Resource and Energy Economics 37 (2014) 122–146

Contents lists available at ScienceDirect

Resource and Energy Economics

journal homepage: www.elsevier.com/locate/ree

Forward trading in exhaustible-resource oligopoly☆

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A R T I C L E I N F O

Article history:
Received 23 May 2013
Received in revised form 28 November 2013
Accepted 4 December 2013
Available online 12 December 2013

JEL classification:
G13
L13
Q30

Keywords:
Exhaustible resources
Oligopoly
Forward contracting

A B S T R A C T

We analyze oligopolistic exhaustible-resource depletion when firms can trade forward contracts on deliveries – a market structure relevant for some resource markets (e.g., storable pollution permits, hydro-based power pools) – and find that trading forwards can have substantial implications for resource depletion. We show that when firms' initial resource-stocks are the same, the subgame-perfect equilibrium path approaches the perfectly competitive path as firms trade forwards frequently. But when the initial stocks differ, firms can credibly escape part of the competitive pressure of forward contracting. It is a unique feature of the resource model that equilibrium contracting and the degree of competition depends on resource endowments.

☆ This research was initiated at the Center for Advanced Studies (CAS) in Oslo. We thank CAS for generous support. Liski also acknowledges support from Yrjö Jahnsson Foundation and Nordic Energy Research and Montero from Instituto Milenio/Basal SCI (P05-004F/FBO-16). Valuable comments and suggestions were provided by Reyer Gerlagh, Larry Karp, Philippe Mahenc, Bernhard Pachl, Ludwig Ressner, as well as seminar participants at CAS, HECER Helsinki, Toulouse School of Economics, UC Berkeley, University of Heidelberg, TOI-Zapallar (2010) and University of Montevideo.

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0928-7655/$ – see front matter
http://dx.doi.org/10.1016/j.reseneeco.2013.12.002

1. Introduction

1.1. Motivation

Hotelling's (1931) theory of exhaustible-resource depletion is a building block for understanding intertemporal allocation of a finite resource stock. The theory is used in myriad of applications which, without exceptions known to us, assume implicitly or explicitly that the commodity stock is sold in the spot market only, thereby ruling out forward trading despite the fact that it is observed in many commodity markets and markets for exhaustible-stocks in particular. Forward trading is typically associated to the desire of some groups of agents to hedge risks but it can also arise in oligopoly settings without uncertainty. For the case of reproducible commodities, Allaz and Vila (1993) have already shown that when forward positions are publicly observable, and hence can be used as a commitment device, the mere opportunity of trading forward contracts forces firms to compete both in the spot and forward markets, creating a prisoner's dilemma for firms in that they voluntarily sell forward contracts (i.e., take short positions) and end up producing more and thus behaving more competitively than in the absence of the forward market.[1] In this paper we are interested in understanding whether and how this pro-competitive effect of forward contracting can also arise in an oligopolistic exhaustible-resource market.[2]

Our point of departure is that in exhaustible-resource markets the pro-competitive implications of forward contracting, as explained by Allaz and Vila (1993), cannot arise from the expansion of output as in such markets firms face an intertemporal capacity constraint coming from their finite stocks. One may then conjecture that for exhaustible resources forward contracting leaves oligopoly rents intact (e.g., Lewis and Schmalensee, 1980; Ulph and Ulph, 1989).[3] This conjecture is not correct, however. We find that, despite the resource constraint, contracting enhances competition, and that the mechanism delivering the pressure is different from that in Allaz and Vila (1993). Also, in the resource context, the equilibrium contracting and degree of competition will depend on the resource endowments as we will show. Are these insights relevant for resource commodity markets? Our main result that "speculating" with contract transactions leads to lower prices, even in the presence of a resource constraint, adds to the heated debate on whether contract trading in commodity markets, many of which are energy related, should be regulated.[4] In particular, our results provide evidence for mitigating one fear often associated with contracting, namely, that the limited supply together with contracting could enhance market manipulation; in contrast, in our setting, the contract market arises endogenously to precisely limit the market power of the sellers. Thus, while the resource scarcity will influence the equilibrium contracting, the scarcity itself will not prevent its pro-competitive effect from arising. Whether the scarcity is an issue – it may not be in the typical non-renewable resource markets one has in mind such as minerals, oil, and gas (see, e.g., Krautkraemer, 1998) – there are energy-related markets and industries where the two basic assumptions of the Hotelling model, i.e., homogeneity and finiteness of the resource, seem to hold.

One notable example where both of the Hotelling assumptions do hold is the market for SO_2 permits created under the US Acid Rain Program (Ellerman and Montero, 2007). An important feature of the SO_2 program was the tightening of future emission limits accompanied by firms' possibility to store today's unused permits for use in later periods. In anticipation of the tighter limit, it was in the firms'

[1] That a firm's forward position is observed by rivals is not only present in the theoretical literature that has followed Allaz and Vila (1993) but also in the more applied analysis of oligopolistic markets (e.g., Bushnell et al., 2008; Sweeting, 2007; Wolak, 2007), including the (exhaustible) nitrate market (Brown, 1963).

[2] Phlips and Harstad (1990) already mentioned that forward contracting can have an important effect on oligopolistic exhaustible-resource markets but they did not explain whether and to what extent firms will sign forwards in equilibrium.

[3] Both Lewis and Schmalensee (1980) and Ulph and Ulph (1989) suggest that the existence of futures markets validates the use of "path strategies", or more generally, allows firms to commit to production plans.

[4] In the US, the Dodd Frank Wall Street Reform and Consumer Protection Act 2010 changed the regulatory environment of the financial industry, including a potential cap the number of contracts a trader can have in oil, natural gas and other commodities. The following citation captures the representative concern: "If orange juice gets too pricey (perhaps because of a speculative bubble), we can easily switch to apple juice. The same does not hold with oil.", Joseph P. Kennedy II, New York Times OpEd, April 10, 2012.

own interest to store permits from early permit allocations and build up a stock of permits to be then gradually consumed, in a relatively short period of time of 10 years or so, until reaching the long-run emissions limit.[5] This build-up and gradual consumption of a stock of permits gives rise to a dynamic market that shares the basic properties of the exhaustible-resource market Hotelling (1931) had in mind. But there are two additional properties that make this market interesting for the purposes of this paper: the presence of strategic players (Liski and Montero, 2011) and of abundant forward trading activity (Ellerman et al., 2000, pp. 172–190).[6] These same features – tighter future limits, storage of permits, forward trading and large agents– are likely to be present in other pollution markets, most notably, in an eventual global market for carbon dioxide emissions with countries as players (Liski and Montero, 2011).[7]

Another relevant market where forward contracting, resource constraints, and potentially strategic producers coexist are electricity wholesale markets with hydro-power producers. Good examples are the Nord Pool (Kauppi and Liski, 2008) and the power markets in Spain (Fabra and Toro, 2005; Fabra and de Frutos, 2012) and New Zealand (Wolak, 2009), among others. In the Nord Pool, for example, about 50 per cent of average consumption is produced by hydroelectricity whose storage from Summer to Winter leads to Hotelling-type price dynamics within the hydrological year (Kauppi and Liski, 2008).[8] Oligopolistic market structure is an issue in all of these markets, as well as suppliers' activity in the contract market.

1.2. Literature

As in Allaz and Vila (1993), we find that forward contracting can also introduce competitive pressure, but, as we show below, the mechanism delivering this pressure cannot be directly seen from their model. As in their model, our subgame-perfect equilibrium (SPE) strategies have a Markov structure in that they depend only on the current state of the market, which in our case corresponds to remaining stocks and existing forward positions. We show that when firms' initial stocks are of equal size the symmetric SPE results in a delivery path that converges to the perfectly competitive path as firms interactions become infinitely frequent (which is the same as saying as spot markets are preceded by a large number of forward openings). Qualitatively, this outcome is not different than Allaz and Vila's (1993) when we let their (single) spot market be preceded by an infinitely large number of forward openings. However, when firms have resource stocks of different sizes, they can credibly contain part of the competitive pressure of forward contracting. It is a unique feature of the resource model that equilibrium contracting and the degree of competition depends on resource endowments.

To illustrate the logic of how forward contracting introduces competition in the symmetric case consider first a stock so small that the one-period demand absorbs the stock without any storage. Forward contracting then plays no strategic role because the overall supply is in any case to be consumed in one period. Take now a larger stock so that consumption takes place over two periods. Contracting preceding spot sales now plays a role: it induces firms to race for a higher capacity share in the first period, the more profitable of the two periods. In effect, forward contracting moves supplies towards the present, leading to a more efficient allocation of the capacity. In the limit, when a given overall stock is sold arbitrarily frequently, firms have a large number of forward openings to race for the more

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[5] As documented by Ellerman and Montero (2007), during the first five years of the U.S. Acid Rain Program constituting Phase I (1995–1999) only 26.4 million of the 38.1 million permits (i.e., allowances) distributed were used to cover sulfur dioxide emissions. The remaining 11.7 million allowances were saved and have been gradually consumed during Phase II (2000 and beyond).

[6] The four largest power utilities received on agregate 43% of the permits allocated during the first phase of SO_2 program. These large players happen to be on the buyer-side of the market which, according to Liski and Montero (2011), reduces substaintially their ability to exercise market power due to a durable-good monopoly problem.

[7] According to Intercontinental Exchange (http://www.theice.com), a global operator of future exchanges, there is steady increase in trading activity for CO_2 derivatives (including forwards, futures and options) not only in the EU-ETS market but already in the California market that has 2013 as the first year of compliance with emission limits.

[8] Trade at the Nord Pool's financial markets, including forwards and contract-for-differences for electricity and forwards for CO_2 allowances, has also increased steadily. More details can be found in http://www.nasdaqomxcommodities.com/digitalAssets/69/69445_tradenordpoolfinancialmarket.pdf

profitable spot markets. The race ends when all spot markets are equally profitable, i.e., when the allocation is perfectly competitive, as in Hotelling (1931).[9]

The above logic changes when stocks are asymmetric. The smaller firm can now credibly use the forward market to increase its presence in the earlier (more profitable) markets because it knows the large firm will find it optimal to reallocate part of its stock to later markets in an effort to soften competition. In fact, in the two-period model, a sufficiently small firm can commit to fully exhaust in the first period by contracting its entire stock. If so, the larger firm has no contracting incentives. In this case, the small firm strictly benefits from the forward market in that it allows it to implement its most profitable, i.e., Stackelberg, outcome.[10] Qualitatively, the equilibrium implies that the small firm free-rides on the large firm's market power and exits the market first, as in Salant (1976).[11]

Our research relates to three strands of literature. First, our work is closely related to the basic exhaustible-resource theory under oligopolistic market structure. This literature has focused on developing less restrictive production strategies for firms (from "path" to "decision rule" strategies)[12] and also on including more realistic extraction cost structure (towards stock-dependent costs).[13] None of the papers in this literature explicitly consider the effect of forward trading on the equilibrium path. However, it is interesting that the resource-depletion path suggested by the two-period model is qualitatively similar to that in Salant (1976) where the overall sales period is also divided into two distinct phases. In Salant's model, there is a large supplier and fringe of competitive suppliers. All suppliers are active in the competitive phase, which is followed by a monopoly phase where only the large firm is active. Forward contracting among asymmetric firms leads to a qualitatively similar equilibrium pattern, although the mechanism is very different as well as the degree of competition arising from a given division of stocks.

Second, there is a recent literature on organization of trade in dynamic oligopolistic competition under capacity constraints (e.g., Dudey, 1992; Anton et al., 2012). These papers focus on dynamic price competition and also on the efficiency losses and changes in division of surplus caused by strategic buyers. We depart from this literature by assuming non-strategic but forward looking buyers, and we consider quantity competition in two dimensions (spot and forward markets). Our result that the firm with smaller capacity sells first and at higher prices sounds similar to Dudey's (1992) but is, in fact, quite different. In our case the large firm is active throughout the equilibrium and makes larger profits overall; the small firm is only free-riding on the large firm's market power, much the same way the fringe is free-riding on the large firm's market power in Salant (1976).

