Measuring the Incentive to Collude: The Vitamin Cartels, 1990–1999*

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Abstract

Why do some cartels survive for a decade but others collapse within a few years? Models of collusion and repeated games are usually difficult to identify from observational data, but the vitamin cartels, one of the most prominent cases in recent history, provide direct evidence on their internal organization in the form of American court documents and European antitrust enforcement. Our estimates suggest the cartel leader's incentive to collude diminished significantly at the time of the vitamin C cartel's actual collapse in 1995, mainly because of deteriorating demand conditions and unexpected increases of fringe supply, whereas the markets for beta carotene, vitamin A, and vitamin E remained stable until prosecution in 1999. We also find that an earlier consummation of the 2001 BASF-Takeda merger would have saved the vitamin C cartel.

Keywords: Antitrust, Cartel, Collusion, Coordinated effect, Merger, Repeated game.

JEL classifications: D43, L13, L41.

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1 Introduction

Vitamins are essential for health, but their markets lacked healthy competition. Vitamin prices nearly doubled during the 1990s because 21 producers across the globe had successfully cartelized the markets for 16 vitamins, including vitamins A, C, and E, as well as beta carotene (Figure 1). The U.S. Department of Justice (DOJ) and the Federal Bureau of Investigation (FBI) eventually discovered the conspiracies and prosecuted them in 1999. With fines and monetary damages totaling over 6.2 billion dollars and European corporate executives serving jail sentences in America, the international vitamin cartels are among the largest antitrust cases in history (see Appendix Table 2). Curiously, six of the 16 plots collapsed spontaneously in the mid 1990s, several years before the investigations started, whereas the other 10 continued until the member firms pled guilty.

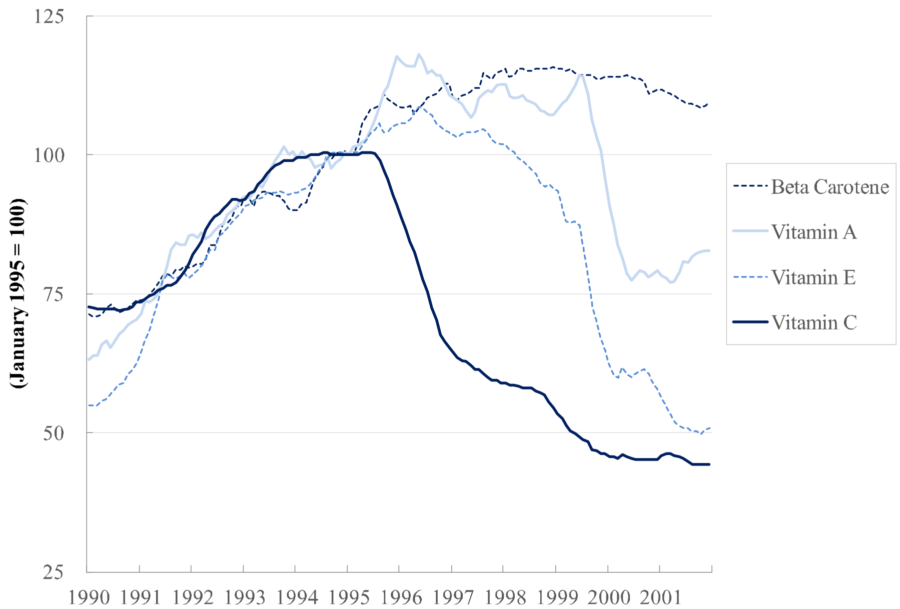
Why did some cartels survive for a decade while others collapsed within a few years? Effective antitrust policy requires clear understanding of the economic incentives surrounding cartels, which in turn requires rigorous measurement. In this paper, we explain the diverging fates of four vitamin cartels by quantifying the firms' incentives to collude and assessing the roles of market conditions, including demand, fringe supply, and market structure (i.e., the "coordinated effects" of a merger).[1]

The incentive to cooperate is a central theme in microeconomic theory, and cartels are one of the core issues in industrial organization. Despite the existence of excellent literature, however, few studies offer quantitative analysis of the incentives of cartel participants. One reason is theoretical. The repeated games literature has shown that almost any market outcome can be supported as an equilibrium, and hence a researcher would need to know and use institutional details to obtain useful theoretical predictions for a particular empirical context. However, cartels (i.e., collusion with explicit communications) are *per se* illegal, which means mere acts of cooperative communication among competitors constitute a crime. Thus theory needs data but records hardly exist due to the covert nature of the activity.

We overcome this problem by studying the vitamin cartels from 1990 to 1999. A wealth of data and direct evidence on the internal operations of cartels became publicly available thanks to the criminal investigations in America and Europe as well as subsequent civil litigations. Vitamins are also an ideal subject for economic analysis because of their simple physical properties as commodity chemical products and stable fundamentals on both the demand and supply sides. Moreover, more than a dozen categories of vitamins (e.g., vitamin

[1] In antitrust policy, a coordinated effect refers to the facilitation of collusion caused by a reduction in the number of competitors.

