optimized strategy requires the extraction decision to be a function of the remaining resource stock. In terms of the production function, producers who take dynamic optimization into account should all other things being equal extract a larger quantity of resources for higher levels of their resource stock. This leads to the following hypothesis:

Hypothesis 2: Producers in treatment HIGH condition their production decision less strongly on their own stock than producers in treatment LOW.

Thirdly, we propose that producers in treatment HIGH focus more on strategic behavior. Relative to treatment LOW, producers in treatment HIGH can have a (potentially) larger impact on market prices. Therefore, it pays off for a producer to pay more attention to what the other producer on their market is likely to do. For producers who behave strategically the extraction decision should be a function of the expected production level of the other producer on the market. This leads to the following hypothesis:

Hypothesis 3: Producers in treatment HIGH condition their production decision more strongly on the expected production level of the other producer than producers in treatment LOW.

5 Experimental Design

The experiment was computerized using PhP/MySQL and consisted of two stages: the prologue and the main part (see table 1). Nearly all participants were students with little to no experience with the Hotelling framework. By contrast, most resource producers in practice (and most notably the rich oil producing countries) employ experts with PhD level training in economics, engineering or mining who are very aware of the Hotelling rule and its implications. Since we did not want the Hotelling rule to fail because of a lack of understanding among our participants, we stuck to a relatively simple set-up by limiting the number of periods to six and market size to two firms.[17] Moreover, all participants had access to an on-screen calculator which allowed them to compute the profits and interest incomes for any period and any production level of themselves and the other producer. Most importantly, we started the experiment with a prologue that helped participants get to know the nonrenewable resource oligopoly problem in a stepwise way.

Upon entry into the laboratory, participants were assigned to a random computer. After sitting down, they immediately received the instructions and check up questions for prologue one on their screen (all instructions, questions and questionnaires are reprinted in the appendix). The goal of prologue one was to familiarize participants with the basics of dynamic optimization. For this purpose, we used a nonrenewable resource monopoly. Relative to a duopoly, this had the advantage that participants only needed to worry about their own production without having to worry about behaving strategically with respect to other producers. Other than having only one firm in a market and a few changes in the parameters (see table 1), prologue one was identical to the main part of the experiment.

Thus, the task consisted of allocating a fixed resource over 6 time periods. Each period, participants had to decide how much of their resource to extract and how much to save for the remaining periods. The resulting decision problem is non-trivial because of discounting; we incorporated discounting into the experiment by explicitly introducing an interest rate, such that profit earned in earlier periods would be worth more.[18] After period 6, participants were informed of their total income, which was calculated by adding profits and interest incomes from all periods and subtracting the fixed cost.

Prologue one started after all participants had finished the instructions. The first part of prologue one was a 15 minute practice stage. During the practice stage, participants could do as many non-incentivized repetitions (or rounds) of the monopoly task as they liked.[19] Thus, each participant 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 for nonrenewable resources -which is to extract more in early periods than at the end.

After the 15 minutes of practice time had expired, participants went through one incentivized round. We included this round to make sure that every participant put in sufficient effort during practice. After all participants had finished the incentivized round, the experiment moved on to prologue two. All in all, prologue one took approximately 35 minutes.

The goal of prologue two was to familiarize participants with the presence of another producer on their market (i.e., strategic behavior). For this purpose we used a standard (fully unconstrained) duopoly set-up. This allowed participants to familiarize themselves with the presence of another producer on the market without having to worry about dynamic optimization. We expected that prologue two would teach participants at least the basic rule of Cournot oligopoly -which is that (up to a point) increasing production in a given period will increase your profits, but decrease the profits of the other producer on the market.

Like in prologue one, participants' task was to make production decisions in a total of 6 periods. In every period, participants decided how much to produce; the market moved on to the next period after both producers had made their decision. During the period, their decision screen gave participants access to the production decisions of both participants and price levels in preceding periods as well as their own

[17]Indeed, we had previously run a pilot Van Veldhuizen (2009) where we had 10 periods and a group size of three and found that a small number of participants occasionally took a very long time (sometimes nearly 10 minutes) to make a single production decision. Since 98% of all decisions in the pilot were made within 90 seconds, we decided to limit the decision time per period to two minutes.

[18]Without discounting, all three benchmarks would collapse into extracting one sixth of the stock in every period.

[19]On average, participants went through 26 practice rounds, with a minimum of 10 and a maximum of 53.

profit in preceding periods. As in prologue one, there was discounting, although this did not affect any of the benchmarks in any way.[20] After six periods, participants were informed about their total income, which was calculated by adding profits and interest incomes from all periods and subtracting a fixed cost (as in prologue one).

Prologue two started with a set of instructions and check-up questions. After all participants had finished these instructions, they then went through three incentivized rounds. Participants were matched to a different participant in each round. After each round, the experiment only moved to the next round after every participant had finished all six periods; all three rounds contributed to final earnings. In total, prologue two lasted approximately 30 minutes.

After everyone had finished both prologues, the experiment moved on to the main part. Treatment variation took place in the main part only (the prologue was identical for both treatments). Hence it forms the basis for the analysis presented in the next section.

In the main part, participants' task was very similar to the prologue, except that they had to take into account both the limited resource (as in prologue one) and the presence of another producer on the market (as in prologue two). In every period, participants had to decide how much of their remaining resource to extract. During the period, their decision screen gave participants access to the production decisions of both participants, price levels and their own profits in preceding periods, as well as the currently remaining resource stocks of both participants.[21] As in prologue two, the market only moved on to the next period after both producers had made their decision. After the sixth and final time 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.

At the start of the main part, all participants received a final set of instructions and questions. After all participants had finished the instructions, they went through ten incentivized rounds. In every round, participants were matched to a different participant in their matching group.[22] In total the main part lasted approximately one hour.

One final thing to note about the main part is that in every *even round* participants were asked in every period to indicate how much they expected the other firm to produce in that period. Any strategic production decision directly depends on the expected production strategy of other producers; an advantage of experiments is that expectations can be elicited directly. Predictions were incentivized; at the end of the experiment, participants received a payment depending on the accuracy of one randomly determined prediction. For this purpose, we asked one subject to come forward and roll a die to determine the round and period that would be used to determine payment. Prediction income was then computed 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.[23]

After finishing the last round of the main part, participants received an overview of their earnings over the whole experiment. They were then asked to fill out a questionnaire, which consisted of some background questions, some questions relating to the way they played in the experiment as well as the shortened version of the Stanford Time Perspective Inventory (D'Alessio et al., 2003), a questionnaire related to time preferences. After finishing the questionnaire, participants collected their earnings and were kindly requested to leave the laboratory.

[20]Since production levels were unconstrained, the benchmark production levels were equal to the unconstrained benchmark in all periods.

[21]An example of a decision screen is given at the end of the appendix.

[22]Matching groups consisted of between 6 and 10 participants, depending on the number of participants in the session. Participants could only be matched to participants from their matching group.

[23]Note that the elicited expectations can be used to infer participants' price expectations by noting that $Ep_t = a - bq_t^i - bEq_t^j$.

6 Results

The experiment was conducted in February 2010 at the CREED laboratory of the University of Amsterdam. Participants were recruited using an online registration system. Most participants were students coming from various disciplines, with the largest fraction (58%) studying economics. In total, there were 6 sessions (3 for treatment HIGH and 3 for treatment LOW) in which a total of 136 subjects took part (72 for treatment HIGH, 64 for treatment LOW). On average, participants earned 29.27 euros.

In this section, we first take a brief look at the results of the prologue to check if participants were able to independently understand both strategic behavior and dynamic optimization. We then investigate if producers in treatment HIGH indeed overproduce with respect to the Nash-Hotelling benchmark, as per hypothesis 1.[24] We then estimate the production function to gain insight into which aspect producers paid most attention to when making their production decision (i.e. to investigate hypotheses 2 and 3).

6.1 Prologue

The purpose of prologue one (monopoly) was to familiarize participants with the dynamic optimization aspect of the nonrenewable resource problem. In particular, we expected participants to learn at least the basic rule of dynamic optimization, which dictates that scarcity rents should be monotonically nondecreasing over time. This expectation is supported by the data: scarcity rents were monotonically nondecreasing for 90% of our participants (or 123/136). Moreover, 89% (121/136) displayed a significant positive time trend in scarcity rents.[25] Furthermore, 87% (118/136) exceeded the earnings corresponding to a constant production schedule. In fact, the median participant was within 5 cents (or 4%) of the maximum (theoretical) pay-off. Thus, most producers were very close to the optimum, suggesting that they managed to achieve at least a basic understanding of dynamic optimization.