Third, there is a literature on forward trading starting with Allaz and Vila (1993) who analyze a static Cournot market for a reproducible good. Mahenc and Salanié (2004) show that price competition can reverse the effect of forward trading on competition. Liski and Montero (2006), on the other hand, develop a repeated interaction model of forward and spot transactions showing that forward contracting can expand the scope for collusive behavior in part because the threat of falling into the non-cooperative outcome becomes more effective. Given the result of this paper that contracting can add substantial (non-cooperative) competitive pressure, it is obvious that the same pro-collusion argument applies in the resource context whenever the model is specified to allow for non-stationary strategies. There is also a recent empirical literature looking at the strategic effect of forward contract-

[9] The use of forward contracting in the race for appropriating a larger share of the oligopoly rents resembles somehow the use of private storage in the race for appropriating a larger share of the common and exhaustible resource of Gaudet et al. (2002).

[10] Note that adding more contracting opportunities before the spot openings does not change the outcome in this two period example.

[11] Salant (1976) considers a game in which a large supplier and a fringe of competitive suppliers choose simultaneously their entire production path at time zero. He shows that there will be two distinctive phases in equilibrium: a "competitive" phase with both type of players serving the market followed by a monopoly phase in which only the large supplier serves the market.

[12] Loury (1986), Polasky (1992), and Lewis and Schmalensee (1980) use path strategies; Salo and Tahvonen (2001), for example, use decision-rule strategies. For a more recent survey on the Hotelling model and its extensions, see Gaudet (2007).

[13] Salo and Tahvonen (2001) solve their model with stock-dependent costs, so that the overall amount of the resource used is endogenously determined in equilibrium. In this sense, the resource is only economically exhausted. In our model, the resource is physically exhausted as the cost of using it is independent of the stock level. We leave it open for future research how replacing physical capacity with economic capacity would alter the contracting incentives.

ing on the performance of some oligopolistic markets, in particular, electricity markets (e.g., Fabra and Toro, 2005; Wolak, 2007; Sweeting, 2007; Bushnell et al., 2008; Fabra and de Frutos, 2012).

The rest of the paper is organized as follows. In the next section we present the two-period model and construct a simple example to explain why forward contracting endogenously arises in a oligopolistic exhaustible-resource setting. In Section 3 we first compute the pure-spot SPE and then move to the SPE with forward trading for the case in which firms' initial stocks are equal. In Section 4 we extend the model in two directions. We first allow the spot markets of the two-period model be preceded by a large number of forward openings, not just one. This extension captures well what happens in a more general model where there is an endogenously large number of spot markets and the spot markets near exhaustion are preceded by a large number of forward openings (see our working paper for a formal treatment of this more general case). And second, we allow for firms' initial stocks to differ. We conclude in Section 5 with an explanation of how the results of the paper are affected, if at all, when we relax some of the assumptions, namely, constant extraction cost and public observability of stocks and of forward positions.

2. A two-period model

We develop a two-period model to explore the implications of forward contracting for the equilibrium of a depletable-stock oligopoly. As formally shown in our working paper, the two-period model captures reasonably well the dynamics we see in a more general model with an endogenous number of periods.

2.1. Notation and assumptions

Consider two (risk-neutral) firms (i and j), each holding a stock of a perfectly storable homogenous good, denoted by s_1^i and s_1^j, respectively, to be sold in two periods ($t = 1, 2$). The size of the stocks are public information at all times. There are no production (or extraction) costs other than the opportunity cost of not being able to sell tomorrow what is sold today. These are valid assumptions for the examples that motivate our paper; nevertheless, we discuss the implications of relaxing these assumptions in the concluding section. Firms discount future profits at the common discount factor $\delta < 1$.

Firms attend the spot market in both periods $t = 1, 2$ by simultaneously choosing quantities q_t^i and q_t^j. For tractability, we assume that the spot price at t, which is denoted by p_t^s, is given by the linear inverse demand function $p_t^s(q_t^i + q_t^j) = a - (q_t^i + q_t^j)$, where a is the (choke) price at which consumers (and firms) can buy a substitute good from a perfectly elastic supply.

Firms are also free to simultaneously buy or sell forward contracts that call for delivery of the good at any of the spot markets that follow. We treat these forward contracts as pure financial commitments, so rather than physically delivering or acquiring the good at the spot market firms can close their forward positions at the spot price $p^s \in [0, a]$.[14]

For each period we assume a two-stage structure: the forward market precedes the spot market where physical deliveries take place and contract positions are closed. In a forward market, firms can take positions for any future spot market, including the present period spot market (in this two period model no spot markets will open after $t = 2$). Forward contracts by firm i at $t = 1$ for the first and second spot markets are denoted by $f_{1,1}^i$ and $f_{1,2}^i$, respectively. Similarly, forward contracts at $t = 2$ for period-2 spot market is denoted by $f_{2,2}^i$. We adopt the convention that $f^i > 0$ when firm i is selling forward contracts (i.e., taking a short position) and $f^i < 0$ when is buying forwards (i.e., taking a long position). In this complete-information setting, we further assume that forward positions are observable and enforceable.[15] Note that while position $f_{1,1}^i$ is an obligation that can be only closed at the spot market

[14] This form of contracting is commonly known as a two-way contract for difference; see, for example, Green (1999). Note that like in Allaz and Vila (1993) and Mahenc and Salanié (2004) our results do not change if we restrict forward contracts to physical commitments and where firms could, if necessary, cover their short obligations with the substitute good.

[15] The assumptions for the contract market are the same as in Allaz and Vila (1993), Mahenc and Salanié (2004), and Liski and Montero (2006).

1, the forward position for $t=2$ can be modified at the forward market in 2 by taking an additional (long or short) position $f^i_{2,2}$; thus, the aggregate position for period 2 would be equal to $F^i_2 = f^i_{1,2} + f^i_{2,2}$. Finally, the forward clearing price (i.e., striking or delivery price) at t when taking a position for $\tau \geq t$ is denoted by $p^f_{t,\tau}$.

2.2. Why firms trade forwards? A simple example

Abstract from forward contracting for a moment and suppose the stocks of the two firms are equal and

$$\frac{a(1-\delta)}{2} < s^i_1 = s^j_1 = \frac{s}{2} < \frac{a(2-\delta-\delta^2)}{4}$$

so we can be sure the total stock s is depleted in exactly two periods. Infact, when $s > a(1-\delta)$, price-taking firms prefer to deplete the stock in two periods rather than in one because the price of doing the latter, $a - s$, is smaller than the discounted price of moving a marginal unit of the stock to the second period, δa. On the other hand, when a monopolist owns $s < a(2-\delta-\delta^2)/2$, it rather depletes its stock in two periods than in three because the (discounted) marginal revenue of doing the former,

$$MR_1 = a - 2q_1 = \delta MR_2 = \delta(a - 2q_2)$$

where $q_1 + q_2 = s$,[16] is larger than the discounted marginal revenue from moving a marginal unit of the stock to a third period, $\delta^2 a$.

Now that we know the oligopoly solution will entail depletion in exactly two periods, we can safely present the first-order conditions that must be satisfied in a duopoly equilibrium

$$MR^i_1 = a - 2q^i_1 - q^j_1 = \delta MR^i_2 = \delta(a - 2q^i_2 - q^j_2) \quad (1)$$

where $q^i_1 + q^i_2 = s/2$ and for both i and j. If j is playing q^j_1 in period 1, which automatically determines $q^j_2 = s/2 - q^j_1$, firm i's best response is to play according to (1), which is

$$q^i_1(q^j_1) = \frac{2a(1-\delta) + 3s\delta}{4(1+\delta)} - \frac{1}{2}q^j_1 \quad (2)$$

and $q^i_2(q^j_1) = s/2 - q^i_1(q^j_1)$. Eq. (2) exhibits intertemporal strategic complementarity in that firm i will move production from the first to the second period if firm j decides to increase its period-1 deliveries and vice versa.

This strategic complementarity plays a crucial role in understanding the emergence of a forward market. To see that, we first solve (1) for the equilibrium quantities to obtain

$$q^j_1 = \frac{2a(1-\delta) + 3\delta s}{6(1+\delta)} \quad (3)$$

and $q^j_2 = s/2 - q^j_1$ for both j and i, which yield the equilibrium spot prices

$$p^s_1 = \frac{a(1+5\delta) - 3\delta s}{3(1+\delta)} \quad (4)$$

and

$$p^s_2 = \frac{a(5+\delta) - 3s}{3(1+\delta)} \quad (5)$$

[16] Note that solving the two equations obtains

$$q_1 = \frac{a(1-\delta) + 2\delta s}{2(1+\delta)}$$

Given that the first period is the most profitable of the two, i.e.,

$$p_1^s - \delta p_2^s = \frac{a}{3}(1-\delta) > 0, \tag{6}$$

a natural question that arises is whether there is anything a firm, say j, can do to commit a larger fraction of its stock to the first period (and a smaller to the second). Using the best-response function (2), we now compute j's optimal delivery path if it could commit to it before i starts production. Such path would solve

$$\max_{q_1^j} p_1^s(q_1^j + q_1^i(q_1^j))q_1^j + \delta p_2^s(s - q_1^j - q_1^i(q_1^j))\left(\frac{s}{2} - q_1^j\right) \tag{7}$$

where $q_1^i(q_1^j)$ is given by (2). It is not difficult to see that the solution of (7) is bigger than the quantity in (3); and the reason is precisely the price inequality in (6). Following a Stackelberg logic, firm j would like to move first to increase its period 1 delivery and take advantage of the higher price.

In a pure-spot world, and where firms move simultaneously, there is nothing a firm can do to credibly communicate to its rival that it will allocate a larger share of its stock to period 1, that is, larger than the quantity in (3). But, what if a firm, say i, decides at the beginning of period 1 offers to take a financial short position of size $f_{1,1}^i = f > 0$? Suppose the position trades with price p^f, so that the firm's total profit is

$$p_1^s(\cdot)q_1^i + (p^f - p_1^s(\cdot))f + \delta p_2^s(\cdot)\left(\frac{s}{2} - q_1^i\right)$$

where the position is closed after the realization of the spot price p_1^s. Under perfect information, we have $p^f = p_1^s$ so that no direct profit or loss follows from the contract position; however, when choosing q_1^i, the firm is effectively maximizing

$$p_1^s(\cdot)(q_1^i - f) + \delta p_2^s(\cdot)\left(\frac{s}{2} - q_1^i\right)$$

because amount f has already been sold. To see why offering f can be profitable for i, suppose f is very small so prices (4) and (5) virtually do not change. Since i has already allocated a fraction f of its stock to the first period, it must now decide how to allocate its remaining stock, $s/2 - f$, between the two periods at the prevailing prices (4) and (5). Using the equilibrium expression in (3), but replacing s by $s - 2f$, we obtain that i has increased its delivery for period 1 in $f/(1+\delta)$ and decrease its delivery for period 2 in the exact same amount, which, according to (6) entails a profit gain of

$$\Delta = \frac{af(1-\delta)}{3(1+\delta)}$$

for f very small. Clearly, selling some forwards is a profitable strategy for i when j is not selling forwards, which shows why in equilibrium we cannot have both firms not selling forwards. How would firms, in equilibrium, choose their forward positions $f_{1,1}^i, f_{1,1}^j > 0$ if allowed to do so at the beginning for period 1? Below, we set up the forward-contracting game and show that in subgame-perfect equilibrium (SPE) symmetric firms contract (see (17) below)

$$f_{1,1}^i = f_{1,1}^j = \frac{a}{5}(1-\delta)$$

which leads to a more front-loaded delivery of the resource stock (see (18) below),

$$q_1^i = \frac{1}{(1+\delta)}\left(\frac{2}{5}a(1-\delta) + \frac{1}{2}\delta s\right),$$

relative to that would be without contracts, i.e., (3). The mere opportunity of trading forward has created a prisoner's dilemma for the two firms bringing them closer to competitive pricing (they still take positions below the competitive mark $a(1-\delta)/2$). Forward trading makes both firms worse off relative to the case in which they stay away from the forward market. If firm j does not trade any forwards, then firm i has all the incentives to make forward sales (i.e., $f_{1,1}^i > 0$) as a way to allocate a larger fraction of its total stock s_1^i to the first period, which is the most profitable of the two (recall that $p_1^s > \delta p_2^s$). In the reproducible commodity (Cournot) game, forward trading allows a firm to capture Stackelberg profits – given that the other firm has not sold any forwards – by credibly committing in advance to the Stackelberg production. In our depletable-stock game, forward trading allows a firm to capture Stackelberg profits by committing a larger fraction of its overall stock to the first period.[17]

Two lessons follow from this example. First, firms choose contracts to reallocate a given resource endowment in a more competitive manner. Thus, although there is no overall expansion of production, contracts are still pro-competitive. In fact, when contracting opportunities prior to the physical deliveries are increased without limit, the equilibrium outcome becomes perfectly competitive, as we will illustrate below. Second, in this context, the contract market arises endogenously due to the imperfect competition. While Allaz and Vila (1993) outline the microstructure for the forward market that justifies these conclusions, it may be useful to explain why the mere existence of oligopoly rents gives rise to the contract market. Consider a pure-spot Cournot oligopolist who is approached by a third-party with a proposal of a bilateral delivery contract to be signed before the spot market. If the contract is observable and enforceable, it is a credible commitment to serve part of the demand (the third party can deliver the contracted amount to the spot market), so only some residual demand is left for the spot competition. Since the contract creates rents by increasing the profits of the oligopolist, the third party and the oligopolist can always find an agreement that profits both at the expense of the remaining oligopolists.[18] This way there will be entry to the "commitment market" until these rents are dissipated. If each entrant can provide unlimited commitment, it takes only two speculators to arbitrate away the rents in the contract market.