Figure 1: Cartels and Vitamin Prices



Note: Roche's monthly average U.S. transaction prices ($/kg) are rescaled with January 1995 as the base period for comparison across the four vitamin categories. The vitamin C cartel collapsed spontaneously after August 1995, whereas the other three cartels continued operations until 1999, when the U.S. government prosecuted them. See section 3 for details.
Source: Roche ROVIS data from Roche Data Books *cit. in* "Expert Report of B. Douglas Bernheim," *In Re: Vitamins Antitrust Litigation*, MDL No. 1285, Misc 99-0197. We reverse-engineered the price data by digitizing Figures 9-1 through 9-4 of this expert report.

C and beta carotene) share basic industry characteristics including the rules of cartels but feature different market structures from each other, thereby constituting a natural laboratory for comparative case studies. Thus vitamins represent an ideal empirical context to study the incentives to collude using standard theories and methods.

We develop a repeated game model of endogenous cartel breakdown, estimate the cartel members' incentive to collude, and assess the effects of demand, supply, and a hypothetical merger on the cartel's breakdown. Our empirical analysis focuses on four categories of vitamins for which the records are most complete (i.e., vitamin A, vitamin C, vitamin E, and beta carotene), and proceeds in three steps. First, we estimate demand and costs in each period by using the firms' first-order conditions along with data on prices, outputs, and cartel activities. Second, we calculate hypothetical market outcomes (i.e., prices, outputs, and profits) in each period under static Nash equilibrium, the cartels' quota schemes, and unilateral deviations from it. Third, we calculate the discounted present values of collusion and defection to evaluate the incentive compatibility condition, which can then be used to assess whether the cartel could have survived under different circumstances (i.e., more favorable demand conditions, less aggressive expansion of fringe supply, and an earlier consummation of the BASF-Takeda merger).

We find the cartel leader's incentive to collude diminished significantly at the time of the vitamin C cartel's actual collapse in 1995, whereas those for beta carotene, vitamin A, and vitamin E remained stable and positive until the prosecution in 1999. Our comparative statics (or more precisely, comparative dynamics) analysis suggests the main cause of the breakup of the vitamin C cartel was a confluence of demand and supply factors. Specifically, the growth of demand for vitamin C temporarily slowed down in the mid 1990s, and buyers became gradually more price-sensitive. Moreover, output from fringe competitors increased unexpectedly. Chinese exports of bulk vitamins were negligible across all categories until the 1990s, but the discovery and widespread use of a new production method for vitamin C suddenly made Chinese state-owned enterprises uniquely cost-competitive. Taken individually, each of these developments would not have killed the vitamin C cartel, but their interaction proved to be a powerful force that led to its collapse.

Finally, our counterfactual merger simulations shows that an earlier consummation of the 2001 BASF-Takeda merger,[2] which reduced the number of large players from four to three, would have saved the vitamin C cartel. Thus the coordinated effect of a four-to-three merger in a homogeneous-good market would appear economically significant and warrants attention from the antitrust authorities in their merger enforcement.

The paper is organized as follows. The remainder of section 1 explains the literature background. Sections 2, 3, and 4 describe our model, the industry background, and the data. Section 5 explains our empirical analysis of the vitamin C market and measures the incentive to collude. Section 6 shows our comparative dynamics analysis to quantify the effects of demand, supply, and a hypothetical merger on the cartel's breakdown. Section 7 concludes. The Appendix contains our analysis of the three other markets (beta carotene, vitamin A, and vitamin E), as well as other background information and robustness checks.

[2] See section 6.2 and the U.K. Competition Commission's (2001) report for details.

1.1 Literature

Collusion is a central topic to apply theoretical analyses of repeated games to. Classic papers by Abreu (1986) and Abreu, Pearce, and Stacchetti (1986) characterize the best symmetric equilibrium in oligopolistic (Cournot or differentiated-Bertrand) repeated games with public monitoring.[3] Although Abreu, Pearce, and Stacchetti (1990) characterizes all (not only symmetric) perfect public equilibrium payoffs in a general stage game, since the characterization is provided as a fixed point of a mapping which is not a contraction, it is hard to analytically describe the best equilibrium in oligopoly.[4] In this paper, we have an access to the documents of cartel agreements, which allows us to identify the strategies played by firms.

It is common to use investigated cartel agreements to identify strategies in the analysis of repeated games with private monitoring.[5] Since the characterization of equilibria is hard to obtain,[6] papers by Harrington and Skrzypacz (2007 and 2011) look at the recent investigation of a lysine cartel and construct a theoretical model to explain the strategy actually played by firms there. In this paper, we look at EC's investigation of vitamin cartels, and figure out that the firms set prices very similar to each other, even when a firm deviates from the agreed quantity to sell. Hence we conclude that monitoring is public. In addition, we proceed further to identify parameters of interest by taking advantage of the richness of the data provided.

The current paper also sheds light on the folk theorem of the repeated game, which shows that any feasible and individually rational payoff is supportable in equilibrium if players are sufficiently patient.[7] The folk theorem implies that a lot of outcomes are consistent with the equilibrium, and we typically lack identification of parameters of interest if we allow all the equilibria. We benefit from the availability of the document which describes how the vitamin cartels operate. Based on the record of the cartel meetings, we *a priori* know what strategy they play. This finding is interesting, for it allows us to predict equilibrium outcomes, despite the richness of the set of all the perfect public equilibria.