The purpose of prologue two (unconstrained oligopoly) was to familiarize participants with strategic behavior. Overall, market production levels were quite close to the Nash benchmark on average.[26] To check if participants understood the strategic behavior aspect, we use a panel regression to estimate their production function. Producers display evidence of strategic behavior if they condition their production strategy on the expected production strategy of the other producer. Since we did not elicit expectations in the prologue, we proxy for expectations using last period's other producer quantity. Table 2 documents the results of the regression. On average, participants increased their production if their rival previously produced a high quantity. All in all, the finding that average production levels are close to the Nash level and that participants production decisions are correlated to last period's other producer quantity suggest that most participants also gained some understanding of strategic behavior.

6.2 Market Outcomes in the Main Part

If hypothesis 1 is true, producers in treatment HIGH should overproduce relative to the Nash benchmark. At this point, it is important to restate that when we refer to the Nash, Walras or Collusive benchmarks in this section, we refer to the benchmarks that depend on the current state of the market (i.e. the period/stock level combination). In particular, since in period 1 different markets will in general produce different quantities, stock levels will differ between markets from period 2 onwards. As a consequence, each market will in general have a different Nash, Collusive and Walras benchmarks from period 2 onwards

[24] In the remainder of this section, we will use the terms Nash and Nash-Hotelling interchangeably to refer to the dynamic benchmark.

[25] The trend was estimated using a linear regression of scarcity rent on a constant and a linear time trend; significance was obtained using a two-sided t-test with a significance level of 5%.

[26] At the market level, production levels were not significantly different from the Nash benchmark either overall or in any individual period.

Table 2: Unconstrained Oligopoly Production Function

	Dependent Variable: Quantity in period t
Other producer quantity in $t-1$	.1512***
	(.0386)
Observations	2040
Adj. R^2	.1640

* p<0.1%; ** P<0.05%; *** p<0.01%

Notes. This table displays a fixed effects regression of period t quantity on other producer quantity in period $t-1$. Fixed effects are included for both individuals and time periods; time-individual fixed effects are omitted because of possible multicollinearity. Standard errors are clustered by individual and reported in parentheses below the associated coefficient. P-values are calculated using two-sided t-tests. The regression uses data from all three rounds; in every round the first period is omitted since lagged quantities are only available from period two onwards.

as well.[27]

Figure 4 and table 3 give an overview of scarcity rents and production levels in the main part. In addition, figure 5 and figure 6 plot the distribution of normalized production quantities ($\frac{q_t - q_t^N}{q_t^N - q_t^C}$) over all periods. Such a normalization is necessary since (1) raw production quantities are lower in later periods, (2) the benchmark quantities depend on remaining stock and are thus potentially different for every producer and (3) the meaning of a one unit deviation changes between periods with small and large predicted production.

For treatment HIGH, average production levels are higher than the Nash level in all periods; as a result the average scarcity rents are lower.[28] For treatment LOW, the scarcity rent is indistinguishable from the Nash benchmark in the first three periods; in periods 4 and 5 scarcity rents are actually higher than Nash and indistinguishable from the Collusive level.[29] Figures 5 and 6 show that a similar story holds when we look at the whole distribution, though there is evidence for some individual heterogeneity as well. All in all, the Nash-Hotelling rule consistently fails in treatment HIGH because of overproduction, whereas in treatment LOW it describes the data quite well, in line with hypothesis 1.

Thus producers in treatment LOW are closer to the Nash benchmark than producers in treatment HIGH *on average.* Figures 5 and 6 show that a similar pattern holds for the distribution as a whole. The peak of the distribution of both treatments lies close to the Nash level both at the producer level and at the market level, but it falls slightly towards the Collusive side of the Nash level in treatment LOW and towards overproduction in treatment HIGH. In terms of market (producer) production levels, 70.5% (62.4%) of all production levels are larger than the (feedback) Nash benchmark in treatment HIGH, whereas the respective percentages are 28.3% (30.5%) for treatment LOW.[30]

In summary, we have seen that producers paid more attention to the dynamic optimization aspect in treatment LOW and that this induced them to produce closer to the Nash-Hotelling benchmark than producers in treatment HIGH. At the same time, it is worthwhile to point out that on average producer behavior was quite close to the Nash-Hotelling level in both treatments. As a result, scarcity rents are actually increasing in both treatments, in line with the Hotelling rule and contrary to the findings of most

[27] Note that these benchmarks are independent of expectation about the other producer's behavior, since the other producer's behavior is fully determined by the state of the market as well. Expectations will play a role for producers who do not expect their competitor to strictly follow a benchmark, however.

[28] Since scarcity rents and prices are an affine transformation of market quantities, the test statistics for market quantities, prices and scarcity rents are identical.

[29] Note also that Collusive benchmark can be a very good dynamic strategy especially if both producers adhere to it.

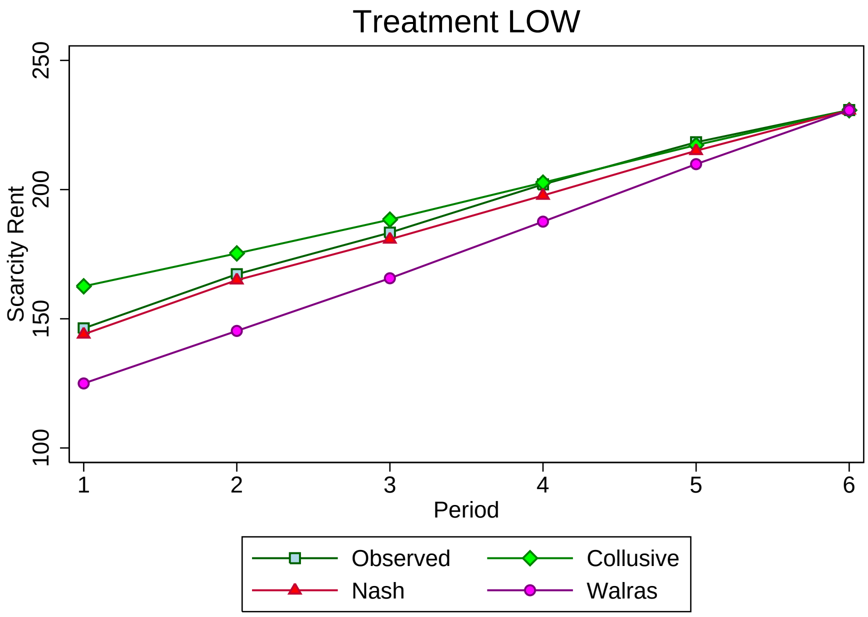
[30] The finding that in treatment HIGH producers are more likely to overproduce should also be reflected by their earnings. To see if this is indeed the case, we compare average realized earnings to potential earnings in the Nash benchmark and weigh this using the distance between the Nash benchmark and the Collusive benchmark. This results in the normalized earnings index $Y_{norm} = \frac{Y - Y_N}{Y_C - Y_N}$, where Y_N is the theoretical Nash profit, Y_C is the theoretical Collusive profit and Y is actual income. The average index is equal to -6.70 for treatment HIGH and -1.72 for treatment LOW, the difference is significant at the 1% level (Mann-Whitney, z(64,72)=6.422). In other words, earnings were significantly lower in treatment HIGH in terms of the index. This is in line with the finding that producers were more likely to overproduce with respect to Nash in treatment HIGH.

Table 3: Main Part Market Quantity and Benchmarks

Period	Average Quantity	Nash	Collusive	Walras
Treatment LOW (N=320)				
Period	Average Quantity	Nash	Collusive	Walras
1	101.70	100	85***	123***
	(2.192)			
2	80.75	83.04	72.70**	102.69***
	(2.322)	(2.691)	(2.596)	(2.692)
3	64.65	67.23	59.62*	82.32***
	(1.338)	(2.184)	(2.149)	(2.476)
4	45.975	50.28**	45.31	60.40***
	(1.149)	(1.270)	(1.146)	(1.595)
5	29.67	32.97***	30.77*	38.14***
	(1.924)	(.737)	(.494)	(1.029)
6	17.21	17.27	17.27	17.27
	(2.646)	(.037)	(.037)	(.037)
Treatment High (N=360)				
Period	Average Quantity	Nash	Collusive	Walras
1	192.22	180***	166***	207***
	(3.686)			
2	178.74	168.79***	159.43***	193.10***
	(1.940)	(2.448)	(2.510)	(2.510)
3	170.30	160.44**	152.46***	178.15**
	(2.070)	(3.138)	(3.186)	(3.186)
4	158.11	149.40***	143.71***	161.13
	(1.567)	(2.004)	(2.022)	(2.022)
5	141.96	135.46***	132.63***	141.49
	(2.492)	(1.318)	(1.219)	(1.219)
6	117.03	117.97**	117.97**	117.97**
	(4.571)	(.357)	(.357)	(.357)

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

Notes. This table compares the observed average market quantity per period to the Collusive and Walras and Nash benchmarks for every treatment. Here we use the dynamic benchmarks that depend on the current state of the market. For this purpose, all three benchmarks are calculated for every data point conditional on period, producer stock and other producer stock and then summed over both producers on the market. In the first period, all benchmark quantities are integers since all producers have the same resource stock and only integer amounts can be produced. In the final period, fully exhausting the resource is always the optimal strategy regardless of benchmark and treatment. Standard errors are clustered at the matching group level. Significance is determined using two-sided t-tests.