3. Equilibrium solution

To understand the effect of forward contracting on the equilibrium path it is useful to start with the case in which firms can only trade in the spot markets. We do that first and only then consider the SPE when firms are also allowed to take forward positions.

3.1. Pure-spot trading

A strategy for player i in a pure-spot game specifies an output for period 1, $q_1^i \leq s_1^i$, and an output for period 2, q_2^i, that is a function of the remaining stocks in period 2, s_2^i and s_2^j, where $s_2^i = s_1^i - q_1^i$. The SPE strategies are to be found by backward induction.

At $t = 2$ and given stocks $s_2^i \geq 0$ and $s_2^j \geq 0$, firm i's best response to an output $q_2^j \geq 0$ by firm j is given by

$$R_2^i(q_2^j) = \min\{s_2^i, \arg\max_{q_2^i} p_2^s(q_2^i + q_2^j)q_2^i\} \tag{8}$$

which leads to the (unique) equilibrium strategy

$$q_2^i(s_2^i, s_2^j) = \begin{cases} \dfrac{a}{3} & \text{if} \quad s_2^i \geq \dfrac{a}{3} \text{ and } s_2^j \geq \dfrac{a}{3} \\ s_2^i & \text{if} \quad s_2^i < \dfrac{a}{3} \text{ and } s_2^j \geq 0 \\ R_2^i(s_2^j) & \text{if} \quad s_2^i \geq \dfrac{a}{3} \text{ and } s_2^j < \dfrac{a}{3} \end{cases} \tag{9}$$

[17] Obviously, if we change the mode of competition in the spot market from quantity to price competition, as Mahenc and Salanié (2004) do for the reproducible good, our pro-competitive result is reversed and for the same reason: under price competition firms have incentives to underinvest in forwards, that is, to go long. For a discussion of how and why the results are reversed depending the mode of competition see Liski and Montero (2006).

[18] In the language of Segal (1999), forward contracting involves an externality because parties at the contracting stage do not take into account the dissipation of oligopoly rents that affect all suppliers with each contract.

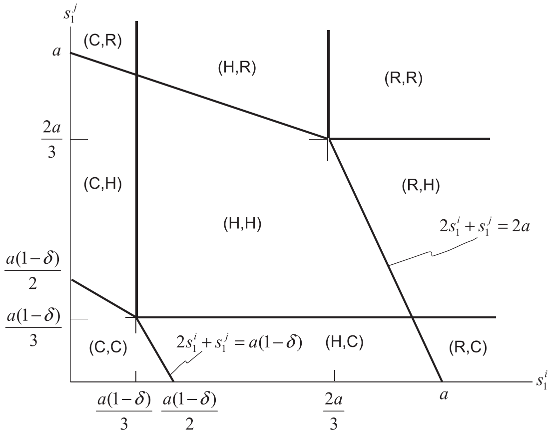

Fig. 1. Spot trading equilibrium as a function of initial stocks.

for both i and j. These equilibrium strategies are simply Cournot strategies with capacity constraints that result in output pairs within the inner envelope of the best-response functions.

Consider now decisions in the first period. Depending on the size of the initial stocks, s_1^i and s_1^j, we can have extreme cases in which firms never get to produce in period 2 or that their first period decisions do not affect what they produce in period 2. As shown in Fig. 1, the former occurs when stocks lie in region (C,C), that is, when both firms are sufficiently capacity constrained by their initial stocks that they sell everything in period 1. The equilibrium condition for this to happen is that the marginal revenue (MR) of selling an extra unit in period 1 is equal to or greater than the marginal revenue of selling that unit in period 2 at price a, i.e., $MR_1^i \equiv a - 2s_1^i - s_1^j \geq \delta a$ for both i and j. The latter case, on the other hand, occurs when stocks are in the region (R,R), that is, when stocks are so large that firms behave as if they where selling a zero-cost reproducible good. The equilibrium condition for this is that marginal revenues equal zero in both periods and for both firms. It is clear that this happens when firms produce the Cournot output in each period, which requires $s_1^i, s_1^j \geq 2a/3$.

Fig. 1 also depicts cases of initial stocks within these two extreme. When stocks are in region (H,C), for instance, we have that firm j is capacity constrained and sells everything in period 1 (i.e., $MR_1^j \geq \delta MR_2^j$) whereas firm i operates in a Hotelling world of scarcity rents, that is, according to Hotelling's equilibrium condition for an exhaustible resource (i.e., $\delta a \geq MR_1^i = \delta MR_2^i \geq 0$). Anticipating (9), for j to exhaust its stock in period 1 and i to exhaust his in period 2 requires, respectively

$$a - 2s_1^j - q_1^i \geq \delta(a - q_2^i) \tag{10}$$

$$\delta a \geq a - 2q_1^i - s_1^j = \delta(a - 2q_2^i) \geq 0 \tag{11}$$

where $q_2^i = s_1^i - q_1^i$. These equilibrium inequalities define the range of initial stocks that make region (H,C). It is obvious from (10) that j does not want to move any of its production to period 2. It is less obvious why could not we have an equilibrium in which j is forced to move part of its production to period 2 so both firms end-up producing in both periods. Such an equilibrium would require i to produce in period 1 beyond what is dictated by the equality in (11) resulting in $MR_1^i < \delta MR_2^i$; a violation of the Hotelling equilibrium condition. Hence, when stocks are in region (H,C) the unique period-1 equilibrium strategies are given by $q_1^i = [a(1-\delta) + 2\delta s_1^i - s_1^j]/2(1+\delta)$ and $q_1^j = s_1^j$.

The remaining regions of Fig. 1 are obtained in the same fashion. In region (H,H), both i and j's production paths satisfy $MR_1^i = \delta MR_2^i$, where $MR_t^i = a - 2q_t^i - q_t^j$, which gives $q_1^i = [a(1-\delta) + 3\delta s_1^i]/3(1+\delta)$ and $q_2^i = s_1^i - q_1^i$ for both i and j; in (R,H) firm i's production path satisfies $MR_1^i = MR_2^i = 0$ while j's satisfies (11) which leads to $q_1^i = [2a(1+2\delta) - 3\delta s_1^j]/6(1+\delta)$ and $q_1^j = [a(1-\delta) + 3\delta s_1^j]/3(1+\delta)$; and in (R,C) firm i's path satisfies $MR_1^i = MR_2^i = 0$ while j's satisfies (10) which gives $q_1^i = (a - s_1^j)/2$ and $q_1^j = s_1^j$.

Finally, note that from inequality (10) we can immediately see that $p_1^s > \delta p_2^s$. Unlike in a perfectly competitive exhaustible-resource market, here prices grow at a rate strictly lower than the interest rate (marginal revenues grow at the interest rate). In other words, oligopoly pricing depart from competitive pricing by shifting production from the present to the future.

3.2. Forward trading

We now allow firms to engage in forward trading in addition to spot trading. To facilitate the exposition we consider first the case in which firms have stocks of equal size $s_1^i = s_1^j > 0$, and leave the asymmetric case for the next section. A strategy for player i in this richer game specifies (i) a vector of forward quantities or positions for period 1, $\mathbf{f}_1^i = (f_{1,1}^i, f_{1,2}^i)$, (ii) an output for period 1 as a function of $\mathbf{f}_1^i$ and $\mathbf{f}_1^j$, (iii) a forward position for period 2, $f_{2,2}^i$, as a function of $\mathbf{f}_1^i$, $\mathbf{f}_1^j$ and remaining stocks s_2^i and s_2^j, where $s_2^i = s_1^i - q_1^i \geq 0$, and (iv) an output for period 2, q_2^i, as a function of $F_2^i = f_{1,2}^i + f_{2,2}^i$, F_2^j and the remaining stocks s_2^i and s_2^j.

As in the pure-spot game, the SPE is highly dependent on firms' initial stocks. If stocks are very small, for example, we will see that forward contracting plays no strategic role since everything is produced in the first period. If, on the other hand, stocks are extremely large, we are back to Allaz and Vila's (1993) analysis of forward contracting for reproducible goods (and where a fraction of the stock remains on the ground). Note that this result is particular to the two-period model because we are (artificially) restricting the number of spot market openings. In the general model the number of periods in which firms serve the spot market is endogenously determined, so no stock remains in the ground.

To show how the equilibrium transits from one extreme to the other, it helps to start by considering initial stocks large enough that firms serve both spot markets in equilibrium and that firms are only allowed to sell/buy forwards for the first spot market, i.e., $f_{1,2}^i = f_{2,2}^i = 0$ for both i and j (we will see shortly that in some relevant cases this restriction in the number of forward openings is innocuous for the equilibrium). Working backwards and given stocks $s_2^i > 0$ and $s_2^j > 0$, firm i's best response to an output $q_2^j \geq 0$ by firm j is given by (8). Invoking symmetry (i.e., $s_2^i = s_2^j$),[19] period-2 equilibrium quantities reduce to

$$q_2^i(s_2^i, s_2^j) = \min\left\{s_2^i, \frac{a}{3}\right\} \tag{12}$$

which is the standard Cournot outcome with capacity constraints.

Consider now decisions in the first spot market. Given $f_{1,1}^i$ and $f_{1,1}^j$, firm i's best response to output q_1^j is given by

$$R_1^i(q_1^j, f_{1,1}^i, f_{1,1}^j) = \underset{q_1^i}{argmax}[W_1^i = p_1^s(\cdot)q_1^i + (p_{1,1}^f - p_1^s(\cdot))f_{1,1}^i + \delta p_2^s(\cdot)q_2^i(s_2^i, s_2^j)]$$

where W_1^i is firm i's payoff at the spot market in period 1 and $q_2^i(s_2^i, s_2^j)$ is given by (12). Term $(p_{1,1}^f - p_1^s(\cdot))f_{1,1}^i$ is the open contract position that is to be closed immediately after the spot price is realized. We will see that in equilibrium the closing value of this position is zero; nevertheless, firm i has an incentive to influence the value of the position in the spot market as the spot price is yet to be determined. We rearrange the payoff as

$$W_1^i = p_1^s(\cdot)(q_1^i - f_{1,1}^i) + \delta p_2^s(\cdot)q_2^i(\cdot) + p_{1,1}^f f_{1,1}^i \tag{13}$$

[19] Throughout this section and to save space, we will only focus on symmetric stocks and positions because it is the relevant case for computing the equilibrium path.

where $s_2^i = s_1^i - q_1^i$. Since the last term in (13) enters as a constant,[20] the relevant spot sale for firm i's profits is not total production q_1^i but $q_1^i - f_{1,1}^i$. Firm i's best response to q_1^j satisfies the intertemporal optimization principle that discounted marginal revenues should be equalized across periods, that is,

$$a - 2q_1^i - q_1^j + f_{1,1}^i = \delta(a - 2q_2^i - q_2^j) \geq 0 \tag{14}$$

where $q_2^i \leq s_1^i - q_1^i$.