Pioneering empirical works include Porter (1983) and Ellison (1994), both of which stud-

[3] Monitoring is public when each player observes a common signal. For example, in cartels of producing a commodity good (such as OPEC), the commodity good price (such as crude oil price) is a common signal.

[4] Notable exceptions are, among others, Levin (2003), Fuchs (2007), and Athey and Bagwell (2008).

[5] Monitoring is private when each player observes a private signal not observed by other players. For example, in cartels of selling differentiated products to large industrial buyers, since the price and quantity are set in a confidential meeting between a seller and a buyer, each firm cannot observe the other firms' price or quantity.

[6] See Kandori (2002) and Mailath and Samuelson (2006).

[7] See Fudenberg and Maskin (1986), Fudenberg, Levine, and Maskin (1994), and many others.

ied the Joint Executive Committee, an American railroad cartel from 1880 to 1886, which predated the Sherman Act and therefore its existence was public. Their research questions centered on whether and when price wars occurred, building on Green and Porter's (1984) model and testing theories of cartel stability with price wars as part of equilibrium behaviors. The models of Rotemberg and Saloner (1986) and Bagwell and Staiger (1997) also featured price wars on equilibrium path. These papers' focus on regime switching between collusive and competitive periods reflects a broader agenda in the literature at the time (i.e., to empirically test and demonstrate the relevance of game-theoretic models). We aim to advance this traditional agenda with a contemporary case of major policy interest and with solid evidence from criminal investigations and civil litigations, showing that a standard repeated-game model could explain the survival and breakdown of cartels as well as quantify the impact of competitive fringe and the coordinated effects of hypothetical mergers.

More recent efforts to explicitly model and estimate a dynamic game with collusion include Fershtman and Pakes (2000) and a series of papers by de Roos (2001, 2004, 2006). The former extends Ericson and Pakes's (1995) empirical framework to incorporate the possibility of a cartel, which the latter subsequently applied to the markets of lysine and Vitamin C. These earlier papers use empirical examples as either motivations for applied models or materials for calibration (or estimation with relatively limited data contents) primarily due to lack of data, whereas this paper benefits from the wealth of data that became publicly available after these papers were written. These data permit us to tighten the connection between theoretical and empirical components of our analysis, to the extent that we can actually measure the incentives to collude under less restrictive assumptions than in these previous works.

Another strand of empirical literature has collected and established various stylized facts about cartels. For example, Harrington (2006) summarized the operational procedures and market outcomes of approximately 20 cartel cases on which the European Commission ruled from 2000 to 2004, including the vitamin cartels. Levenstein and Suslow (2006, 2011, 2014) provide an overview on this literature and a meta analysis on the price impact and duration of cartels. Finally, Marshall and Marx (2014) also compile basic facts and crystallize the insights from empirical cartel studies in the form of a textbook. These works have directly benefited this paper by informing our choice of the vitamin cartels as one of the most important, prominent, and representative cases in recent history of cartel enforcement.

Finally, a related but somewhat distinct literature is that of bidding rings, which are most usefully analyzed in the auction models. Nevertheless, both cartels and bidding rings share the common theme of collusion, and our empirical strategy shares the spirit of Asker (2010) in that we exploit direct evidence on the internal organization of the cartel to specify and estimate our model. Other recent examples in the bidding ring literature include Kawai and Nakabayashi (2015), which focuses on a different but important theme of detecting collusion in procurement auctions.

2 Model

2.1 Baseline Model

In the baseline analysis, we assume that firms play the following repeated game. There is fixed set of firms $I = \{1, ..., n\}$. We treat a specific category (such as vitamin C) as an independent market.[8] In the data, the participants of a cartel of a specific category is very stable, and hence we exclude the possibility of entry and exit, assuming that I is fixed.

In each period t, economic state $\tilde{X}_t$ is realized, which is observable to each firm. Given its history h_i^t (to be defined), each firm decides its supply $q_{i,t}$. Given the total supply $Q_t = \sum_{i \in I} q_{i,t}$, the market price $P_t = \frac{dP}{dQ}_t \times \left(Q_t + Q_{fri,t} - \tilde{X}_t\right)$ is realized, where $\frac{dP}{dQ}_t$ is the price sensitivity to the total quantity (linear demand),[9] $\tilde{X}_t$ is the observable demand shifter, and $Q_{fri,t}$ is the supply from the competitive fringe suppliers. Given firm i's marginal cost $c_{i,t}$, its profit is given by $(P_t - c_{i,t})\, q_{i,t}$.

The data shows that, even when a firm undercuts its own price to oversell beyond the agreed quantity in the cartel, the prices charged by different firms are very close to each other (see Figure 11 in Appendix). Hence it is reasonable to assume that the market price is common and observable.