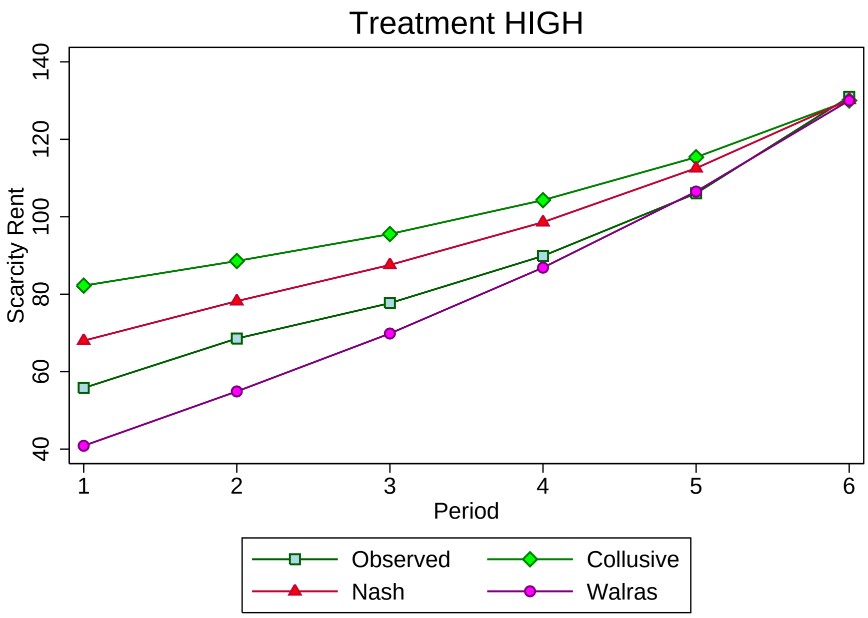


Figure 4: Scarcity Rents

Notes. The figure plots the time series of the average observed scarcity rent as well as the benchmark Nash, Collusive and Walras scarcity rent with respect to the unconstrained Nash price. The scarcity rents are computed by subtracting a fixed number ($p_U^N = 124$) from the observed and benchmark prices respectively (i.e. $p^i - p_U^N$, where p^i is the observed, Nash, Collusive or Walras price respectively). Here we use the dynamic benchmarks that depend on the current state of the market.

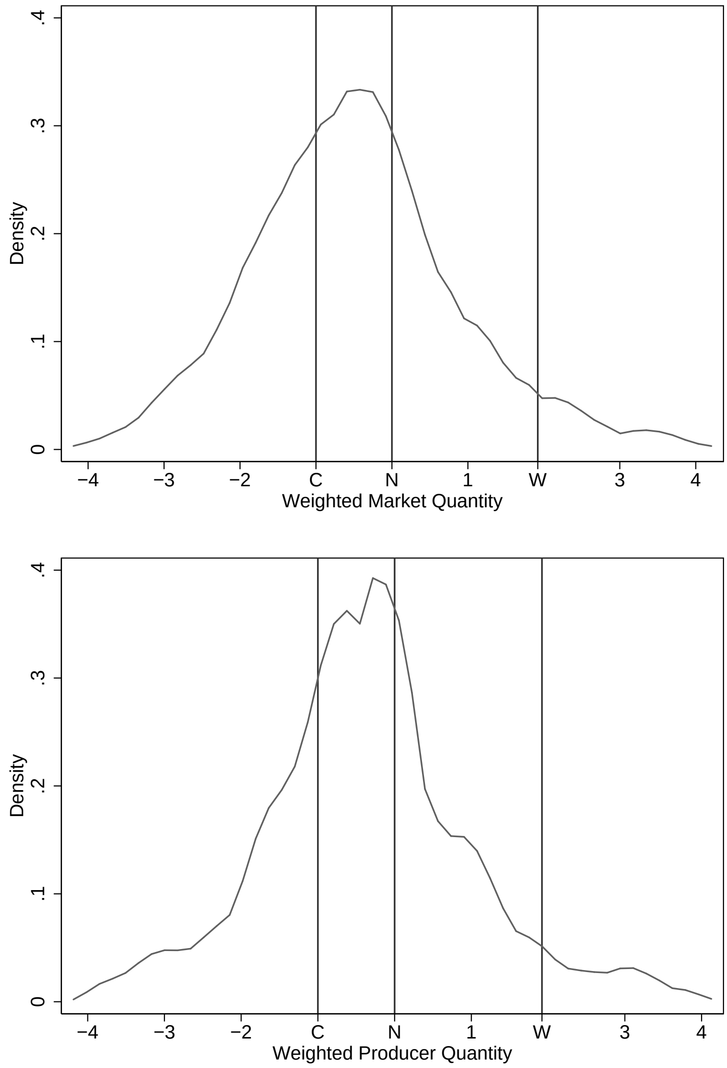


Figure 5: Treatment LOW Density Plots

Notes. The top panel plots the smoothed density (Epanechnikov kernel, bandwidth = .26) of the deviation from the Nash quantity weighted by the distance between the Collusive quantity and the Nash quantity (i.e. $\frac{q_t - q_t^N}{q_t^N - q_t^C}$) in periods one to five. The lower panel does similarly but then for producer quantity (bandwidth = .28). We look at deviations since from period two onwards the three benchmarks are different for every market; we use weights since a unit deviation from the Nash quantity means more in periods where the three benchmarks are closer together. C, N and W represent Collusive, Nash and Walras levels respectively; the Collusive and Nash levels are -1 and 0 by the normalization whereas the Walras level differs between markets (average =1.91, always bigger than zero). For the Collusive and Walras benchmarks in the individual graph, we assume the market is divided between both producers in proportion to their remaining stock. Period 6 is omitted since all benchmarks are equal to the resource stock in this period.