Solving (14) for i and j, we obtain the period-1 equilibrium output

$$q_1^i(f_{1,1}^i, f_{1,1}^j) = \min\left\{\frac{a + 2f_{1,1}^i - f_{1,1}^j}{3}, \frac{a(1-\delta) + 3\delta s_1^i + 2f_{1,1}^i - f_{1,1}^j}{3(1+\delta)}\right\} \geq 0 \tag{15}$$

The first term in the bracket is the relevant equilibrium quantity when, in equilibrium, $q_1^i + q_2^i < s_1^i$ (i.e., $MR_1^i = \delta MR_2^i = 0$). This is the reproducible-good case where the effect of forward contracting is well documented in Allaz and Vila (1993). Whenever firms hold short positions, $f_{1,1}^i, f_{1,1}^j > 0$, they care less about the price effect of an increase in production and therefore end up producing above the Cournot total output.[21]

The more relevant case for our analysis, however, is when in equilibrium $q_1^i + q_2^i = s_1^i$ for both i and j (i.e., $MR_1^i = \delta MR_2^i > 0$). When the stock is fully exhausted, the period-1 equilibrium output is given by the second term in (15). Despite a firm's total production is limited by its stock, the second term in (15) shows that forward positions can still have an effect on spot competition in this exhaustible-resource setting by moving production across periods (if firms hold no forward positions, i.e., $f_{1,1}^i = f_{1,1}^j = 0$, we obtain the oligopoly solution for region (H,H) in Fig. 1). When firms hold short positions, $f_{1,1}^i, f_{1,1}^j > 0$, the spot market becomes more competitive in that firms are credibly committing more production to period 1 (and less to period 2). This can be seen from condition (14): contracts increase firms' marginal revenues making them to behave more aggressively in the spot market at 1. In fact, if $f_{1,1}^i = f_{1,1}^j = a(1-\delta)/2$, the perfectly competitive solution is implemented.[22] Conversely, if firms take long positions, i.e., $f_{1,1}^i f_{1,1}^j < 0$, the spot market becomes less competitive; and when $f_{1,1}^i = f_{1,1}^j = -a(1-\delta)/4$, the monopoly solution is implemented.[23]

Obviously, in equilibrium firms do not trade any arbitrary amount of forwards. In deciding how many contracts to buy/sell, firm i's evaluates the following payoff at the forward stage in period 1[24]

$$V_1^i = W_1^i(f_{1,1}^i, f_{1,1}^j)$$

where $W_1^i(f_{1,1}^i, f_{1,1}^j)$ are the spot (subgame-perfect) profits. There are no payments at the forward stage, only writing of contracts. Rearranging terms, firm i's overall profits as a function of $f_{1,1}^i$ and $f_{1,1}^j$ can be written as

$$V_1^i = (p_{1,1}^f - p_1^s)f_{1,1}^i + p_1^s q_1^i(f_{1,1}^i, f_{1,1}^j) + \delta p_2^s q_2^i(s_2^i(f_{1,1}^i, f_{1,1}^j), s_2^j(f_{1,1}^i, f_{1,1}^j))$$

where $p_t^s = p_t^s(q_t^i(f_{1,1}^i, f_{1,1}^j) + q_t^j(f_{1,1}^i, f_{1,1}^j))$ for $t = 1, 2$. As in Allaz and Vila (1993), the arbitrage payoff $(p_{1,1}^f - p_1^s)f_{1,1}^i$ is zero. Speculators and/or consumers share the same information as producers and

[20] Note that if forward contracts were defined as physical obligations, the term $p_{1,1}^f f_{1,1}^i$ would not appear in (13) because it constitutes a revenue the firm pockets at the forward stage. Under financial obligations, forward positions are closed at the spot stage, which explains why $p_{1,1}^f f_{1,1}^i$ enters in (13). Nevertheless, it enters as a constant, so it makes no difference for firms' spot decisions, and thereby, for their (strategic) forward decisions.

[21] Note that if for some reason firms' forward positions are long enough that $a + 2f_{1,1}^i - f_{1,1}^j < 0$, firms will produce nothing in period 1 and close their positions at the choke price a (this also applies to the second term in (15)).

[22] The competitive allocations when exhaustion takes two periods are $q_1^* = [a(1-\delta) + 2\delta s_1]/2(1+\delta)$ and $q_2^* = s_1 - q_1^*$. Note that because of scarcity rents, firms do not need to be fully contracted to implement the competitive solution.

[23] The monopoly allocations are $q_1^m = [a(1-\delta) + 4\delta s_1]/4(1+\delta)$ and $q_2^m = s_1 - q_1^m$.

[24] Note that under physical commitments, the term $p_{1,1}^f f_{1,1}^i$ would enter in i's payoff.

therefore compete for forwards until $p^f_{1,1} = p^s_1$, where p^s_1 is the expected period-1 spot price that is a function of forward quantities $f^i_{1,1}$ and $f^j_{1,1}$.[25] Thus, firms are left with the contract-coverage dependent Cournot profit from the two periods, $p^s_1 q^i_1 + \delta p^s_2 q^i_2$.

Continuing with the case in which $q^i_1(f^i_{1,1}, f^j_{1,1}) + q^i_2(f^i_{1,1}, f^j_{1,1}) = s^i_1$, firm i's best response to j's forward position is

$$G^i_{1,1}(f^j_{1,1}) = \frac{a}{4}(1-\delta) - \frac{1}{4} f^j_{1,1} \tag{16}$$

which leads to the equilibrium forward sales

$$f^i_{1,1} = f^j_{1,1} = \frac{a}{5}(1-\delta), \tag{17}$$

period-1 equilibrium output

$$q^i_1 = \frac{1}{3(1+\delta)}\left(\frac{6}{5}a(1-\delta) + 3\delta s^i_1\right) \tag{18}$$

and period-2 equilibrium output $q^i_2 = s^i_2 = s^i_1 - q^i_1$.

Note that the (symmetric) equilibrium characterized above is unique; any other equilibrium, if it existed, would require one firm, say i, serving only in period 1 and the other firm, j, serving in both periods. The latter can certainly happen for asymmetric forward positions; for example, if $f^i_{1,1} = a(1-\delta)/4$ and $f^j_{1,1} = 0$. But these forward positions do not constitute an equilibrium since j's best response to $f^i_{1,1}$ is not 0 but $G^j_{1,1}(f^i_{1,1}) > 0$. This "revision" lowers the spot price in period 1, which, in turn, makes i revise its forward position downward and j revise his upward until both positions converge to the equilibrium positions in (17) and with both firms serving in both periods.[26]

We can now extend our discussion to the case where firms can also take forward positions $f^i_{2,2}$ (later we will also allow for positions $f^i_{1,2}$). Working backwards and given stocks $s^i_2 = s^j_2 > 0$ and positions $f^i_{2,2} = f^j_{2,2}$, consider the spot subgame at $t = 2$. Firm i's best response to an output $q^j_2 \geq 0$ by firm j is given by

$$R^i_2(q^j_2, f^i_{2,2}, f^j_{2,2}) = \underset{q^i_2}{\arg\max} W^i_2 = [p^s_2 q^i_2 + (p^f_{2,2} - p^s_2) f^i_{2,2}] \leq s^i_2$$

where W^i_2 is firm i's payoff in the spot market at 2. Solving, we obtain the period-2 equilibrium output

$$q^i_2(f^i_{2,2}, f^j_{2,2}) = \min\left\{ s^i_2, \frac{a + 2f^i_{2,2} - f^j_{2,2}}{3} \right\} \geq 0. \tag{19}$$

Unlike in period 1, it is evident from (19) that forward contracting may do nothing to period-2 spot competition if the remaining stocks s^i_2 and s^j_2 are small enough.

Lemma 1. *If $s^i_2 = s^j_2 \leq a/3$, firms hold any positions for period 2 (including no positions) that ensure exhaustion in period 2 (i.e., $q^i_2(f^i_{2,2}, f^j_{2,2}) = s^i_2$ for both i and j).*

The proof is simple. Take $s^i_2 = s^j_2 = a/3$ and suppose firm j sells no forwards for period 2 (i.e., $f^j_{2,2} = 0$) and ask what would be i's optimal amount of contracting. It is evident that it is the amount that allows

[25] Note that even if firms and expeculators conjecture for some reason firms will end up producing less than their (short) forward positions, i.e., $q^i_1 + q^j_1 < f^i_{1,1} + f^j_{1,1}$, the forward market does not clear at the choke price a but at the spot price $p^s = a - q^i_1 - q^j_1$ (unless $q^i_1 = q^j_1 = 0$).

[26] The reason why the contracting stage does not introduce the multiplicity of equilibria introduced by the first-period production stage of Saloner (1987) is because firm i's period-1 output is decreasing in $f^j_{1,1}$, so j has incentives to sell some forwards even if it believes i has contracted enough to implement its Stackelberg outcome. In other words, forward contracting provides partial commitment unlike irreversible production.

i to implement its Stackelberg outcome. But if $s_2^i = a/3$ the best i can do is to produce $q_2^i = a/3$ and let j produce likewise; in other words, implement the Cournot outcome (and more so if $s_2^i = s_2^j < a/3$). Taking a long position, however, can be detrimental for i if it ends up selling less than s_2^i, that is, if $a + 2f_{2,2}^i - f_{2,2}^j < 3s_2^i$. Thus, in equilibrium firms hold any forward position (including no position) consistent with the equilibrium outcome $q_2^i(f_{2,2}^i, f_{2,2}^j) = s_2^i$.

The situation changes when $s_2^i = s_2^j > a/3$ because now firms have Stackelberg incentives to take short positions.

Lemma 2. *If $s_2^i = s_2^j > 2a/5$, firms hold short positions $f_{2,2}^i = f_{2,2}^j = a/5$ and sell only a fraction of their remaining stocks in period 2 (i.e., $q_2^i(f_{2,2}^i, f_{2,2}^j) = 2a/5 < s_2^i$ for both i and j).*

The proof, including the uniqueness of equilibrium, is in Allaz and Vila (1993). When stocks are sufficiently large the exhaustion restriction is no longer binding, so firms operate as if they were selling a reproducible good.

The most interesting case for our analysis is the one in which remaining stocks are neither too small nor too large such that firms operate in a Hotelling world where forward contracting does matter.

Lemma 3. *If $a/3 < s_2^i = s_2^j \leq 2a/5$, firms hold short positions for period 2 that ensure exhaustion in period 2 (i.e., $f_{2,2}^i \geq 3s_2^i - a > 0$ and $q_2^i(f_{2,2}^i f_{2,2}^j) = s_2^i$ for both i and j).*

The minimum amount of contracting $3s_2^i - a$ is readily obtained from (19). The intuition is as follows. If for some reason j takes a short position below $3s_2^j - a$, firm i's best response, in an effort to come closer to its period-2 Stackelberg outcome (i.e., produce s_2^i and let j produce $R_2^j(s_2^i) < s_2^j$), is to increase its forward position above $3s_2^i - a$ enough to ensure its exhaustion while forcing j to leave part of its stock on the ground. But this is clearly suboptimal for j. Here again firms face a prisoner's dilemma. It would be better for them to sell no contracts and produce $a/3 < s_2^i$ in period 2, but firms have no means to stay away from the forward market.

Now that we understand the Stackelberg rationale for forward contracting in a market where the total supply (i.e., stock) is fixed, we can extend our discussion to cover the case where firms can also take forward positions for period 2 in period 1 (i.e., $f_{1,2}^i$ positions) and where initial stocks can be of any size (we retain the symmetry of the problem). Since forward contracting affects spot competition either by shifting production across periods, when the exhaustion restriction is binding, or by adding more production, when part of the stock is left on the ground, it will also alter the thresholds that define the regions where firms operate in equilibrium, namely, (C,C), (H,H) or (R,R). See Fig. 1. It is useful to structure the discussion that follows around the computation of these two thresholds.

In computing the first threshold, the one that separates region (C,C) from (H,H), we start by finding the size of the initial stocks below which forward contracting plays no strategic role in equilibrium.

Lemma 4. *If $s_1^i = s_1^j \leq a(1-\delta)/3$, firms hold any positions (including no positions) that ensure exhaustion in period 1 (i.e., $q_1^i(f_{1,1}^i, f_{1,1}^j, f_{1,2}^i, f_{1,2}^j) = s_1^i$ for both i and j).*

The logic here follows that of Lemma 1. If j signs no forwards, there is nothing i can do to displace part of j's production to period 2 since $MR_1^j \equiv a - 2s_1^j - s_1^i > \delta a$. And since everything is sold in period 1, there is no strategic role for forward contracting for period 2.

But as soon as s_1^i (and s_1^j) goes above $a(1-\delta)/3$, there are Stackelberg motives to sell forwards.