Finally, we assume that players observe the quantity profile with L periods of lag: $\left((q_{j,\tau})_{j\in I}, Q_{fri,\tau}\right)_{\tau \leq t-L}$. The EC's criminal investigation revealed that the cartel members exchanged internal sales records at quarterly meetings and used government statistics to verify and monitor each member's adherence to the output quota agreement. Since one period of the model is one month, this suggests their monitoring is perfect with three-month lag (we parameterize this lag as $L = 3$).

[8] We exclude the possibility of the "multi-market contract," where a deviation in one market will be punished in all the other markets. As seen in section 3, the cartels of vitamins A and E, and beta carotene lasted until FBI's investigation even after the breakdown of vitamin C cartel. See Matsushima (2001), Kobayashi and Ohta (2012), and Sekiguchi (2015) for the theoretical study.

[9] See section 5.4 for another specification of the demand function.

In total, firm i's private history at the beginning of period t is

$$h_i^t = \left((q_{j,\tau}, Q_{fri,\tau})_{j \in I, \tau \leq t-3}, q_{i,t-2}, q_{i,t-1}, (P_\tau)_{\tau \leq t-1} \right),$$

and the public history is

$$h^t = \left((q_{j,\tau}, Q_{fri,\tau})_{j \in I, \tau \leq t-3}, (P_\tau)_{\tau \leq t-1} \right).$$

For the baseline analysis, we assume that the firms know past $\frac{dP}{dQ}_t$'s, $\tilde{X}_t$'s, and $c_{j,t}$'s and have perfect foresight of future $\frac{dP}{dQ}_t$'s, $\tilde{X}_t$'s, and $c_{j,t}$'s: $\left(\frac{dP}{dQ}_\tau, \tilde{X}_\tau, (c_{j,\tau})_{j \in I} \right)_{\tau=1}^{\infty}$ is common knowledge (so we omit them from the history). As will be seen in section 5.1, during the sample period, we identify $\frac{dP}{dQ}_t$, $\tilde{X}_t$, and $(c_{j,t})_{j \in I}$, and we assume that the firms expect demand and costs after the sample period to remain constant at their December 1998 levels. The marginal cost is very stable over time, and so it is reasonable to assume that they have a good understanding of it. See section 5.4 for another specification of the expectation about demand.

The evolution of $\frac{dP}{dQ}_t$, $\tilde{X}_t$, and $c_{j,t}$ is assumed not to depend on the firms' quantity. Given $\frac{dP}{dQ}_t$, $\tilde{X}_t$, and $c_{j,t}$, let $q_{i,t}^N$ be the unique equilibrium quantity in the static Nash equilibrium. Since $\tilde{X}_t$ and $c_{j,t}$ are independent of the firms' strategy, producing $q_{i,t}^N$ in each period t is an equilibrium.

Finally, as will be explained in detail in section 5.3, the EC's (2003) criminal investigation reveals that the cartel members have a static expectation about $\{Q_{fri,t}\}_t$: in each period t, they assume $Q_{fri,\tau} = Q_{fri,t-3}$ for each $\tau \geq t$.

2.2 Equilibrium Concept

In the baseline analysis, we assume that the firms are playing the following strategy. The cartel is formed to control the supply. In each period t, given the perfect foresight of $\left\{ \frac{dP}{dQ}_\tau, \tilde{X}_\tau, \{c_{j,\tau}\}_{j \in I} \right\}_{\tau \geq t}$ and the static expectation $Q_{fri,\tau} = Q_{fri,t-3}$ for each $\tau \geq t$, the members agree market supply $\left(\bar{q}_{i,\tau|t} \right)_{i \in I, \tau \geq t}$. (We write $\tau|t$ since this is the expected future cartel production plan given the static expectation $Q_{fri,\tau} = Q_{fri,t-3}$ formed in period t.) As will be seen, they agree on $\left(\bar{q}_{i,\tau|t} \right)_{i \in I, \tau \geq t}$ to maximize the total profit

$$\sum_{i \in I} \left(\frac{dP}{dQ}_\tau \left(Q_\tau + Q_{fri,\tau|t} - \tilde{X}_\tau \right) - c_{i^*,\tau} \right) q_{i,\tau|t},$$

where i^* is a specific firm (namely, Roche for vitamin C case). As will be seen, $c_{i,\tau}$ differs for different firms, but a difference is small. Moreover, Roche plays a leading role in the meeting. Hence, we assume that they maximize the total profit, as if each firm shares the same cost as Roche.

We say that a non-compliance is confirmed in period τ if, given the government statistics, it becomes common knowledge that some firm did not produce $\left(\bar{q}_{i,s|t}\right)_{i\in I}$ in period $\tau-3$ for the first time: For each $s<\tau-3$ and $i\in I$, we have $q_{i,s|t}=\bar{q}_{i,s|t}$, but there exists $i\in I$ with $q_{i,s-3|t}\neq\bar{q}_{i,s|t}$.