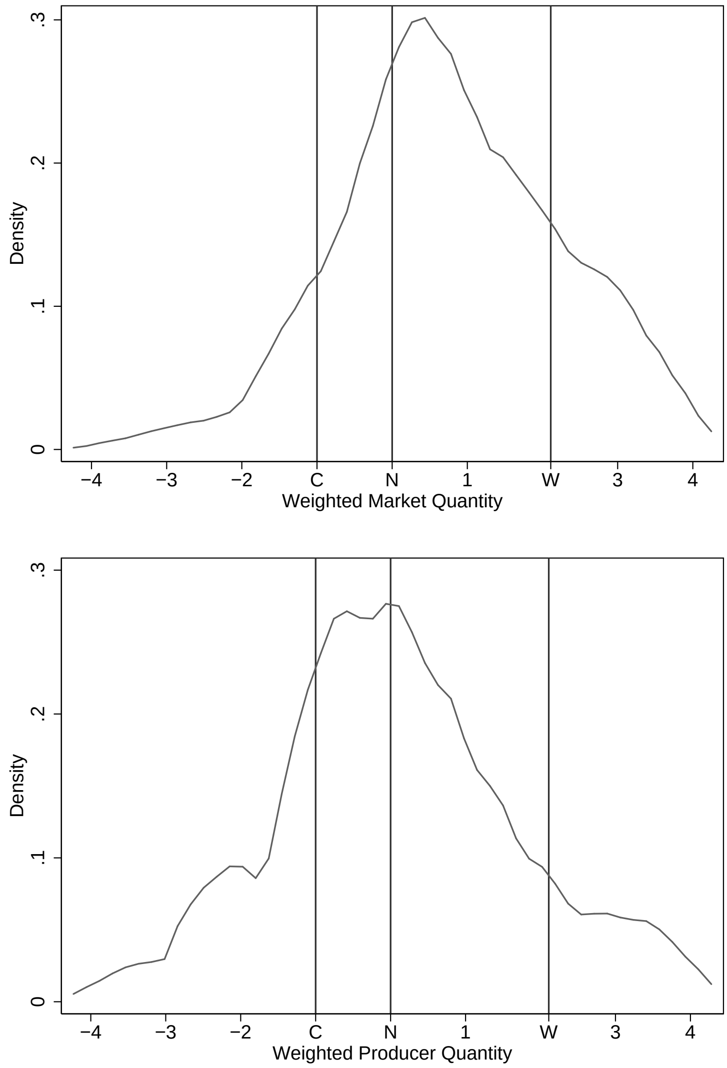


Figure 6: Treatment HIGH Density Plots

Notes. The top panel plots the smoothed density (Epanechnikov kernel, bandwidth = .22) of the deviation from the Nash quantity weighted by the distance between the Collusive quantity and the Nash quantity (i.e. $\frac{q_t - q_t^N}{q_t^N - q_t^C}$) in periods one to five. The lower panel does similarly but then for producer quantity (bandwidth = .19). We look at deviations since from period two onwards the three benchmarks are different for every market; we use weights since a unit deviation from the Nash quantity means more in periods where the three benchmarks are closer together. C, N and W represent Collusive, Nash and Walras levels respectively; the Collusive and Nash levels are -1 and 0 by the normalization whereas the Walras level differs between markets (average =2.11, always bigger than zero). For the Collusive and Walras benchmarks in the individual graph, we assume the market is divided between both producers in proportion to their remaining stock. Period 6 is omitted since all benchmarks are equal to the resource stock in this period.

previous empirical studies. Importantly, however, producers in treatment HIGH deviate most from the Nash-Hotelling benchmark and do so in the direction predicted by hypothesis 1. Thus, even producers who –based on the evidence of treatment LOW– should be able to approximate the Nash-Hotelling time path almost perfectly still overproduce if their stock levels are relatively high.

6.3 Producer Focus in the Main Part

We now turn to hypotheses 2 and 3 and investigate the degree to which producers pay attention to either dynamic optimization or strategic behavior by estimating their production function. For this purpose we estimate the following panel regression:

$$\mathrm{q}_{rit} = \beta * \mathrm{E}[\mathrm{q}_{rjt}] + \gamma_1 * \mathrm{S}_{rit} + \gamma_2 * \mathrm{S}_{rjt} + \mathrm{T}_t + \delta_i + \epsilon_{rit} \tag{3}$$

This equation posits that producer i's quantity in period t of round r is a function of both strategic and dynamic optimization variables. $\mathrm{E}[\mathrm{q}_{rjt}]$ is producer i's prediction for the quantity of producer j (the other producer); this variable represents the degree to which producer i pays attention to strategic behavior.[31][32] S_{rit} is the producer i's stock, which represents dynamic optimization. S_{rjt} is the other producer's stock; this variable is relevant only if both dynamic optimization and strategic behavior play a role, as in the Nash-Hotelling benchmark. Finally, the regression also includes time fixed effects (T_t) and individual fixed effects (δ_i) to correct for differences between people and periods.[33] Throughout the analysis, standard errors are clustered by producer.[34] Note also that the inclusion of the prediction variable means that the analysis will only use data from rounds where predictions were requested (i.e. all even rounds).[35]

Table 4 displays the results of the regression for both treatments. For the dynamic optimization variable stock, the results are in line with hypothesis 2. In particular, the coefficient for stock is larger for treatment LOW in absolute size and has a lower p-value. The difference in coefficients is significant at the 1% level.[36] Moreover, the coefficient for stock is not significantly different from the Nash coefficient for stock in treatment LOW, whereas it is significantly lower at the 1% level for treatment HIGH (the optimal coefficients are .37 and .33 respectively). All in all, these results suggest that producers were indeed less mindful of the dynamic optimization aspect in treatment HIGH, in line with hypothesis 2.

When it comes to the strategic behavior variable "predicted other producer quantity", results are less clear cut. On the one hand, the results are in the direction predicted by hypothesis 3: a change in predicted other producer quantity had a larger effect in treatment HIGH than in treatment LOW. On the other hand, the difference between treatments is small and not significant at conventional levels.[37]

[31] Since expected prices are a linear combination of quantity and other producer quantity, including this variable is equivalent to including price expectations.

[32] Predictions are very accurate on average. They are never significantly different from actual production levels in any period. The largest differences are in period 2 for treatment HIGH (prediction of 90.4 versus actual production of 89.2) and period 1 for treatment LOW (prediction 48.8 versus actual production 50.5)

[33] We do not include individual specific time fixed effects since that would greatly increase the number of parameters per individual, which would put too much strain on the data. It is possible to include round fixed effects, but these are never significant in any treatment and including them does not affect the coefficient estimates; hence we do not include them here.

[34] It would have also been possible to do the clustering by matching groups. However, the resulting standard errors are smaller and perhaps less reliable because of the relatively small number of matching groups per treatment. Hence we stick to the more conservative estimate.

[35] Another feasible regressor would have been lagged quantity, since it is not infeasible that a producer's production decision would be partially influenced by his previous production decision even after correcting for the other variables. However, including lagged quantity as a regressor would have made the the model dynamic, which would have made unbiased inference very difficult. For the same reason we also excluded lagged predictions. We also excluded lagged other producer quantity, since its p-value always exceeds .2 and including it would have resulted in the removal of the first period of every round from the analysis.

[36] All comparisons between coefficients in table 4 are based on a pooled regression with data from all treatments, that includes all the variables (and fixed effects) of table 4 as well as interaction terms between a treatment dummy and these variables. The difference in coefficients between treatments is significant only if the corresponding interaction terms are.

[37] We also ran two separate sessions where production in the main part was unconstrained. Repeating the regression

Table 4: Main Part Production Function

	Dependent Variable: Quantity			
	LOW		HIGH	
	Coeff.	Std Err.	Coeff.	Std Err.
Predicted other producer quantity	.3050***	.0809	.3340***	.0632
Stock	.4269***	.0422	.1890***	.0629
Other producer stock	−.0884***	.0250	−.0189	.0157
Observations	1600		1800	
Adj. R^2	.7436		.4766	

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

Notes. This table contains the results of a panel regression of quantity on the predicted quantity of the other producer, stock and the stock of the other producer. Period and producer fixed effects are also included but not reported; standard errors are clustered at the producer level. Predictions were only elicited in even rounds; moreover, the final period is omitted from the analysis since all benchmarks are trivially equal to the remaining resource stock in the final period. Thus, the number of observations per individual in all treatments is equal to 25, from 5 rounds with 5 observations each. P-values are calculated using two-sided t-tests.

Table 5: Main Part Production Function Early and Late Periods

	Dependent Variable: Quantity			
	LOW		HIGH	
	Coeff.	Std Err.	Coeff.	Std Err.
Predicted other producer quantity	.4676***	.1257	.3768***	.0769
Prediction X period 3-5	−.3370**	.1368	−.0778	.0689
Stock	.4162***	.0415	.1871***	.0627
Other producer stock	−.0494*	.0256	−.0185	.0157
Observations	1600		1800	
Adj. R^2	.7502		.5000	

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

Notes. This table contains the results of a panel regression of quantity on the predicted quantity of the other producer, the interaction between this prediction and a dummy that equals one for periods 3-5, stock and the stock of the other producer. Period and producer fixed effects are also included but not reported; standard errors are clustered at the producer level. Predictions were only elicited in even rounds; moreover, the final period is omitted from the analysis since all benchmarks are trivially equal to the remaining resource stock in the final period. Thus, the number of observations per individual in all treatments is equal to 25, from 5 rounds with 5 observations each. P-values are calculated using two-sided t-tests.

The final variable (the other producer's stock) should only be significant for producers who adopt a dynamic Nash-Hotelling strategy that incorporates both dynamic optimization and strategic behavior. This variable is significant only in treatment LOW (in the direction predicted by the Nash benchmark), which suggests that producers in treatment LOW were more likely to adopt a dynamic Nash-Hotelling strategy. This is in line with the finding that dynamic optimization behavior appears more strongly in treatment LOW and that there is little evidence for treatment differences in the level of strategic behavior.

The previous regression examined the importance of dynamic optimization and strategic behavior between treatments. However, it is also possible that the importance of these aspects also varies within a treatment. For example, strategic behavior could be more important in early periods. To test this, we run a regression (table 5) that interacts the prediction variable with a dummy for periods 3 to 5.[38] The results suggest that the strategic behavior variable "predicted other producer quantity" matters equally in all perios in treatment HIGH, but matters less in later periods in treatment LOW. This is in line with the reasoning of hypothesis 3, except that it seems that strategic behavior only starts playing a smaller role in later periods.