Lemma 5. *If $a(1-\delta)/3 < s_1^i = s_1^j \leq 2a(1-\delta)/5 \equiv s_1^{CH}$, firms hold short positions for period 1 enough to ensure exhaustion in period 1 (i.e., $f_{1,1}^i \geq 3s_1^i - a(1-\delta) > 0$ and $q_1^i(f_{1,1}^i, f_{1,1}^j) = s_1^i$ for both i and j) and no positions for period 2 (i.e., $f_{1,2}^i = 0$).*

Analogous to Lemma 3, the minimum amount of contracting $3s_1^i - a(1-\delta)$ is readily obtained from the second term in (15). Again, when stocks are relatively small both firms end up taking forward positions that allocate all the stocks to period 1, so there is no strategic reason to take a forward position for period 2.

Lemma 5 also indicates that $s_1^{CH} \equiv 2a(1-\delta)/5$ – the threshold that separates region (C,C) from (H,H) – is higher than in Fig. 1, $a(1-\delta)/3$, because of the competitive pressure introduced by forward trading that forces firms to sell more in period 1. Thus, if stocks are above s_1^{CH}, firms will necessarily serve both periods in equilibrium; and if they are very large, firms will operate as if they were selling a reproducible good.

Lemma 6. *If $s_1^i = s_1^j > 29a/35 \equiv s_1^{HR}$, firms hold short positions for period 1 (i.e., $f_{1,1}^i = a/5$ for both i and j) and for period 2 (i.e., $f_{1,2}^i = f_{2,2}^i = a/7$ for both i and j) and sell a fraction of their stocks (i.e., $q_1^i = 2a/5$ and $q_2^i = 3a/7$, where $q_1^i + q_2^i = s_1^{HR} < s_1^i$).*

Again, the proof follows from Allaz and Vila (1993), as the overall capacity does not constrain sales. The threshold s_1^{HR} that separates region (H,H) from (R,R) is also higher than in Fig. 1 for the same competitive reasons. When stocks are above s_1^{HR}, the two spot markets become disconnected from each other in equilibrium. The spot market in period 2 is the more competitive of the two because it is proceeded by two forward openings and firms take short positions in both.[27] Note that in the general model, where there is an unlimited number of spot openings, spot markets are always intertemporally connected because firms have always the opportunity to attend the next spot market and obtain δa.

We are now ready to complete our characterization of the equilibrium when stocks are in region (H,H), which is the most relevant case for our analysis because it illustrates the basic workings of the general model.

Proposition 1. *If $s_1^{CH} < s_1^i = s_1^j \le s_1^{HR}$, the SPE outcome for both i and j is given by*

$$(i) f_{1,1}^i - \delta f_{1,2}^i \equiv H_1^i = \frac{a}{5}(1-\delta),$$

$$(ii) f_{1,2}^i \geq \frac{5}{1+\delta}\left[s_1^i - \frac{4a}{5}\right],$$

$$(iii) f_{2,2}^i + f_{1,2}^i \equiv F_2^i \geq \frac{3}{1+\delta}\left[s_1^i - \frac{a(11-\delta)}{15}\right],$$

(iv) q_1^i is given by (18), and (v) $q_2^i = s_2^i = s_1^i - q_1^i > 0$.

Proof. see Appendix. □

Note that item (i) states that the equilibrium joint position of contracts, as captured by $f_{1,1}^i - \delta f_{1,2}^i$, for the two periods is just equal to that in (17) where we assumed that contracts for the second spot market do not exist. This is already indicative of the fact that the equilibrium outcome in terms of delivered quantities will be the same irrespective of whether contracts are written for both periods, or only for one. However, in reality there are no exogenous restrictions on contracting, and then the second period contracts must satisfy items (ii) and (iii) that put limits on the second period contracts. The intuition behind parts (ii) and (iii) is that firms will not take a position in period 1 that they will not be able to credibly (i.e., sequentially rationally) undo in period 2.

Proposition 1 shows a multiplicity of equilibria in the amount of forward contracting (but not in the resource consumption) that naturally raises a concern regarding the difficulty this may impose for computing equilibrium strategies in games with a large number of market openings, like in the general model that we discuss below. Fortunately, such multiplicity vanishes as we move to the more relevant cases. As already seen in Lemma 6, it does when the exhaustion restriction is not binding. But more importantly for our analysis, the multiplicity also disappears when the stock at the period of exhaustion is sufficiently small that is typically the case when the number of periods needed for

[27] Note also that because $p_1^s > \delta p_2^s$ firms and/or consumers have no incentives to store today's production for tomorrow's use.

the stock exhaustion is endogenous. Indeed, Lemma 1 shows that if $s_2^i \le a/3$,[28] forwards positions for period 2 become strategically irrelevant (i.e., we can just let $f_{1,2}^i = f_{2,2}^i = 0$ without any equilibrium consequences). And if they do, there is a unique equilibrium solution, as explained above.

4. Towards a more general formulation

Proposition 1 shows why and how forward trading can have pro-competitive effects in a exhaustible-resource market. There are nevertheless additional considerations to be made. While helpful in explaining the basic mechanism, the extensive form of the two-period model is in principle incomplete because firms should be able to choose how long the market interaction lasts in equilibrium. In a more general setting, with an endogenously large number of periods and where deliveries and future contract positions are chosen on a period-by-period basis depending on current physical stocks and existing forward positions inherited from the past (the formal set up of the general model is in Appendix), firm *i* may respond to firm *j*'s heavy contracting in period *t* by avoiding its own contracting at *t* and allocating more capacity to a less contracted period *t* + 1 instead.[29] Despite this limitation, we show in our working paper that the main conclusions of the two-period model carry through, although with considerable additional complexity, to a more general setting. We explain below why this is so but with a more tractable extension of the two-period model that consists of adding forward openings preceding the two spot markets. The second consideration we address below is the role that asymmetries in firms' initial stocks may have in the pro-competitive effect of forward contracting.

4.1. Additional forward markets

Imagine now that the initial stocks $s_1^i = s_1^j$ are not exactly firms' initial stocks but rather their remaining stocks after several periods of production and consumption. In that case, one can view our two-period game as the last two periods of a much longer horizon game. But if that is so, one could reasonably argue that our equilibrium solution may not be valid because the spot market at $t = 1$ would no longer be preceded by one forward opening (the one at $t = 1$) but by as many as the number of periods of production/consumption that have gone by before $t = 1$.

Allaz and Vila (1993) also tackle this problem, but without the link between spot markets created by the resource constraint. They find that competition in the spot market intensifies with the number of forward openings that precede the opening of the spot market. The reason is that firms face the same prisoner's dilemma in each of the forward trading periods; hence, they end up contracting in each of the forward openings. As the number of forward openings tend to infinity, firms reach the spot market fully contracted and prices approach marginal costs. Forward trading has thus completely eliminated the otherwise existing Cournot profits.

Back to our two-period model, suppose then that before $t = 1$ there is an additional period, denoted by $t = 0$, where firms can trade forward contracts that call for delivery in any of the two spot markets. From Proposition 1 we know that we can focus exclusively on forward contracts that call for delivery in the spot market at $t = 1$, which we denote by $f_{0,1}^i$.[30] Since *i* can sign additional contracts at the forward market in $t = 1$, the firm's aggregate position at $t = 1$ for the spot market at $t = 1$ will be $F_1^i = f_{0,1}^i + f_{1,1}^i$.

Given $f_{0,1}^i$ and $f_{0,1}^j$, firm *i*'s payoff function at the forward subgame at $t = 1$ can be conveniently written as (recall that there are no arbitrage profits)

$$V_1^i = p_1^s(q_1^i + q_1^j)f_{1,1}^i + p_1^s(q_1^i + q_1^j)(q_1^i - F_1^i) + \delta p_2^s(q_2^i + q_2^j)q_2^i$$

[28] Or, alternatively, if $s_1^i \le a(11 - \delta)/15$ (see part (ii) of Proposition 1). Note also that $4a/5 > a(11 - \delta)/15$.

[29] This difference in extensive form is also an important difference relative to the Allaz and Vila (1993) model where firms are trapped to face the prisoners' dilemma in a particular spot market.

[30] Note that in the general model, where firms have always the opportunity to serve the next spot market and obtain δa, the stock of each firm at the period of exhaustion will necessarily fall below $a(1 - \delta)/3$, i.e., lay on the region (C,C) of Fig. 1. Thus, the two-period analysis of Section 4 tells us that in the general model we can ignore forward sales to the very last spot market served by the two firms and work backwards from the next to the last period.

Using the envelope theorem, firm i's reaction function reduces to (after rearranging terms)

$$4F_1^i + F_1^j = a(1-\delta) + 3f_{0,1}^i$$

which leads to the forward equilibrium strategy

$$F_1^i = \frac{a}{5}(1-\delta) + \frac{4}{5}f_{0,1}^i - \frac{1}{5}f_{0,1}^j \tag{20}$$

Expression (20) says that firms' overall contract coverage at the outset of the spot market is an increasing function of earlier forward commitments. As explained before, the reason for this is that past contracts, i.e., $f_{0,1}^i, f_{0,1}^j > 0$, increase firms' marginal revenues making them to behave more aggressively in all markets that follow, including both forward and spot markets.

It remains to see how much period-0 forwards firms trade in equilibrium. Given $f_{0,1}^j$, firm i's payoff from trading $f_{0,1}^i$ is

$$V_0^i = p_{0,1}^f f_{0,1}^i + \delta V_1^i(f_{0,1}^i, f_{0,1}^j) = \delta[p_1^s(q_1^i + q_1^j)q_1^i + p_2^s(q_2^i + q_2^j)q_2^i]$$

where $V_1^i(f_{0,1}^i, f_{0,1}^j)$ are the profits from the subgame that starts at the forward market in $t = 1$, and $q_t^i = q_t^i(F_1^i, F_1^j)$. Solving we find that in equilibrium

$$F_1^i = F_1^j = \frac{2a}{7}(1-\delta) > \frac{a}{5}(1-\delta)$$

In equilibrium firms cannot stay away from the new forward market (i.e., $f_{0,1}^i = f_{0,1}^j = a(1-\delta)/7$), resulting in a more competitive outcome. It can be shown more generally that

Proposition 2. *If the spot market at $t = 1$ is preceded by N forward trading periods, the overall contract coverage at the outset of that spot market is*

$$F_1^i = F_1^j = \frac{aN}{3+2N}(1-\delta) \tag{21}$$

The proof of the proposition is easily constructed from looking at the solution of the general model in our working paper. More interestingly, Proposition 2 indicates that a large N, $\lim_{N\to\infty} F(N) = a(1-\delta)/2$, leads to perfectly competitive pricing (i.e., $p_1^s = \delta p_2^s$).[31]

4.2. Stock asymmetries

We now look at the case in which initial stocks are of different sizes. Letting firm j be the smaller of the two firms, we will study how the equilibrium in the two-period game changes as we let s_1^j move from $s_1^j = 0$ to the symmetric case $s_1^j = s_1^i$, where s_1^i is some fixed value in the interval $[a(1-\delta)/2, a(11-\delta)/15]$. Rather than looking at all possible asymmetries in Fig. 1, we restrict attention to values of s_1^i that ensure no contracting for the second period but nevertheless capture the essence of the asymmetric problem.

The case $s_1^j = 0$ is immediate. A monopolist (i.e., firm i) will never sign forward contracts because this would only introduce more competition to the spot market (selling forwards has the same competition effect as selling part of the stock to a fringe of competitive suppliers). Now, to understand how stock asymmetries affect the equilibrium path when both firms hold some initial stock, it is useful to recall what firms seek to implement through forward contracting: if one firm does not sell forwards, the other can achieve Stackelberg profits by entering the forward market. Consider first the Stackel-

[31] Note that unlike in Allaz and Vila (1993), in our depletable-stock market firms do not need be fully contracted at $t = 1$ (i.e., $F_1^i = q_1^i$) for reaching competitive pricing.

berg outcome for the larger firm. Firm i's first-best is to implement $q_1^j = s_1^j$ and $q_2^j = 0$, i.e., it is optimal for i to let j exhaust in period 1, if

$$s_1^j \leq \frac{1}{4}a(1-\delta). \tag{22}$$

Thus, when j is small enough, i will let j to sell only to the more profitable first period, even if i could commit part of its sales before j takes any action.[32]

Consider now firm j's Stackelberg outcome. If allowed to move first, j would like to sell its entire stock in the first period as long as

$$s_1^j \leq \frac{1}{2}a(1-\delta). \tag{23}$$

It is intuitively clear that when we consider j's own stock, j's first-best (i.e., Stackelberg) threshold for leaving stock for the less profitable second period is larger than in (22).