For each period t, given the expectation formed in period t, the firms agree to play the following strategy for period $\tau\geq t$: (i) if no non-compliance is confirmed previously in period τ, then each firm takes $q_{i,\tau|t}=\bar{q}_{i,\tau|t}$; and (ii) if some non-compliance is confirmed in some period $s\leq\tau$, then each firm takes a static Nash equilibrium quantity $q_{i,\tau}=q^N_{i,\tau|t}$. Let us call this strategy the "trigger strategy."[10]

For notational convenience, let $\pi^C_{i,\tau|t}$ be firm i's payoff with $\left(\bar{q}_{j,\tau|t}\right)_{j\in I}$; let $\pi^D_{i,\tau|t}$ be its optimal non-compliance payoff against $\left(\bar{q}_{j,\tau|t}\right)_{j\neq i}$; and let $\pi^N_{i,\tau|t}$ be its static Nash equilibrium payoff.

Complying with the cartel agreement from period τ on gives firm i the payoff of

$$V^C_{i,\tau|t}=\sum_{s\geq\tau}\beta^{\tau-1}\pi^C_{i,s|t}, \tag{1}$$

where $\beta\in(0,1)$ is the discount factor. When firm i does not comply in period τ, then since no punishment is conducted until it is verified by the government data in three periods, the optimal deviation payoff is

$$V^D_{i,\tau|t}=\sum_{s=\tau}^{\tau+2}\beta^{s-1}\pi^D_{i,s|t}+\sum_{s\geq\tau+3}\beta^{s-1}\pi^N_{i,s|t}. \tag{2}$$

For each t, given $V^C_{i,\tau|t}$ and $V^D_{i,\tau|t}$ for $\tau\geq t$, if there exist $i\in I$ and $\tau\geq t$ with which $V^C_{i,\tau|t}<V^D_{i,\tau|t}$, then it becomes common knowledge among the players that some player will deviate in period τ and the action will be a static Nash equilibrium from period $\tau+3$. Then the situation is the same as finitely repeated game, and each firm deviates in period t. Hence

[10] Given the static expectation, firms in period t expect that $q_{i,\tau|t}=q_{i,\tau|\tau}$ for each $\tau\geq t$. Hence, if their expectation is correct and $Q^{fringe}_\tau=Q^{fringe}_{t-3}$ for each τ in reality, then this description is exactly the trigger strategy: given agreed production $(\bar{q}_{i,\tau})_{\tau\geq t}$, a deviation will lead to the repetition of the static Nash equilibrium.

the trigger strategy is equilibrium given period t's expectation if and only if

$$\min_{i\in I,\tau\geq t}\left(V^C_{i,\tau|t}-V^D_{i,\tau|t}\right)\geq 0. \tag{3}$$

Recall that we assume that players form the static belief about $Q_{fri,\tau}$. As will be seen, for the vitamin C cartel (the only one that collapsed before the criminal investigation, among the four cases we study in depth), $Q_{fri,t}$ increases over time, and hence players revise the expectation of $Q_{fri,\tau}$ more and more negatively as t goes on. It is period t with which (3) does not hold for the first time when the cartel breaks down. That is, for the market in which the cartel broke down, we do not interpret the entire sequence of the play as a part of one equilibrium strategy. Rather, at the beginning, players expected that the future environment would make the trigger strategy equilibrium (in particular, no break down would happen on equilibrium path); and then by the unforeseen negative news about $Q_{fri,t}$, they started to believe that the trigger strategy is not an equilibrium, and switched to the repetition of Nash equilibrium.

As will be seen in sections 3 and 6, the vitamin C cartel broke down partly because Chinese firms, treated as competitive fringe here, exported vitamin C more and more after they invented a completely new production process. EC's (2003) criminal investigation shows that this invention came as a surprise, and the cartel members, which formed the static expectation, updated their belief with surprises.

2.3 Assumptions Behind the Theoretical Model

In the baseline model, we make the following assumptions about the strategy. First, complying with the cartel agreement is defined as supplying the agreed quantity $\bar{q}_{i,t}$ to the market. The first assumption – using quantity $\bar{q}_{i,t}$ as a cartel instrument – is motivated by the EC's criminal investigation. It is reported that the cartel members used the sales quota as a primary number to agree on.

Second, the firms have perfect foresight of $\left\{\frac{dP}{dQ}_t, \tilde{X}_t, (c_{j,t})_{j\in I}\right\}_t$. As will be seen in section 5.4, our result is robust to the other specifications such as adaptive expectations of $\left\{\tilde{X}_t\right\}_t$.

Third, no punishment is conducted until a non-compliance is verified with the government statistics. Since we assume $\tilde{X}_t$ and P_t are commonly observed at the beginning and end of period t, respectively, and since $P_t = \frac{dP}{dQ}_t\left(Q_t + Q_{fri,t} - \tilde{X}_t\right)$, one may wonder that each firm can calculate Q_t from P_t, $\frac{dP}{dQ}_t$, $Q_{fri,t}$, and $\tilde{X}_t$ at the end of period t (assuming the static belief about $Q_{fri,t}$). Given the EC's investigation, each firm simply waited until the government statistics came in and they held the next cartel meeting before starting the punishment when vitamin C cartel broke down. Theoretically, we can formulate $P_t = \frac{dP}{dQ}_t \left(Q_t + Q_{fri,t} - \tilde{X}_t\right) + \varepsilon_t$, where ε_t is an i.i.d. noise. Then each firm cannot calculate Q_t from P_t; and it is rational expectation to believe that the other firms follow the equilibrium strategy after any P_t given the full support of ε_t. Since each firm's payoff is linear in P_t (given $q_{i,t}$, which is known to firm i), having ε_t with $\mathbb{E}[\varepsilon_t] = 0$ does not change any analysis. Hence we omit ε_t for simple notation.[11]