Another way to examine the importance of strategic behavior and dynamic optimization is to correlate

of table 4 for these sessions gives a higher coefficient (.3941, with S.E. .0793) for predicted other producer quantity, the difference in coefficients with treatment LOW and treatment HIGH was also not significant.

[38] We thank the associate editor for suggesting this regression to us.

Table 6: Correlations between the Prologue and the Main Part

	LOW	HIGH
Main part dispersion & Prologue 1 dispersion	.4019***	.0430
Main part first period quantity & Prologue 2 first period quantity	.1640	.1743
Main part income & Prologue 1 income	.3431***	.1922
Main part income & Prologue 2 income	.0236	.0350
Observations	64	72

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

Notes. This table contains Pearson correlation coefficients. Main part dispersion is the difference between the first period and sixth period scarcity rents in the main part averaged over all rounds. Prologue 1 dispersion is the difference between the first and sixth period scarcity rents in prologue 1. Main part (prologue 2) first period quantity is the quantity produced in the first period of the main part (prologue 2) averaged over all 10 (3) rounds. For the third correlation, main part income is the total income over 6 periods in the main part for the first round only. Prologue 1 income is a dummy variable that indicates if the producer achieved a positive profit in at least one of his first three trial rounds. For the fourth correlation, main part income is the total income over 6 periods in the main part averaged over all 10 rounds. Prologue 2 income is the total income over 6 periods in prologue 2 averaged over all three rounds.

behavior in the main part to behavior in the prologue. Specifically, if hypotheses 2 and 3 are correct, the degree to which behavior correlates between the prologue and the main part could also depend on the treatment. Behavior in treatment LOW should then be most correlated to behavior in the monopoly prologue (prologue one), whereas behavior in treatment HIGH should be most correlated to the unconstrained oligopoly prologue (prologue two).

To test this idea we correlate indicators of behavior and success in the main part with similar indicators from the prologue. From prologue one we take the difference between the first period scarcity rent and last period scarcity rent (or dispersion) as an indicator of dynamic optimization. For prologue 2 we take the first period production quantity as a measure of the intention to produce cooperatively. Moreover we take a measure of income in both prologues and correlate that with main part income to see if success is also correlated between the prologue and the main part.[39]

Table 6 shows the resulting correlation coefficients. Firstly, participants with a high dispersion in prologue 1 also had a high dispersion in the main part, but only in treatment LOW.[40] Participants who were successful in prologue 1 were more successful in treatment LOW in terms of income as well. On the other hand, there is no significant correlation for either the intention to behave cooperatively (first period quantity) or for success in prologue 2 for either treatment. Thus there seems to be some evidence that behavior and success in the monopoly prologue are correlated to behavior and success in treatment LOW (but not treatment HIGH); however there is no correlation between prologue 2 and treatment HIGH (or treatment LOW). Overall, these findings are in line with the results of the panel regression; there appears to be a difference between treatments for the importance of dynamic optimization, but not for strategic behavior.

7 Discussion

The most important theoretical result in the field of nonrenewable resource economics is the Hotelling rule, which states that prices net of marginal costs should increase over time at the rate of interest. However, the Hotelling rule has received little empirical support. This article uses the methods of experimental

[39]In comparing the unconstrained oligopoly with the main part we correlated overall income in the unconstrained oligopoly to overall income in the main part. However, for prologue one there are several complications: (a) because of practice almost all participants were able to do well in prologue 1; as a result there was little variation in the production schedule used in the incentivized round. Moreover, (b) starting from round two participants in the main part could also adopt the production schedule they learned from the other producer in a preceding round. To solve the first problem, we constructed a dummy variable which was equal to one only if the participant managed to run a profit in at least one of his first three practice rounds (the results are similar if we take the first four, five or six practice rounds instead). This split the sample roughly in half, since 57% of participants managed to run a positive profit in one of the first three practice rounds. To address possible learning considerations we used only the first round of the main part.

[40]The results are identical if we use the differential between the highest and lowest scarcity rent instead.

economics to investigate a possible cause for this lack of empirical support.

In this article, we have argued that the lack of empirical support for the Hotelling rule is the result of the multifacetedness of the nonrenewable resource problem. The nonrenewable resource problem consists of many different aspects like dynamic optimization and strategic behavior, but also technological developments, exploration, etc. In practice, producers may not be willing or able to take every aspect fully into account. We have argued that the degree to which a producer pays attention to a given aspect of the resource problem depends on the size or longevity of her resource stock. In particular, for a relatively scarce resource it pays off for producers to compute a dynamically optimal production path. However, for a more abundant resource, computing a dynamically optimal production path may be infeasible, non-salient or suboptimal from a cost-benefit perspective. Instead, we have argued that producers with a relatively large stock should focus more on other aspects of the decision problem, such as strategic behavior. These producers will then (partially) ignore the dynamic consequences of their extraction decision, which results in suboptimally low prices and the failure of the Hotelling rule. Our results showed that when resource stocks are large (treatment HIGH in the experiment), producers overproduce with respect to the Nash-Hotelling rule and choose to partially ignore the dynamic component of their production decision. However, when resource stocks are small (as in treatment LOW), producers extract close to the Nash-Hotelling level.

In terms of real world markets, the relative abundance of many non-renewable resources may have induced producers to overextract, leading to the failure of the Hotelling rule. At the same time, we do not believe that this is the whole story; indeed in the experiment scarcity rents are still increasing over time in both treatments. A full explanation of the failure of the Hotelling rule may also require other elements, including for example the discovery of new deposits, capacity constraints or technological progress. In future work, it could be worthwhile to use the experimental approach to try to disentangle the relative explanatory power of these elements. Indeed, we believe that experimental data can serve as a complement to field data to aid the profession in gaining a better grasp of the mechanisms driving the behavior of producers on nonrenewable resource markets.

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References

Abbink, Klaus and Jordi Brandts. 2008. "Pricing in Bertrand Competition with Increasing Marginal Costs." *Games and Economic Behavior* 63 (1):1–31.

———. 2009. "Collusion in Growing and Shrinking Markets: Empirical Evidence from Experimental Duopolies;." In *Experiments and Competition Policy*, edited by J. Hinloopen and H.-T. Normann. Cambridge University Press, 34–60.

Adelman, Martin A. 2002. "World Oil Production and Prices 1947-2000." *The Quarterly Review of Economics and Finance* 42:169–91.

Apesteguia, Jorge, Steffen Huck, and Jörg Oechssler. 2007. "Imitation - theory and experimental evidence." *Journal of Economic Theory* 136 (1):217–35.

Apesteguia, Jorge, Steffen Huck, Jörg Oechssler, and Simon Weidenholzer. 2010. "Imitation and the evolution of Walrasian behavior: theoretically fragile but behaviorally robust." *Journal of Economic Theory* 145 (1):1603–17.

Arrow, Kenneth J. and Sheldon Chang. 1978. "Optimal Pricing, Use and Exploration of Uncertain Natural Resource Stocks." *Journal of Environmental Economics and Management* 9 (1):1–10.

Başar, Tamar and Geert-Jan Olsder. 1999. *Dynamic Noncooperative Game Theory.* Philadelphia: Society for Industrial and Applied Mathematics.

Berck, Peter and William R. Bentley. 1997. "Hotelling's Theory, Enhancement, and the Taking of the Redwood National Park." *American Journal of Agricultural Economics* 79 (2):287.

BP, British Petroleum. 2010. "British Petroleum Statistical Review 2010." *Available from http://www.bp.com/* (accessed August 24th, 2010).

Brown, Alexander L., Zhikang Eric Chua, and Colin F. Camerer. 2009. "Learning and Visceral Temptation in Dynamic Savings Experiments." *Quarterly Journal of Economics* 124 (1):197–231.

Bulletin, Energy. 2006. "Clinton: not briefed on peak oil." *http://www.energybulletin.net/node/18138* (accessed December 14th, 2010).

Cairns, Robert D. 1986. "More on Depletion in the Nickel Industry." *Journal of Environmental Economics and Management* 13:93–8.

Cairns, Robert D. and Graham A. Davis. 1998. "On Using Current Information to Value Hard-Rock Mineral Properties." *The Review of Economics and Statistics* 80 (4):123–40.

Caputo, Michael R. 2011. "A nearly complete test of a capital accumulating, vertically integrated, nonrenewable resource extracting theory of a competitive firm." *Resource and Energy Economics* 33 (3):725–744.

Chermak, Janie M. and Kate Krause. 2002. "Individual Response, Information, and Intergenerational Common Pool Problems." *Journal of Environmental Economics and Management* 43:47–70.

Chermak, Janie M. and Robert H. Patrick. 2002. "Comparing tests of the theory of exhaustible resources." *Resource and Energy Economics* 24 (4):301–325.