These inequalities imply that both firms prefer j's early exhaustion in period 1 when j is small enough, i.e., (22) holds, and then there are no incentives to contract by either firm. However, j can extend its commitment to sell early by using the forward market even when its stock exceeds the level identified by (22).

Proposition 3. *If*

$$\frac{1}{4}a(1-\delta) < s_1^j \leq \frac{5-2\sqrt{2}}{5}a(1-\delta) \equiv s_1^{ST},$$

firm j implements its Stackelberg (i.e., first-best) solution: There is a two-period equilibrium where i does not contract at all (i.e., $f_{1,1}^i = 0$*) and j commits to sell only in period 1 by contracting* $f_{1,1}^j$ *according to*

$$f_{1,1}^j \geq f_{\min}(s_1^j) \equiv \frac{4}{3}s_1^j - \frac{1}{3}a(1-\delta)$$

Proof. See Appendix.[33] □

Proposition 3 says that j needs to contract at least $f_{\min}(s_1^j)$ to achieve its first-best. Note that contracting incentives just disappear, i.e., $f_{\min}(s_1^j) = 0$, when $s_1^j = a(1-\delta)/4$. Note also that if j contracts nothing when its stock is above the threshold in (22), i could achieve its first-best by taking a short position that would shift part of j's sales to period 2. But j can prevent this by making the spot market in t = 1 less profitable to i through its own contracting – minimum contracting $f_{\min}(s_1^j)$ is calculated as a position that keeps i unwilling to sign contracts. Contracting more than $f_{\min}(s_1^j)$, e.g., $f_{1,1}^j = s_1^j$, is more than enough to keep i away from the forward market until (23) holds as an equality.

When j's stock is above the Stackelberg threshold s_1^{ST} in Proposition 3, i's first-best is to make j to deliver also in period 2, for example, by taking a short position for period 1. If i takes such position, firm j contracts according to (16), i.e., $G_{1,1}^j(f_{1,1}^i) > 0$, which leads j to delivering in both periods. But if j is expected to deliver in both periods, firm i's best contracting response must also be given by (16). Therefore, when both firms are active in both periods the only possible equilibrium is "symmetric" in forward contracting with both firms taking position $a(1-\delta)/5$ in the forward stage.[34]

[32] The proof is immediate and, therefore, ignored here. Set $f_{1,1}^j = 0$ and solve for i's best response in the forward market and then use the chosen position to find the equilibrium deliveries. Alternatively, one can change the timing in the pure spot market model to find the Stackelberg allocations.

[33] Note that $s_1^{ST} = 0.434a(1-\delta)$.

[34] This multiplicity is specific to the two-period setting and is inconsequential more generally because even small asymmetries in initial stocks will generate large asymmetries in the future as the smaller firm exhausts its stock (in our working paper we formally show how this multiplicity dissapears in a three-period model where the smaller firm is active in the first two periods). Furthermore, this multiplicity (note also that $s_1^{ST} > s_1^{CH}$) complicates, at least in some regions, the redrawing of Fig. 1 when both spot and forward trading are present.

Note that this symmetric contracting equilibrium extends below the threshold s_1^{ST} in Proposition 3. In fact, for $s_1^j \in [2a(1-\delta)/5, s_1^{ST}]$ both equilibria coexist – and possibly with one in mixed strategies – but the asymmetric equilibrium Pareto dominates (i.e., better for both firms) the symmetric one, so it is the most likely outcome of the game when $s_1^j < s_1^{ST}$ (when $s_1^j = s_1^{ST}$ firm i is pay-off indifferent between the two equilibrium outcomes; see the Appendix). Likewise, the asymmetric equilibrium extends above s_1^{ST} up to the threshold $a(1-\delta)/2$ in (23); within this range there is no Pareto ranking of equilibria, however. The smaller firm likes the asymmetric one while the larger firm likes the symmetric one.

This two-period model illustrates how asymmetries can help firms to escape the competitive pressure introduced by the forward market. In fact, the smaller firm can greatly benefit from the forward market in that it may be able to implement its Stackelberg solution (unlike the larger firm which has nothing to gain from the opening of the forward market). Another way to appreciate how such stock asymmetries can suppress the pro-competitive effect of forward trading is to ask what would be the equilibrium consequences of adding, as in the previous section, a forward market before the opening of the spot markets, say, at $t=0$. Unlike in the symmetric case, there would be no consequences when $s_1^j < s_1^{ST}: f_{0,1}^j \geq f_{\min}(s_1^j)$ and $f_{0,1}^i = f_{1,1}^i = f_{1,1}^j = 0$. Note that the latter will not change with more forward openings (i.e., N large). At the very first forward opening j will sign $f_{\min}(s_1^j)$.

The most interesting case, however, is when $s_1^j \in (s_1^{ST}, a(1-\delta)/2)$. We know from the discussion above that in this case either equilibrium is possible. But as seen in the previous section, the addition of forward openings makes the symmetric-contracting equilibrium more competitive which, in turn, makes it less attractive to i (and also to j) relative to the asymmetric one. Therefore, the addition of forward openings moves up the threshold "s_1^{ST}" in which both companies prefer to implement the asymmetric equilibrium. And this threshold can go all the way to $a(1-\delta)/2$ if N is large.

The two-period model also illustrates how forward contracting reinforces the fact that asymmetric firms will generally exit the market at different times. It expands the stock threshold for which firm j would exit the market after the first period from $s_1^j \leq a(1-\delta)/3$ – the threshold under pure-spot trading (see Fig. 1) – to $s_1^j \leq s_1^{ST}$. This is because forward contracting makes the small firm to increase its deliveries to earlier periods (to $t=1$ in this two-period model) while the large firm to do the same to later periods (where the smaller firm is absent).[35]

Finally, it is interesting to point out that the introduction of firms' asymmetries in the resource model has a different effect than in the reproducible-good model of Allaz and Vila (1993). Asymmetries in the reproducible-good model come from considering firms of different marginal cost of production with the "large" firm being the one with lower costs.[36] As shown in Appendix, it is now the large firm the one that can greatly benefit from the forward market. In fact, when the cost difference is large enough the large firm can use the forward market to credibly implement its Stackelberg solution that is to fully displace the small firm from the market.[37]

5. Concluding remarks

We have found that forward contracting can have substantial implications for resource depletion in a non-cooperative oligopolistic environment. In fact, we showed for symmetric firms that the subgame-perfect equilibrium path approaches the perfectly competitive path as firms take an increasing number of periods to deplete their stocks. We also showed, however, that when firms have initial

[35] To see the latter consider any s_1^j such that under pure-spot trading firm j would serve both periods but that with forward trading would only serve period 1. Firm i's deliveries in period 1 under pure-spot-trading and with forward-trading are, respectively, $\tilde{q}_1^i = [a(1-\delta)+3\delta s_1^i]/3(1+\delta)$ and $q_1^i = [a(1-\delta)+2\delta s_1^i - s_1^j]/2(1+\delta)$. Then, $q_1^i < \tilde{q}_1^i$ (and $q_2^i > \tilde{q}_2^i$) iff $s_1^j > a(1-\delta)/3$, which precisely indicates the range where j serves both periods in pure-spot equilibrium.

[36] A lower marginal cost in the reproducible-good model implies a larger market share in the pure-spot (Cournot) game. Similarly, a larger stock in the resource model implies a lower opportunity cost of selling today instead of tomorrow.

[37] Fabra and de Frutos (2012) also find that firms' asymmetries affect the way forward contracting influence the degree of competition in the spot market.

stocks of different sizes, they can credibly contain part of the competitive pressure of forward contracting. It is then a unique feature of the resource model that equilibrium contracting and the degree of competition depends on resource endowments.

These results are most relevant for resource markets that not only exhibit an oligopolist structure and forward trading activity but most importantly that effectively follow the Hotelling rule for the pricing of exhaustible resources. Good examples are storable pollution permits (e.g., US SO_2 market) and hydro-based power pools (e.g., Nord Pool). Furthermore, these markets posses characteristics that for most part are consistent with the assumptions of our model, namely, constant (zero) extraction cost and public observability of the stocks and of forward positions. Pollution permits are kept in electronic accounts from which can be "extracted" at no cost (other than the opportunity cost of not selling the good tomorrow); the same applies for water stored in hydro-power reservoirs. It is also relatively easy to keep track of the evolution of the stocks in these markets, based on direct observation or simple calculations. In the case of pollution permits, the information needed to compute permit stocks – initial permit allocations, current permit holdings and past emissions – is all public since it is essential for enforcement and compliance purposes. It is perhaps less evident that forward positions are that easy to observe. If they are not, the strategic aspect of forward contracting is gone and with that all the results of the paper. But the response to this is that it is always in the firms' best interest to make their forward positions fully public.

It is nevertheless interesting to ask what would happen to our results if we indeed relax the zero-cost and observable-stock assumptions. There are already several papers looking at the issue of increasing costs but in the pure-spot-trading context (e.g., Lewis and Schmalensee, 1980; Salo and Tahvonen, 2001). Besides the additional technicalities of opening those models to forward contracting, the basic message of our paper would remain intact. In an effort to capture a larger share of the oligopoly rents (i.e., sell in the most profitable periods), firms will take forward positions in equilibrium.[38] Relaxing the second assumption is more challenging, not only technically but also conceptually. It may be that firms can now use forward contracts, provided they are observable, to credibly signal the size of their stocks. It may also happen in this signaling game that some firms go long and others short. Clearly, this is an area that deserves more research.

One may also ask about the implications of forward contracting on firms' incentives to engage in exploration activities that can enlarge their initial stocks. Since forward contracting introduces more competition it is evident that these incentives should be reduced. Even in those "stock-asymmetric" cases in which forward contracting may suppress competition, by allowing the small firm to commit to sell first, it is still the case that forward contracting reduces the incentives for exploration. The smaller find would not like to extend its initial stock if this induces the larger firm to also sell forwards in equilibrium.

Finally, it is yet to be discussed whether and to what extend forward contracting could also affect the possibility of collusion in this market. Recall that for a reproducible-commodity market, Liski and Montero (2006) have already shown that forward trading increases the scope of collusion – independently of the form of competition – by allowing firms to either construct harsher punishments or limit the deviation profits. Whenever non-stationary and collusive strategies are feasible in a pure spot-trading equilibrium in the resource context, then forward contracting should make it easier to sustain them. In the resource model, collusive strategies can exist when the overall consumption horizon is infinite, for example, due to (high) stock-dependent extraction costs or an infinite choke price – the price at which demand falls to zero. But when the choke price is finite and there is a gap between this price and the cost of extracting the last unit, as in our model, the consumption horizon is finite (both under perfect competition and monopoly), stipulating additional modeling assumptions facilitating the construction of collusive strategies.[39]

[38] An easy way for exploring such an extension is to build on Harstad and Liski (2013) who show that when there is economic exhaustion due to stock-dependent extraction costs, firms see their current resource savings as strategic investments. The contract market is an additional channel for strategic investments, and is likely to have similar pro-competitive effects as in the current paper, although the equilibrium contracting pattern can differ.

[39] One may borrow an insight from the durable-good monopoly literature and ask whether firms could sustain a collusive path that only asymptotically approaches the choke price, very much in the spirit of Gul (1987). Such a collusive path is however

Appendix A.