Fourth, the punishment is the infinite repetition of the static Nash equilibrium. In the theoretical literature, Abreu (1988) constructs "stick-and-carrot" equilibrium; and Fudenberg and Maskin (1986), Abreu, Pearce, and Stacchetti (1990), and Fudenberg, Levine, and Maskin (1994) show that we can implement a severe punishment incentivized by a continuation payoff. The data in vitamin C shows that the market is very stable after the cartel broke down, and does not exhibit the movement of continuation payoffs.[12]

3 The Vitamin Cartels, 1990–1999[13]

As summarized in the introduction, vitamins represent an ideal natural laboratory for an empirical analysis of cartels. This section explains the industry background such as product characteristics, demand, manufacturers' profile, and details about the cartels.

3.1 Definition of Vitamins

Vitamins are organic substances that: (i) are natural components of foods, (ii) are essential in small amounts for normal physiological function, (iii) are not synthesized by the host (i.e., human or animal) in adequate amounts, and (iv) cause a specific deficiency syndrome when absent. Choline and carotenoids are not among the 13 substances generally recognized as vitamins, but are considered below because they were integral part of the antitrust litigations. Chemically speaking, vitamins function as (i) a stabilizer of cell membranes, (ii) a facilitator of either redox or acid-base reactions, (iii) a co-enzyme, or (iv) a hormone, and promote a number of biological activities, including blood formation (vitamins B9 and B12), antioxidant

[11] A theoretical work by Fudenberg, Ishii, and Kominers (2014) points out more sophisticated ways to punish when an evidence arrives with delay. Again, we assume firms wait until the evidence, motivated by the EC's investigation.

[12] Of course this does not exclude the possibility that the distribution of continuation payoffs depend on the strategies, but by chance the realization looks stationary.

[13] This section heavily relies on Bernheim (2002, Appendix E) and Connor (2007).

status (vitamins C and E), energy metabolism (vitamins B1, B2, and B6), bone formation (vitamin D), and protein metabolism (vitamin A).

Each vitamin product category or "family" (e.g., vitamin C) constitutes a separate market because of differences in demand and supply characteristics. The metabolic functions for each vitamin are unique, and hence one vitamin cannot substitute for another. Likewise, the manufacturing process for one vitamin will not work for another (see Table 3 in Appendix for a list of raw materials and intermediates for each vitamin). However, vitamins are homogeneous goods within each category. Although multiple quality grades (e.g., for humans and animals) and strength levels (e.g., 100%, 50%, and 30% concentration) are available for most bulk vitamins, little or no differentiation exists across producers. A vitamin has a unique molecular structure with unique biological properties, and production processes are similar across firms.[14]

Thus bulk vitamins are widely viewed as commodities for which the only factor driving buyers' purchase decision is delivered price net of discounts. According to Connor (2007, p. 256), "for each vitamin there is likely to be one variety, typically the modal one, which drives the prices of all other varieties of the same vitamin. Human-grade tends to sell in fixed price relationship to the same vitamin's feed grade; the same is true of different strength when converted to a 100%-pure basis. Prices of 100%-pure human and 100%-pure feed versions of the same vitamin are very highly correlated over time. This customary pricing practice is convenient for collusion, because sellers need only agree on one price for each vitamin, from which the prices of all other types will be priced using historical premiums or discounts. The only departure from perfect product homogeneity may be in after-sales services provided by the leading manufacturers." Figure 11 (in Appendix) confirms this observation by showing firm-level prices of four specific vitamin products (Vitamin E 50% Adsorbate Feed Grade, Vitamin E Acetate Oil USP, Ascorbic Acid 100% USP, and Beta Carotene 30% Fluid Soluble), which are highly correlated and close to each other in levels.

3.2 Demand

Avoidance of deficiency symptoms has historically been the primary role of vitamins in nutrition, but the recognition of their broader role has increased. In the human-nutrition segment, epidemiological studies have shown strong correlations between vitamin intake and both improved organism performance and increased disease resistance. Although proof of

[14] Bernheim (2002, Appendix E) reveals the details of the production processes at some of the major firms, which are almost identical.

causal effects is incomplete in many cases, educational marketing has spawned the steady growth of demand for vitamins. Cosmetics are another segment of the commercial vitamin market but it is relatively small (see Table 4 in Appendix for relative market size by segment).

By contrast, the use of vitamins in animal agriculture has become a highly disciplined science. Animal nutritionists use sophisticated algorithms to formulate feed on a cost-benefit basis, and these developments in animal husbandry have led to substantial increases of demand over the past several decades.