D'Alessio, Marisa, Angela Guarino, Vilfredo De Pascalis, and Philip G. Zimbardo. 2003. "Testing Zimbardo's Stanford Time Perspective Inventory (STPI) -Short Form: An Italian Study." *Time and Society* 12:333–47.

Deffeyes, Kenneth S. 2005. *Beyond Oil: The View from Hubbert's Peak.* New York: Hill and Wang.

Déry, Patrick and Bart Anderson. 2007. "Peak Phosphorus." *http://www.energybulletin.net/node/33164* (accessed December 14th, 2010).

Devarajan, Shantayanan and Anthony C. Fisher. 1981. "Hotelling's Economics of Exhaustible Resources: Fifty Years Later." *Journal of Economic Literature* 19 (1):65–73.

Engel, Christoph. 2010. "How Much Collustion? A Meta-Analysis of Oligopoly Experiments." *Journal of Competition Law and Economics* 3 (4):491–549.

Farrow, Scott. 1985. "Testing the Efficiency of Extraction from a Stock Resource." *Journal of Political Economy* 93 (3):452–87.

Fischer, Maria-Elisabeth, Bernd Irlenbusch, and Abdolkarim Sadrieh. 2004. "An Intergenerational Common Pool Resource Experiment." *Journal of Environmental Economics and Management* 48:811–36.

Gaudet, Gérard. 2007. "Natural Resource Economics under the Rule of Hotelling." *Canadian Journal of Economics* 40:1033–59.

Gerlagh, Reyer and Matti Liski. 2011. "Strategic Resource Dependence." *Journal of Economic Theory* 146 (2):699–727.

Gray, Lewis C. 1914. "Rent under the Assumption of Exhaustibility." *Quarterly Journal of Economics* 28:466–89.

Griffin, James M. 1985. "OPEC Behavior: a Test of Alternative Hypotheses." *American Economic Review* 75 (5):954–63.

Groot, Fons, Cees Withagen, and Aart De Zeeuw. 2003. "Strong Time-Consistency in the Cartel-versus-Fringe Model." *Journal of Economic Dynamics and Control* 28 (2):287–306.

Hall, Darwin C. and Jane V. Hall. 1984. "Concepts and Measures of Natural Resource Scarcity with a Summary of Recent Trends." *Journal of Environmental Economics and Management* 11 (4):363–79.

Halvorsen, Robert and Tim R. Smith. 1991. "A Test of the Theory of Exhaustible Resources." *The Quarterly Journal of Economics* 106 (1):123–140.

Hamilton, James D. 2009. "Understanding Crude Oil Prices." *Energy Journal* 30 (2):179–206.

Heaps, Terry. 1985. "The Taxation of Nonreplenishable Natural Resources Revisited." *Journal of Environmental Economics and Management* 12 (1):14–27.

Heinberg, Richard. 2007. "Peak Coal: Sooner than you Think." *http://www.energybulletin.net/29919.html* (accessed December 15th, 2010).

Hotelling, Harold. 1931. "The Economics of Exhaustible Resources." *Journal of Political Economy* 39:137–75.

Huck, Steffen, Hans-Theo Normann, and Jörg Oechssler. 1999. "Learning in Cournot Oligopoly: an Experiment." *Economic Journal* 109:80–95.

———. 2004. "Two are few and four are many: number effects in experimental oligopolies" *Journal of Economic Behavior & Organization* 53 (4):435–446.

Krautkraemer, Jeffrey A. 1998. "Nonrenewable Resource Scarcity." *Journal of Economic Literature* 36 (4):2065–107.

Kronenberg, Tobias. 2008. "Should We Worry About the Failure of the Hotelling Rule." *Journal of Economic Surveys* 22 (4):774–93.

Lewis, Tracy R. and Richard Schmalensee. 1980. "On Oligopolistic Markets for Non-Renewable Natural Resources." *Quarterly Journal of Economics* 95 (3):475–91.

Livernois, John. 2009. "On the Empirical Significance of the Hotelling Rule." *Review of Environmental Economics and Policy* 3 (1):22–41.

Livernois, John and Patrick Martin. 2001. "Price, Scarcity Rent and a Modified r per Cent Rule for Non-Renewable Resources." *The Canadian Journal of Economics* 34 (3):827–45.

Loury, Glenn C. 1986. "A Theory of 'Oil'igopoly: Cournot Equilibrium in Exhaustible Resource Markets with Fixed Supplies." *International Economic Review* 27 (2):285–301.

Mead, Walter J. 1979. "The Performance of Government Energy Regulations." *American Economic Review* 69 (2):352–6.

Miller, Merton H. and Charles W. Upton. 1985. "A Test of the Hotelling Valuation Principle." *Journal of Political Economy* 93 (1):1–25.

Mouawad, Jad. 2008. "Oil hits $ 104 as OPEC rebuffs Bush." *http://www.nytimes.com/2008/03/05/business/worldbusiness/05cnd-opec.html* (accessed January 18th, 2011).

Newbery, David M.G. 1981. "Oil Prices, Cartels, and the Problem of Dynamic Consistency." *Economic Journal* 91:617–46.

Offerman, Theo, Jan Potters, and Joep Sonnemans. 2002. "Imitation and Belief Learning in an Oligopoly Experiment." *Review of Economic Studies* 69:973–97.

Pindyck, Robert S. 1978. "The Optimal Exploration and Production of Nonrenewable Resources." *Journal of Political Economy* 86 (5):841–61.

———. 1980. "Uncertainty and Exhaustible Resource Markets." *Journal of Political Economy* 88 (6):1203–25.

———. 1981. "Models of Resource Markets and the Explanation of Resource Price Behavior." *Energy Economics* 3:130–9.

Polasky, Stephen. 1992. "Do Oil Producers Act as 'Oil'igopolists?" *Journal of Environmental Economics and Management* 23 (3):216–47.

Potters, Jan, and Sigrid Suetens. 2013. "Oligopoly Experiments in the Current Millennium" *Journal of Economic Surveys* 27 (3):439–460.

Rassenti, Stephen, Stanley Reynolds, Vernon Smith, and Ferenc Szidarovszky. 2000. "Adaptation and Convergence of Behavior in Repeated Experimental Cournot Games." *Journal of Economic Behavior & and Organization* 41 (2):117–146.

Sadrieh, Abdolkarim. 2003. "Equity versus Warm Glow in Intergenerational Giving." *CentEr Discussion Paper 2003-35* .

Salo, Seppo and Olli Tahvonen. 2001. "Oligopoly Equilibria in Nonrenewable Resource Markets." *Journal of Economic Dynamics and Control* 25:671–702.

Shafiee, Shahriar and Erkan Topal. 2009. "When will fossil fuel reserves be diminished?" *Energy Policy* 37 (1):181–189. URL `http://linkinghub.elsevier.com/retrieve/pii/S0301421508004126`.

Slade, Margaret E. 1982. "Trends in Natural-Resource Commodity Prices: An Analysis of the Time Domain." *Journal of Environmental Economics and Management* 9 (2):122–37.

Slade, Margaret E. and Henry Thille. 1997. "Hotelling Confronts CAPM: A Test of the Theory of Exhaustible Resources." *The Canadian Journal of Economics* 30 (3):685.

Smith, George O. 1920. "Where the World Gets Its Oil." *The National Geographic Magazine* 37 (2):181–202.

Smith, James L. 2005. "Inscrutable OPEC? Behavioral Tests of the Cartel Hypothesis." *The Energy Journal* 26 (1):51–82.

Solow, Robert M. 1974. "The Economics of Resources or the Resources of Economics." *American Economic Review* 64 (2):1–14.

Sorrell, Steve, Jamie Speirs, Roger Bentley, Adam Brandt, and Richard Miller. 2010. "Global oil depletion: A review of the evidence." *Energy Policy* 38 (9):5290–5295. URL `http://linkinghub.elsevier.com/retrieve/pii/S0301421510003204`.

Spiro, Daniel. 2012. "Resource prices and planning horizons." *Working Paper* .

Stollery, Kenneth R. 1985. "User costs versus markups as determinants of prices in the nickel industry: reply." *Journal of Environmental Economics and Management* 12 (4):397–400.

Van Veldhuizen, Roel. 2009. *Strategic Behavior on a Natural Resource Market: An Experiment.* Master's thesis, Tinbergen Institute.

Williams, James L. 2009. "Oil Price History and Analysis (Updating)." *http://www.wtrg.com/prices.htm* (accessed April 22nd, 2010).