A.1. Proof of Proposition 1

We first prove (i) and (iv). Let us work backwards from the spot market at $t=1$. Given $s_1^i, f_{1,1}^i$ and $f_{1,2}^i$ (for both i and j), if firms anticipate that in equilibrium $s_2^i, s_2^j > 0$ and that these stocks will be exhausted in period 2, then, at the period-1 spot market, they will choose quantities that equalize marginal revenues, that is,

$$a - 2q_1^i - q_1^j + f_{1,1}^i = \delta(a - 2q_2^i - q_2^j + f_{1,2}^i), \text{ or}$$
$$a - 2q_1^i - q_1^j + (f_{1,1}^i - \delta f_{1,2}^i) = \delta(a - 2q_2^i - q_2^j)$$

where $q_2^i = q_2^i(s_2^i, s_2^j) = s_2^i$ for both i and j. Therefore, the payoff-relevant variables in the forward subgame are not the individual positions $f_{1,1}^i$ and $f_{1,2}^i$ but the composite position $H_1^i = f_{1,1}^i - \delta f_{1,2}^i$. Note that because firms correctly anticipate exhaustion in period 2, forward positions $f_{2,2}^i$ play no role as to how firms deplete the stock in equilibrium. By the same backward induction arguments laid out before (see Eqs. (16) and (17)), we obtain that in equilibrium firms will choose $f_{1,1}^i$ and $f_{1,2}^i$ so as to satisfy $H_1^i = a(1-\delta)/5$. On the other hand, given composite positions H_1^i and H_1^j, the period-1 equilibrium output is given by the second term in (15) with $f_{1,1}^i$ replaced by H_1^i; and plugging equilibrium positions $H_1^i = H_1^j = a(1-\delta)/5$ gives (18). It is relatively open for firms how much to trade in the forward markets, as long as their composite position H_1^i satisfies $f_{1,1}^i - \delta f_{1,2}^i = a(1-\delta)/5$. For example, firms could fully contract their period-2 deliveries (i.e., $f_{1,2}^i = q_2^i$) and simultaneously take short positions for period 1 equal to $f_{1,1}^i = a(1-\delta)/5 + \delta q_2^i$.

Parts (ii) and (iii) of Proposition 1, however, put limits as to how much firms contract in equilibrium. To derive these limits, let us now work backwards from the spot market at $t=2$. Given equilibrium positions H_1^i and H_1^j, remaining stocks are

$$s_2^i = \frac{1}{1+\delta}\left[s_1^i - \frac{2a}{5}(1-\delta)\right] \tag{24}$$

for both i and j. Thus, if firm i's aggregate position for period 2 is $F_2^i = f_{1,2}^i + f_{2,2}^i$, the period-2 equilibrium output is given by expression (19), after replacing $f_{2,2}^i$ by F_2^i. Hence, the exhaustion of symmetric stocks at $t=2$ requires $F_2^i + F_2^j \geq 6s_2^i - 2a$. Replacing s_2^i by its equilibrium value in (24) and maintaining symmetry (i.e., $F_2^i = F_2^j$), we obtain part (iii) of the proposition. We now move onto the forward stage at $t=2$. Given stocks $s_2^i = s_2^j$ and forward positions $f_{1,2}^i = f_{1,2}^j$, the equilibrium positions $f_{2,2}^i(f_{1,2}^i, f_{1,2}^j)$ will depend on firms' rational expectations as to whether exhaustion will occur at $t=2$ or not. If past positions, i.e., $f_{1,2}^i$ and $f_{1,2}^j$, are such that exhaustion is not expected to occur, we can proceed as in Lemma 6 to show that period-2 equilibrium positions, in such reproducible-good setting, are given by

$$f_{2,2}^i(f_{1,2}^i, f_{1,2}^j) = \frac{a}{5} - \frac{1}{5}f_{1,2}^i - \frac{1}{5}f_{1,2}^j$$

and, thereby, that equilibrium aggregate positions are given by $F_2^i(f_{1,2}^i, f_{1,2}^j) = f_{1,2}^i + f_{2,2}^i(f_{1,2}^i, f_{1,2}^j)$ for both i and j. If, on the other hand, exhaustion is expected to occur, then, aggregate equilibrium positions are given by $F_2^i(f_{1,2}^i, f_{1,2}^j) + F_2^j(f_{1,2}^i, f_{1,2}^j) \geq 6s_2^i - 2a$. Based on these aggregate equilibrium responses for

harder to sustain here: in Gul (1987) the punishment path entails zero profits for firms (so it is always possible to fashion an asymptotic collusive path where the present value from colluding is greater than the one-shot deviation profit), whereas here the sellers receive a positive resource rent that may provide more surplus than the collusive plan, at least in the final part of the collusive plan.

varying values of $f^i_{1,2}$ and $f^j_{1,2}$, we can obtain the period-2 equilibrium output as a function of period-1 forward positions as follows

$$q^i_2(f^i_{1,2}, f^j_{1,2}) = \min\left\{s^i_2, \frac{2a}{5} + \frac{3}{5}f^i_{1,2} - \frac{2}{5}f^j_{1,2}\right\} \geq 0$$

Therefore, if at the opening of the forward market in period 1 firms anticipate that they will be exhausting at 2, then, their forward equilibrium positions must be such that $2a + 3f^i_{1,2} - 2f^j_{1,2} \geq 5s^i_2$. Again, replacing s^i_2 by its equilibrium value in (24) and maintaining symmetry (i.e., $f^i_{1,2} = f^j_{1,2}$), we obtain part (ii) of the proposition. The intuition behind part (ii) is that firms will not take a position in period 1 that will not be able to credibly (i.e., sequentially rationally) undo in period 2.

The proof of part (v) – that firms will exhaust in period 2 if $s^i_1 \in (s^{CH}_1, s^{HR}_1]$ – is directly obtained from the application of Lemmas 1 and 6. In regard to Lemma 6, note that if $s^i_1 = s^j_1 = s^{HR}_1$, Proposition 1 predicts the following equilibrium outcome: (i) $f^i_{1,1} - \delta f^i_{1,2} = a(1-\delta)/5$, (ii) $f^i_{1,2} \geq a/7(1+\delta)$, (iii) $F^i_2 \geq 2a/7(1+\delta) + a\delta/5(1+\delta)$, (iv) $q^i_1 = 2a(1-\delta)/5(1+\delta) + 29a\delta/35(1+\delta)$ and (v) $q^i_2 = s^{HR}_1 - q^i_1$. There seems to be a discrepancy between the predictions of Proposition 1 and of Lemma 6 at the border s^{HR}_1. There is none, however, because right at the border, discounting plays no role in the intertemporal allocation of output in equilibrium (i.e., $MR^i_1 = MR^i_2 = 0$); hence, we have a corner solution that for purposes of computing the equilibrium outcome calls for $\delta = 0$.

A.2. A more general formulation

We present here the more general model we solve in our working paper. There are $t = 1, \ldots, N < \infty$ periods; each with a forward market opening followed by a spot market opening. At the forward stage in t, firms simultaneously decide the (additional) forward positions they will take for each and every future spot market, i.e., $\mathbf{f}^i_t = (f^i_{t,t}, f^i_{t,t+1}, \ldots, f^i_{t,N})$ for both i and j. Likewise, at the spot market in t firms simultaneously decide their (non-negative) deliveries q^i_t and q^j_t.

The history of the game after $t-1$ periods (i.e., at the beginning of period t) is denoted by h_t and composed by the initial stocks, s^i_1 and s^j_1, and the sequence of forward positions and deliveries, $(\mathbf{f}^i_1, \mathbf{f}^i_1, \ldots, \mathbf{f}^i_{t-1}, \mathbf{f}^i_{t-1})$ and $(q^i_1, q^i_1, \ldots, q^i_{t-1}, q^i_{t-1})$, respectively. Given these sequences, remaining stocks at the end of $t-1$ are equal to $s^i_t = s^i_1 - \sum_{k=1}^{t-1} q^i_k$ for both i and j, and aggregate forward holdings for future spot markets are equal to $\mathbf{F}^i_{t-1} = (F^i_t(t-1), F^i_{t+1}(t-1), \ldots, F^i_N(t-1))$ for both i and j, where $F^i_h(t) = \sum_{k=1}^{t} f^i_{k,h}$ is the aggregate position that firm i holds at t for the spot market that opens at $h \geq t$. Thus, for example, $F^i_t(t) = F^i_t(t-1) + f^i_{t,t}$.

A forward-sale strategy for firm i is a collection of functions

$$\mathbf{f}^i = (\mathbf{f}^i_1(\cdot), \ldots, \mathbf{f}^i_N(\cdot))$$

where function $\mathbf{f}^i_t(h_t)$ specifies firm i's (additional) forward positions as a function of the history h_t. A forward-strategy profile is denoted by $\mathbf{f} = (\mathbf{f}^i, \mathbf{f}^j)$.

A spot-sale strategy for firm i, on the other hand, is a collection of functions

$$\mathbf{q}^i = (q^i_1(\cdot), \ldots, q^i_N(\cdot))$$

where function $q^i_t = q^i_t(h'_t)$ specifies firm i's output as a function of the history at the opening of the spot market in t, $h'_t = (h_t, \mathbf{f}^i_t, \mathbf{f}^j_t)$. A spot-sale strategy profile is denoted by $\mathbf{q} = (\mathbf{q}^i, \mathbf{q}^j)$. Thus, a strategy profile $(\mathbf{f}, \mathbf{q})$ together with the initial history $h_1 = (s^i_1, s^j_1, \mathbf{f}^i_0 = \mathbf{f}^j_0 = \mathbf{0})$ generate an outcome path that characterizes the development of the stocks, $s^i_{t+1} = s^i_t - q^i_t$, and of the contract coverages, $\mathbf{F}^i_t = \mathbf{F}^i_{t-1} + \mathbf{f}^i_t$, for both i and j.

Given some strategy profile $(\mathbf{f}, \mathbf{q})$ and history h'_t, firm i's payoff at the spot stage in t is

$$W_t^i(h'_t, \mathrm{f}, \mathrm{q}) = p_t^s(\cdot)q_t^i + \sum_{k=1}^{t} p_{k,t}^f f_{k,t}^i - p_t^s(\cdot)F_t^i(t) + \delta V_{t+1}^i(h_{t+1}, \mathrm{f}, \mathrm{q})$$

where $V_{t+1}^i(h_{t+1}, \mathrm{f}, \mathrm{q})$ is the continuation payoff at the forward stage in $t+1$ and $h_{t+1} = (h'_t, q_t^i, q_t^j)$. At the spot stage, firms not only attend the spot market but also close their forward positions at the spot price p_t^s. But as explained in the two-period model, forward contracts for period t are traded at the expected spot price at t; hence, in equilibrium $p_{k,t}^f = p_t^s$ for all k (agents correctly anticipate the effect of forward positions on future spot prices, or more precisely, on firms' deliveries). In addition, since forward markets are only used to write contracts (i.e., to take positions), firm i's payoff at the forward stage in t is simply

$$V_t^i(h_t, \mathbf{f}, \mathbf{q}) = W_t^i(h'_t, \mathbf{f}, \mathbf{q}).$$

The strategy profile (f, q) constitutes a subgame-perfect equilibrium (SPE) if for any t and history h_t

$$\mathrm{f}_t^i(h_t) = \underset{\mathbf{f}_t^i}{argmax} V_t^i(h_t, (\mathbf{f}^i, \mathrm{f}^j), \mathrm{q}) \tag{25}$$

and for any t and history h'_t

$$\hat{q}_t^i(h'_t) = \underset{q_t^i}{argmax} W_t^i(h'_t, \mathrm{f}, (\mathbf{q}^i, \mathrm{q}^j)) \tag{26}$$

where $\mathbf{f}^i = (\ldots, \mathbf{f}_t^i, \mathrm{f}_{t+1}^i(\cdot), \ldots, \mathrm{f}_N^i(\cdot))$ and $\mathbf{q}^i = (\ldots, q_t^i, \hat{q}_{t+1}^i(\cdot), \ldots, \hat{q}_N^i(\cdot))$.[40] Using backward induction we can construct the SPE strategies, which was already done in Section 2 for the case $N=2$. There, we also showed that the pay-off relevant history at the beginning of period $t=1, 2$ was just the current state that consisted of remaining stocks, s_t^i and s_t^j, and existing aggregate positions, $\mathbf{F}_{t-1}^i$ and $\mathbf{F}_{t-1}^j$, so we could safely write $h_t = (s_t^i, s_t^j, \mathbf{F}_{t-1}^i, \mathbf{F}_{t-1}^j)$. We can then extend the analysis to show that the same holds for any $N>2$.[41] However, in the working paper we restrict attention to the symmetric case, which we can solve explicitly.

A.3. Proof of Proposition 3

We derive $f_{\min}(s_1^j)$ as follows. First, we find the Stackelberg (i.e., first-best) payoff and deliveries for i (the larger firm), given that j is holding some contracts $f_{1,1}^j$. This defines the most i can achieve in the original game. Second, we find the contracting level $f_{1,1}^j$ that induces j, "the follower", to produce only in the first period. This will define $f_{\min}(s_1^j)$. Given this level of contracting by j, i can implement its first-best in the original game by taking no position and letting j to sell only to period 1. Third, we will derive the Stackelberg threshold s_1^{ST}, under which this characterization holds.