In the United States, the Food and Drug Administration (FDA) has regulatory authority over vitamins in human food and animal feed, which provided Recommended Daily Intake (RDI) for labeling of food and supplement products. Human-nutrition products must meet the specifications delineated in the United States Pharmacopoeia (USP) or the Food Chemical Codex (FCC), which are consistently more stringent than those applied to animal-nutrition products. Nevertheless, "vitamins for human nutrition lack a fully accepted fact-based correlation between consumption and objective performance measures" and "except when used as chemical antioxidants, vitamins are included in foods for their label value."[15] Consequently, the legal restrictions seem to have become less significant than marketing considerations.

The broad role of vitamins means a large number of buyers exist for them. After the criminal investigation and prosecution of the cartels, private treble damages suits resulted in the largest antitrust settlements in history at the time, with approximately 4,000 plaintiffs. Most of these direct buyers were manufacturers of animal feeds, foods, or pharmaceuticals; some were farmers or their cooperatives. Thus buyer concentration is generally low.[16]

3.3 Manufacturers

Table 1 compiles the market shares of selected companies in the cartels. Virtually all major manufacturers were the members. At most three or four firms dominate each vitamin category. Connor (2007, 2008) assembled and investigated these data at the global level along with regional sales data, and concluded that "overall market control by Vitamins, Inc. in Western Europe and the United States was practically the same as at the global level" (Connor 2007, p. 253). See Table 5 (in Appendix) for market size by region.

Hoffmann-La Roche (henceforth Roche) is a Swiss drug company that pioneered and dominated synthetic volume production of most vitamins until the 1970s, when Badische

[15] Bernheim (2002, Appendix E, pp. 9–10).
[16] See Connor (2007, pp. 254–256) for details.

Table 1: Global Market Shares (%) by Category in Early 1990s

Market: Firm	A	B1	B2	B3	B4	B5	B6	B9	B12	C	D3	E	H	Carotinoids	All
Roche	48	44	54	–	–	36	49	39	–	46	43	46	45	83	46
BASF	30	2	30	–	15	21	3	–	–	7	13	28	–	16	17
RP	21	–	–	–	–	–	–	–	62	–	–	13	–	–	8
Takeda	–	31	3	–	–	–	12	23	–	26	–	–	–	–	7
Eisai	–	–	–	–	–	–	–	–	–	–	–	12	–	–	2
Daiichi	–	–	–	–	–	29	12	–	–	–	–	–	–	–	1
E. Merck	–	–	–	–	–	–	5	–	–	10	–	–	10	–	2
Hoechst	–	–	–	–	–	–	–	–	7	–	–	–	–	–	1
Others	–	–	–	86	75	–	–	35	–	–	44	–	42	–	9
Cartel total	99	77	87	86	90	86	81	97	69	89	100	99	97	100	93
Non-members	1	23	13	14	10	14	19	3	31	11	0	1	3	0	7

Source: Connor (2007, 2008).

Anilin und Soda Fabrik (BASF), a German chemical giant, successfully imitated its processes in several categories. Rhône-Poulenc (RP), a French chemical maker, also began producing a few vitamins. These European "Big Three" became the core of the global cartels in the 1990s.

Takeda Chemical Industries (Takeda) has been the largest pharmaceutical firm in Japan. It began volume production and exports of vitamins in the 1950s. By the 1990s, Takeda had become the second or third largest global manufacturer of several vitamins, followed by Eisai, Daiichi Pharmaceutical, and other domestic rivals. By contrast, American companies had ceased to be major suppliers by the 1980s, despite their early involvement in vitamins.[17] Their facilities were either closed or sold to European makers.

3.4 The Cartels

21 manufacturers joined one or more of the 16 conspiratorial groups, each of which regularly met to set quotas and target prices, exchange internal sales records, and monitor implementation of the quotas. Roche, the industry leader, organized 14 of the 16 cartels, with BASF as its main partner in crime (12 cartels), followed by Takeda (5 cartels) and RP (3 cartels).

[17] For example, Pfizer and American Home Products manufactured vitamins. The first research director of Merck focused on vitamins in 1933, which contributed a large share of the company's total sales in the late 1930s. This U.S.-based Merck is not to be confused with E. Merck, its German parent before World War I. The latter was a cartel member in the 1990s.

Beginning

On June 7, 1989, the heads of the vitamins divisions of Roche and BASF met in Basel, Switzerland to start cartels for vitamins A and E. RP's head of Animal Nutrition division joined two months later at another meeting in Zurich. They agreed to freeze market shares at the 1988 levels for the foreseeable future and to split their predicted 1990 sales proportionally to these quotas. This practice came to be known as the "budget meeting" in every late summer or fall. These top-level annual meetings were supplemented by middle-level meetings held at the quarterly frequency among the heads of worldwide product marketing, who also exchanged progress reports on sales volumes on a monthly basis. At the lowest level, regional product marketing managers also met four times per year to monitor regional quotas, assess trends in demand and supply, and make small adjustments to prices in local currencies. At the January meetings, these managers arranged what economists would regard as "side payments" in the form of compensating sales from under-quota members to those who exceeded their quotas as of the year end. With minor variations, these basic rules and organizational structure for vitamins A and E applied to all of the other cartels.