A Experimental Instructions

This section contains the instructions and questions used in treatment HIGH of the experiment for both the prologue and the main part. Part I and part II refer to prologue one and prologue two respectively, whereas part III refers to the main part. The instructions for treatment LOW were identical except that stock, fixed costs and the conversion rate were different in the main part (part III). An example of a decision screen is provided at the end of this appendix.

Introduction Part I

In part 1 of this experiment, you are the manager of a firm. In particular, you will have to decide on the quantity that your firm is going to produce. Your firm is the only active firm on the market (i.e. it is a monopolist) and as such only your decision determines the market price. In this part of the experiment, the minimum market price is 0 and the maximum market price is 372. Moreover, increasing your quantity by 1 will lower the price by 2. Quantity and price in turn determine revenue according to the following formula:

Revenue = Price X Quantity

The payment you receive at the end of the experiment will be based on total revenue. This part of the experiment consists of several rounds. Each round in turn consists of 6 periods. In each period you have to decide what quantity your firm is going to produce. After 6 periods, the round will end and your pay-off over the round will be determined. After this a new round will start, which will again have 6 periods.

You may have noticed that there is a calculator at the bottom of the screen. It can be used to calculate what will be the price and revenue level if you pick a certain quantity. You can now go to the next page of the instructions. Note that you can always return to this page later by clicking on the blue headers at the top of this page (only the pages you have already been to can be accessed).

The Payment Mechanism

In this experiment, revenue earned in earlier periods is more valuable than revenue earned in later periods. One way to think about this is that your revenue will be put on a bank account, where it will earn 10 % interest per period. The final column in the calculator describes exactly how much a given level of revenue earned in a certain period will be worth in terms of End Income. For example, a quantity of 54 produced in period 1 yields a revenue of 14256, which will yield an end income of 22959 at the end of the round. The same numbers can also be accessed using the calculator by filling in 54 for first period quantity.

At the end of every round, your firm will calculate its total end income by adding up end income levels of all 6 periods. However, your firm also has a fixed cost equal to 98000, which will have to be paid at the end of every round. This fixed cost is unavoidable and will have to be paid regardless of the amount you produced over the round. Think of this amount as the total cost of maintaining a factory over the whole round. As a result, your payment at the end of a round will be determined according to the following formula:

Payment = Total End Income - Fixed Cost

At the end of the experiment, the points from all rounds will be converted into euros at a rate of 2000 points per euro, such that 1000 points are worth 0,50 euros. Be assured though that over the whole experiment it will not be possible to lose money. A negative pay-off over a round can be compensated by a positive pay-out in another round, in another part of the experiment, or by the show-up fee (7 euros), with a minimum possible pay-off of zero over the whole experiment. Note, however, that this is very unlikely to happen.minimum possible pay-off of zero over the whole experiment. Note, however, that this is very unlikely to happen.

Resource Stocks

One thing we have neglected so far is the production process. Producing one unit of your firm's good will require one unit of resource. Over each round, only 280 units of resource are available, so that at most 280 units can be produced. Thus, consuming one unit of resource in the first period means that you will not be able to use it in any of the following periods. At the start of each new round, your resource stock will be replenished.

One thing to note about the resource stock is that you do not have to use it all. Likewise, it is not necessary to produce in every single period. At the same time, it is also very well possible to use up your whole resource stock and produce in all periods. Before we start the actual experiment, you will have some time to practice to familiarize yourself with this set-up.

As a final comment, be sure that you understand the difference between period and round, and also between revenue, end income and payment. One round consists of 6 periods. Similarly, revenue is what your firm earns every period, end income is what your firm's revenue of a period will be worth at the end of the round (i.e. after taking interest into account) and payment is the total amount of points you get at the end of a round.

To make sure you understand these ideas, we have a few questions for you.

Question 1

The first question is about the price mechanism. Suppose your firm is going to produce **58**. What will be the market price? (Integer between 0 and 372). Tip: use the calculator (any period will do, since the price does not depend on the period)!

Question 2

Which of the following statements is true? If you produce 55 in both period 2 and period 3, you will have...

1. Different prices, revenues and end incomes in both periods
2. The same price and end income in both periods and a higher revenue in period 3
3. The same price and end income in both periods and a higher revenue in period 2
4. The same price and revenue in both periods and a higher end income in period 2
5. The same price and revenue in both periods and a higher end income in period 3
6. The same price, revenue and end income in both periods

Question 3

Which of the following statements is <u>false?</u> It is possible to...

1. Produce zero in some periods
2. Produce something in all periods

3. Over all periods produce less than your stock
4. Over all periods produce as much as your stock
5. Over all periods produce more than your stock

Question 4a

Now suppose your firm has arrived in period 5 (out of 6) and still has a stock of 26. However, you are doubting between two different options. Option A entails producing 19 in period 5 and 7 in period 6. Option B would be to produce 7 in period 5 and 19 in period 6. What option would yield the highest end income?

Question 4b

Suppose you have indeed decided to produce **19** in period 5 and **7** in period 6. What end income is your firm going to earn?

End of Instructions

You are now ready to start the experiment. By clicking on the next link, you will go to a practice session as soon as everyone has finished the instructions. The results you obtain during practice will not count towards your pay-out at the end of the experiment. Practice time will last for approximately 10 minutes; during this time you can work through as many rounds as you like. After the practice session has ended you will move on to the part where earnings will be paid out. This part is identical to practice, except that there will be only 1 round. All results obtained in the practice session will be saved and made available during the real experiment, so use practice time to familiarize yourself as well as possible with the set-up.

One more thing to note is that the bottom right corner of the screen will show a timer. You can see an example of the timer in the bottom of right of this screen. The timer indicates the amount of time you have left to make a decision in the current period. In this part of the experiment, you will have a maximum of 40 seconds to make your decision. If you fail to make your decision in time, you will automatically produce zero and move on to the next period. The timer is reset in every period, regardless of how much time you spent in the preceding period. Finally, note that it in many cases only a small fraction of the required time might be needed to make a decision.

Instructions Part II

We will now start with the second part of this experiment. In this part of the experiment, you will be the manager of a firm, like in part I. However, several other aspects have changed. For one, you now face competition from one other firm. For another, you will have an unlimited amount of resources to produce with. Moreover, fixed costs will be slightly higher. These changes will be explained in greater detail below and on the next page.

Dealing with other firms

Firstly, you will now face competition from another firm. The decisions for the other firm will be made by another participant of this experiment. The other firm you face will be the same in every period of the same round but will change in each new round. Moreover, decisions will be made simultaneously, so that you will not know the other firm's production level until after the end of the period, just like the other firm will not know your production level. Similarly, you will not know with whom you will be matched, like others will not know with whom they will be matched. Anonymity is ensured.

As a result of the presence of the other firm, the effect of your quantity on market price has changed. In particular, a one unit increase in production by either you or the other firm will now lower the market price by 1. Moreover, the price will now be between 0 and 360. The calculator has been changed and will now be able to also take the decisions of the other firm into account. You will be able to practice with the new situation in one of the exercises.

Resources and Earnings

Another difference between part II and part I is that you will no longer have a limited stock of resources. As a result, producing a high amount in an early period will no longer limit your production in later periods. The final difference with the first part is that fixed costs are now equal to 100000. Other than that, the payment mechanism in this part of the experiment is identical to the mechanism used in the first part. Your payment after each round is still determined using the following formula:

Payment = Total End Income - Fixed Cost

Your payment will be converted into euros at a rate of 10000 points per euro, such that 1000 points are worth 0,10 euros. Moreover, interest will still be equal to 10%. Before going to the experiment, we would like to ask two checkup questions.

Question 1

This question will make use of the following table (figure A.1. The table can be read as follows: the left column contains your production decision (in red). The top row contains the production decision of the other firm (in blue). The cells in the table indicate what level of revenue your firm will earn (again in red) for the associated combination of production levels by your firm and the other firm. Moreover, the cells also contain the revenue that the other firm will earn (in blue). For example, to look up your revenue in case the other firm produced 60 and your firm produced 120, you would have to go right from 120 and down from 60, where you would find that you would earn a revenue of 216 and the other firm would get 108.

There are a few more things to note about the table. For one, note that the numbers in the table are revenues, which are equal to end income only in the last period. For another, it is important to note that although the set-up for this question is identical to the set-up used in the experiment itself, we have chosen only a few values as examples. For example, in the actual experiment you would also be able to produce 119 or 121 (or any other amount). Moreover, we have underlined the quantity that will give you the highest revenue keeping the other firm's production level constant. In some cases, there may be two such quantities in the table; however, this holds in the table only because of the particular values used for this example. Finally and importantly, the last two digits have been removed from the revenue numbers in the table. Thus, for example 180 would actually be 18000, and the latter is what you would have to fill in below.