Consider the first-best choice of q_1^i. Given q_1^i and $f_{1,1}^j$, j's best-response satisfies (recall that $s_1^i < s_1^{HR}$, which guarantees exhaustion in period 2)

$$a - 2q_1^j - q_1^i + f_{1,1}^j = \delta(a - (s_1^i - q_1^i) - (s_1^j - q_1^j)) - \delta(s_1^j - q_1^j),$$

[40] Note our abuse of notation: the argmax operator in (25) returns a vector of positions not a single argument.

[41] The two-period game serves in turn to define the continuation payoff for a game with three periods. Proceeding in this manner for any $N>2$ we can establish the structure of the equilibrium strategies, as done in Appendix for the symmetric equilibrium. Note the similarity of this procedure to that in Kahn (1986).

which leads to

$$q_1^j(q_1^i, f_{1,1}^j) = (a(1-\delta) + 2\delta s_1^j + f_{1,1}^j - (1+\delta)q_1^i + \delta s_1^i)\frac{1}{2(1+\delta)}.$$

On the other hand and given $f_{1,1}^j$, firm i's first-best payoff is

$$\max_{q_1^i}\{p_1^s(q_1^i, q_1^j(q_1^i, f_{1,1}^j))q_1^i + \delta p_2^s(s_1^i - q_1^i, s_1^j - q_1^j(q_1^i, f_{1,1}^j))(s_1^i - q_1^i)\}.$$

Solving

$$q_1^i(f_{1,1}^j) = (a(1-\delta) + 2\delta s_1^i - f_{1,1}^j)\frac{1}{2(1+\delta)},$$

and evaluating the follower's best-response gives

$$q_1^j(q_1^i(f_{1,1}^j), f_{1,1}^j) = (a(1-\delta) + 4\delta s_1^j + 3f_{1,1}^j)\frac{1}{4(1+\delta)}.$$

Contracting $f_{\min}(s_1^j)$ is defined by

$$q_1^j(q_1^i(f_{\min}), f_{\min}) = s_1^j.$$

Finally, the Stackelberg threshold s_1^{ST} is found as follows. If the second term in (15) results in $q_1^j < s_1^j$ given (symmetric) contracting $f_{1,1}^i = f_{1,1}^j = a(1-\delta)/5$, then, both firms could be active in equilibrium in period 2. This defines a lower threshold, i.e., $s_1^j > 2a(1-\delta)/5$, for the symmetric contracting equilibrium to be valid. The proof follows that of Lemma 5. A second equilibrium is also possible when $s_1^j > 2a(1-\delta)/5$. First, note that since (23) holds, j's best-response to $f_{1,1}^i = 0$ is $f_{\min}(s_1^j)$. On the other hand, firm i's best-response to $f_{\min}(s_1^j)$ is indeed $f_{1,1}^i = 0$ provided s_1^j is not too large (we omit the exact number here). Firm i strictly "prefers" this latter equilibrium if it leads to a payoff larger than that under the symmetric contracting equilibrium. Comparing i's payoffs, we find this to be case if (to save space we do not report the payoff expressions)

$$s_1^j \le \frac{5-2\sqrt{2}}{5}a(1-\delta) \equiv s_1^{ST} = 0.434a(1-\delta).$$

A.4. Allaz and Vila for asymmetric firms

Consider two firms (i and j) producing a reproducible commodity with marginal costs, respectively, c_i and c_j with $c_i < c_j$. Firm i is the "large firm" in the sense that it has a larger market share in the pure-spot (Cournot) game. Firms attend the spot market by simultaneously choosing quantities q^i and q^j. The spot price p^s is given by the linear inverse demand function $p^s(q^i + q^j) = a - (q^i + q^j)$, with

$$c_j - c_i \equiv \Delta < a - c_j$$

so that both firms produce in pure-spot equilibrium. Before the opening of the spot market firms are also free to simultaneously take forward positions for the spot market that follows. Forward transactions are denoted by f^i and f^j and the forward price by p^f.

At the opening of the spot market, and given f^i and f^j, firm i solves

$$\max_{q^i} W^i = p^s(\cdot)q^i - c_i q^i + (p^f - p^s(\cdot))f^i$$

Using both first-order conditions, we find that the subgame-perfect spot quantities are given by

$$q^i(f^i, f^j) = \frac{a - 2c_i + c_j + 2f^i - f^j}{3} \tag{27}$$

$$q^j(f^i, f^j) = \frac{a - 2c_j + c_i + 2f^j - f^i}{3} \tag{28}$$

Anticipating the equilibrium outcome (27)–(28), at the forward stage firm i solves (arbitrage profits vanish, i.e., $p^f = p^s$)

$$\max_{f^i} V^i(q^i(f^i, f^j), q^j(f^i, f^j)) = p^s q^i(f^i, f^j) - c_i q^i(f^i, f^j)$$

with $p^f = p^s = p^s(q^i(f^i, f^j) + q^j(f^i, f^j))$. Applying the envelope theorem leads to

$$\frac{\partial p^f}{\partial q^i}\frac{\partial q^i}{\partial f^i}f^i + \frac{\partial p^f}{\partial q^j}\frac{\partial q^j}{\partial f^i}f^i + p^f + \frac{\partial p^s}{\partial q^j}\frac{\partial q^j}{\partial f^i}(q^i - f^i) - p^s = 0$$

which reduces to

$$-\frac{2}{3}f^i + \frac{1}{3}q^i(f^i, f^j) = 0.$$

Replacing $q^i(f^i, f^j)$, we obtain the (equilibrium) forward positions

$$\hat{f}^i = \frac{a - 3c_i + 2c_j}{5}$$

$$\hat{f}^j = \frac{a - 3c_j + 2c_i}{5}.$$

For $\hat{f}^i$ and $\hat{f}^j$ to be equilibrium positions we require $q^i(\hat{f}^i, \hat{f}^j) > 0$ and $q^j(\hat{f}^i, \hat{f}^j) > 0$. Since the restriction for j is more demanding, we actually require

$$q^j(\hat{f}^i, \hat{f}^j) = \frac{2}{5}[a - 3c_j + 2c_i] > 0$$

or

$$\Delta < \frac{a - c_j}{2} \tag{29}$$

Note that $\hat{f}^j < 0$ is the same as $q^j(\hat{f}^i, \hat{f}^j) < 0$, so we cannot have an equilibrium where j goes long in an effort to increase prices.

Let us now look at firm i's Stackelberg outcome in the absence of forward trading. It is easy to show that it is Stackelberg optimal for i to leave j outside the market if $\Delta > (a - c_j)/2$. In such a case, i will produce $q^i = a - c_j$ leading to an equilibrium price equal to c_j. Therefore, when firms are sufficiently different, i.e., condition (29) does not hold, the opening of the forward market allows the large firm to implement its Stackelberg solution with a price a bit below c_j and leaving firm j outside the market. More precisely, whenever $a - c_j \geq \Delta \geq (a - c_j)/2$, firm i implements its Stackelberg outcome by selling $f^i = f_{\min}$ to just keep j away from the spot market (if $\Delta = (a - c_j)/2$ then $f_{\min} = \hat{f}^i$ and if $\Delta = a - c_j$ then $f_{\min} = 0$) with final quantities equal to

$$q^i(f^i = f_{\min}, f^j = 0) = a - c_j$$

$$q^j(f^i = f_{\min}, f^j = 0) = 0$$

Unlike in the exhaustible-resource case, here it is the large firm the one that strictly benefits from the opening of the forward market.

References

Allaz, B., Vila, J.-L., 1993. Cournot competition, forward markets and efficiency. Journal of Economic Theory 59, 1–16.

Anton, J., Biglaiser, G., Vettas, N., 2012. Dynamic price competition with capacity constraints and strategic buyers, working paper.

Brown, J.R., 1963. Nitrate crises, combinations, and the Chilean government in the nitrate age. The Hispanic American Historical Review 43, 230–246.

Bushnell, J., Mansur, E., Saravia, C., 2008. Vertical arrangements market structure and competition: an analysis of restructured U.S. electricity markets. American Economic Review 98, 237–266.
Dudey, M., 1992. Dynamic Edgeworth–Bertrand competition. Quarterly Journal of Economics 107, 1461–1477.
Ellerman, A.D., Joskow, P., Schmalensee, R., Montero, J.-P., Bailey, E.M., 2000. Markets for Clean Air: The US Acid Rain Program. Cambridge University Press, Cambridge, UK.
Ellerman, A.D., Montero, J.-P., 2007. The efficiency and robustness of allowance banking in the U.S. Acid Rain Program. Energy Journal 28, 47–71.
Fabra, N., Toro, J., 2005. Price wars and collusion in the Spanish electricity market. International Journal of Industrial Organization 23, 155–181.
Fabra, N., de Frutos, M.-A., 2012. How to award pro-competitive forward contracts: the case of electricity auctions. European Economic Review 56, 451–469.
Gaudet, G., Moreaux, M., Salant, S.W., 2002. Private storage of common property. Journal of Environmental Economics and Management 43, 280–302.
Gaudet, G., 2007. Natural resource economics under the rule of Hotelling. Canadian Journal of Economics 40, 1034–1059.
Green, R., 1999. The electricity contract market in England and Wales. Journal of Industrial Economics 47, 107–124.
Gul, F., 1987. Noncooperative collusion in durable goods oligopoly. RAND Journal of Economics 18, 248–254.
Harstad, B., Liski, M., 2013. Games and Resources. In: Shogren, J.F. (Ed.), Encyclopedia of Energy, Natural Resource, and Environmental Economics, vol. 2. Elsevier, Amsterdam, pp. 299–308.
Hotelling, H., 1931. The economics of exhaustible resources. Journal of Political Economy 39, 137–175.
Kahn, C.M., 1986. The durable goods monopolist and consistency with increasing costs. Econometrica 54, 275–294.
Kauppi, O., Liski, M., 2008. An empirical model of imperfect dynamic competition and application to hydroelectricity storage, MIT-CEEPR WP-2008-11.
Krautkraemer, J., 1998. Nonrenewable resource scarcity. Journal of Economic Literature 36, 2065–2107.
Lewis, T., Schmalensee, R., 1980. On oligopolistic markets for nonrenewable resources. Quarterly Journal of Economics 95, 475–491.
Liski, M., Montero, J.-P., 2011. Market power in an exhaustible-resource market: the case of storable pollution permits. The Economic Journal 121, 116–144.
Liski, M., Montero, J.-P., 2006. Forward trading and collusion in oligopoly. Journal of Economic Theory 131, 212–230.
Loury, G., 1986. A theory of 'oil'igopoly: Courtnot-Nash equilibrium in exhaustible resources markets with fixed supplies. International Economic Review 27, 285–301.
Mahenc, P., Salanié, F., 2004. Softening competition through forward trading. Journal of Economic Theory 116 (2), 282–293.
Phlips, L., Harstad, R.M., 1990. Interaction between resource extraction and futures markets: a game-theoretic analysis. In: Selten, R. (Ed.), Game Theory in the Behavioral Sciences. Springer Verlag, Heidelberg.
Polasky, S., 1992. Do oil producers act as 'oil'igopolists? Journal of Environmental Economics and Management 23, 216–247.
Salant, S.W., 1976. Exhaustible resources and industrial structure: a Nash–Cournot approach to the world oil market. Journal of Political Economy 84, 1079–1093.
Saloner, G., 1987. Cournot duopoly with two production periods. Journal of Economic Theory 42, 183–187.
Salo, S., Tahvonen, O., 2001. Oligopoly equilibria in nonrenewable resource markets. Journal of Economic Dynamics and Control 25 (5), 671–702.
Segal, I., 1999. Contracting with externalities. Quartely Journal of Economics 114, 337–388.
Sweeting, A., 2007. Market power in the England and Wales wholesale electricity market. The Economic Journal 117, 654–685.
Ulph, A., Ulph, D., 1989. Gains and losses from cartelisation in markets for exhaustible resources in the absence of binding future contracts. In: van der Ploeg, F., de Zeeuw, A. (Eds.), Dynamic Policy Games in Economics: Essays in Honor of Piet Verheyen. North-Holland Publishing, Amsterdam.
Wolak, F., 2007. Quantifiying the supply-side benefits from forward contracting in wholesale electricity markets. Journal of Applied Econometrics 22, 1179–1209.
Wolak, F., 2009. An assessment of the performance of the New Zealand wholesale electricity market report prepared for the Commerce Commission of New Zealand.