Suppose the other firm produced 60. What revenue would you earn if you produced 120?

Now suppose the other firm produced 90. Firstly, what quantity should you produce to get the highest revenue for you? What quantity should you produce to get the highest revenue for the other? And finally, what quantity would yield the highest combined revenue? Hint: sometimes multiple answers may be possible.

		Other						
		180	150	120	90	60	30	0
Self	180	0 0	54 45	108 72	162 81	216 72	270 45	324 0
	150	45 54	90 90	135 108	180 108	225 90	270 54	315 0
	120	72 108	108 135	144 144	180 135	216 108	252 63	288 0
	90	81 162	108 180	135 180	162 162	189 126	216 72	243 0
	60	72 216	90 225	108 216	126 189	144 144	162 81	180 0
	30	45 270	54 270	63 252	72 216	81 162	90 90	99 0
	0	0 324	0 315	0 288	0 243	0 180	0 99	0 0

Figure A.1: Part 2 Payoff Table

Question 2

In the previous question, you were asked what quantity would yield the highest revenue for your firm if the other firm produced 90. In the table, there were two correct answers: 120 and 150. However, in the experiment itself it will also be possible to pick any integer quantity between 120 and 150. What production level will yield the highest end income for your firm if you are allowed to pick any integer production level? Tip: use the calculator!

End of Instructions

You are now ready to start the experiment. By clicking on the next link, you will go to the experiment as soon as everyone has finished reading the instructions. In this part of the experiment, there will be no time to practice: you will immediately go on to the part where your earnings will be paid out. In total, there will be 3 rounds. In every round you will be matched with a different firm. Because there are no practice rounds, the timer will be set to 1 minute and 40 seconds per period in the first round and to 40 seconds per period in later rounds. Thus, you will have slightly more time in the first round to make a decision. If you fail to make your decision in time, you will automatically produce zero and move on to the next period. The timer is reset in every period, regardless of how much time you had left after the preceding period. Finally, note that in many cases only a small fraction of the required time might be needed to make a decision.

Instructions Part III

We will now start with the third and final part of this experiment. In many ways, this part will be a mix between part I and part II. In particular, you will still be the manager of a firm. Moreover, in this part you will have to deal with one other firm, like in part II. At the same time, you will only have a limited stock of resources available for production, like in part I. Finally, fixed costs will be slightly different from either of these parts. These changes will be explained in greater detail below and on the next page.

Firstly, as in part I you will have only a limited stock of resources available for production. To be more precise, you will have a total resource stock of 480 in every round. As in part I, you do not have to use up all your resources. Likewise, it is not necessary to produce in every single period. At the same time, it is also very well possible to use up your whole resource stock and produce in all periods. At the start of each new round, your resource stock will be replenished, as before. In total, this part of the experiment will consist of 10 rounds.

Moreover, there is one other active firm on the market, like in part II. Once again the other firm you face will be the same in every period of the same round but will change in each new round. You will not know with whom you will be matched, like others will not know with whom they will be matched. Anonymity is ensured.

As a result of these changes, the effect of your quantity on market price has changed. Like in part II, a one unit increase in production by either you or the other firm will lower the market price by 1. However, the resulting prices are slightly different; in particular, prices are now between 0 and 372. The calculator has been updated to take this into account.

Expectations and Earnings

The payment mechanism in this part of the experiment is almost identical to the mechanism used in the first two parts. Your payment after each round is still determined using the following formula:

Payment = Total End Income - Fixed Cost

Your payment will be converted into euros at a rate of 10000 points per euro, such that 1000 points are worth 0,10 euros. Moreover, the interest rate will still be equal to 10%. The only difference is that fixed costs will be equal to 113000.

There is one new thing about this part of the experiment though. In every even round (2,4, etc.), you are also asked to predict the production of the other firm. It will also be made clear before the start of the round whether or not you have to make predictions during that round and it will also be clear from the decision screen. During rounds where predictions are asked you will have slightly more time to make your decision. Other than that, the decision screen will be very similar to the previous parts of the experiment.

At the end of the experiment, we will randomly pick one prediction you made during the experiment and pay you an additional amount of money based on its accuracy. For a perfect prediction, you will earn 5 euros. If you make an error you will earn 5 euros minus the error times 20 cents. Thus, if you make an error of 25, you will earn 0 (and if you make a bigger error you will still earn 0). Take predictions seriously, since they will earn you extra money at the end of the experiment. Before going to the experiment, we would like to ask you one more check-up question.

Question 1

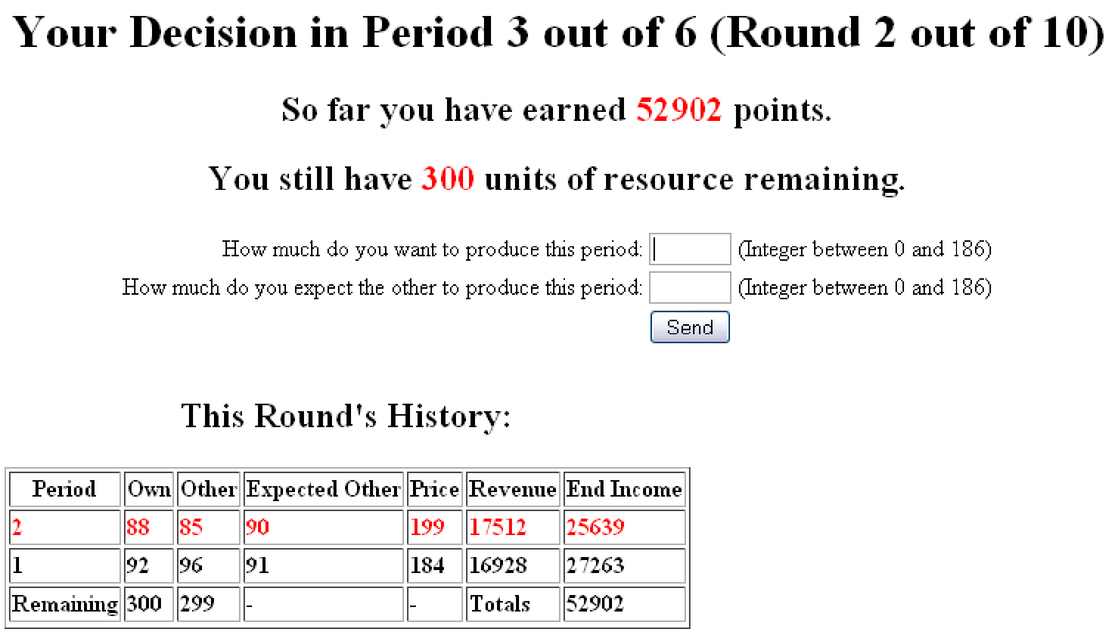
Suppose that you still have a stock remaining of **93**. Suppose also that you are in period 5 (out of 6). Your goal is to allocate the remaining stock optimally over the two remaining periods. Suppose now that the other firm is going to produce 56 in period 5 and 37 in period 6. You now have to choose between implementing two possible production plans. Plan A will entail producing 40 in period 5 and 53 in period 6, whereas Plan B will entail producing 53 in period 5 and 40 in period 6. How much end income will your firm earn with each plan? What will thus be the optimal plan to implement?

End of Instructions

You are now ready to start the experiment. By clicking on the next link, you will go to the experiment as soon as everyone has finished reading the instructions. In this part of the experiment, there will be no time to practice: you will immediately go on to the paid-out part. In total, there will be 10 rounds. In every round you will be matched with a different firm. Because there are no practice rounds, the timer will be set to 1 minute and 40 seconds per period in the first round and to 40 seconds per period in later rounds. When you have to make a prediction, the time will be increased by 20 seconds. Thus, you will have slightly more time in the first round and in prediction rounds. If you fail to make your decision in time, you will automatically produce zero and move on to the next period. The timer is reset in every period, regardless of how much time you had left after the preceding period. Finally, note that in many cases only a small fraction of the required time might be needed to make a decision.

s

B Screenshot



Your Decision in Period 3 out of 6 (Round 2 out of 10)

So far you have earned 52902 points.

You still have 300 units of resource remaining.

How much do you want to produce this period: (Integer between 0 and 186)

How much do you expect the other to produce this period: (Integer between 0 and 186)

Send

This Round's History:

Period	Own	Other	Expected Other	Price	Revenue	End Income
2	88	85	90	199	17512	25639
1	92	96	91	184	16928	27263
Remaining	300	299	-	-	Totals	52902

Figure A.2: Decision Screen

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