In 1990, the three original members recruited Hoechst, a German maker of vitamin B12, and Eisai of Japan, which was the only major producer of vitamin E besides Roche and BASF, to solidify the two existing schemes for vitamins A and E, and to form four more cartels for vitamin B12, two carotenoids (beta carotene and canthaxanthin), and premixes (i.e., customized cocktails for animal feed, consisting mainly of vitamins A and E). These six cartels were operational in 1990. To ensure cooperation of new members, the leading members would often cede some of their historical market shares. Furthermore, Roche contacted Daiichi, E. Merck, and Takeda to cartelize the markets for vitamins B1, B2, B5, B6, B9, C, and H. Takeda also agreed to become a liaison with smaller Japanese makers, including Sumitomo Chemical, Tanabe Pharmaceutical, and Kongo Chemical. By early 1991, all 14 of the Roche-led cartels were successfully raising prices of bulk vitamins.

Operations

Monitoring was close to public. The monthly and quarterly exchange of internal sales records was supplemented by third-party data. The members knew the location of each member's plants, and typically a country would have only one producer for a given product.

Thus international trade statistics from the respective governments could serve to verify self-reported sales information. This reasonably transparent monitoring environment, along with the year-end side payments to adjust for unintentional over- and under-quota achievements (see above), facilitated the implementation of the quota agreement.

The cartels did not specify punishment but the implicit threat was that the members would revert to competitive pricing and the collusion would break down indefinitely, which is typical of cartel agreements in the real world (c.f., Harrington 2006, Marshall and Marx 2014). This is why we define the punishment payoff as the static Nash equilibrium payoff. Such a shared understanding was occasionally aired, for example, by E. Merck in the vitamin H market and by Roche, E. Merck, and BASF in the vitamin C market. EC (2003) records that "the three European producers presented Takeda with an *ultimatum*: unless it agreed to cut back its vitamin C sales, *they would withdraw from the agreement*" (p. 44, emphasis added). Throughout the 1990s, nothing like a full-blown price war was observed, except when several of the cartels collapsed more or less permanently.

Most cartels set different target prices for three regions (Europe and the Middle East, North America, and the rest of the world), but the geographic price spreads were designed to be less than 10%. Vitamins are storable and transportable at modest costs, which opens possibilities for international arbitrage. The 10% rule virtually eliminated such profit opportunities.

End

The 16 cartels ended in one of two ways. Six of them fell apart in 1994 or 1995 apparently because of the entry and expansion by fringe producers and/or the difficulty of aligning relatively many participants. Chinese producers, mostly state-owned enterprises (SOEs), significantly increased markets shares in vitamins B1, B6, B9, and C. Il Sung, a Korean maker, was the fringe producer of vitamin H. Finally, Archer Daniels Midland (ADM), an American food processing and commodities trading company, entered the vitamin B2 market by acquiring facilities from Coors Biotech, a subsidiary of an American beer company, and refused to join the conspiracy.

By contrast, the ten other cartels were operating smoothly until private and government investigations in the United States forcibly terminated them in 1998 or 1999. American investigators first learned about the vitamin cartels in late 1996 from ADM, which was cooperating with the DOJ in its investigation of the separate case concerning the citric acid cartel. In March 1997, the FBI interviewed Dr. Kuno Sommer, then president of Roche's Vitamin and Fine Chemicals division, who denied the existence of any cartel. In March 1998, Boies & Schiller, a law firm, filed a civil price-fixing suit in U.S. District Court for Dallas, Texas on behalf of several direct purchasers of bulk vitamins. These allegations were forwarded to the DOJ and the FBI. In the summer of 1998, Lonza, a Swiss producers of vitamin B3, and Bio-Products, an American producer of vitamin B4, began cooperating with the FBI.

Finally, in January 1999, RP, the world's third largest vitamin firm, applied for (and was granted) amnesty under the DOJ's relatively untested Corporate Leniency Program. RP's managers were rumored to be required to attend the last cartel meeting in February 1999 and tape-record it. Within two months, both Roche and BASF pled guilty and agreed to pay record-breaking fines of $725 million in total. RP saved more than $100 million in U.S. fines, but its main motivation for defection was to seek regulatory approvals for its planned merger with Hoechst, with whom it had colluded in the vitamin B12 market. The American and the European agencies did approve this merger, which created Aventis, one of the two predecessors of Sanofi-Aventis (currently Sanofi). These historical developments raise an interesting question regarding how antitrust agencies can jointly optimize the enforcement of cartel and merger policies; understanding and measuring the incentive to collude would be the first step for improving policy design.

4 Data

4.1 Sources

The criminal and civil litigations described in section 3 have generated a large amount of court documents containing the details of the cartels' internal arrangements as well as data on prices, costs, and production quantities. Specifically, the European Commission (EC)'s decision document contains rich qualitative description of the cartels' functioning (EC 2003), whereas the American court documents reveal quantitative information at the levels of firms, products, and sometimes even plants (Bernheim 2002). These two legal/court documents constitute our primary source of data and evidence, based on which we specify and estimate our model.

Many economists participated in these litigations on the sides of both plaintiffs and defendants, several of whom subsequently published academic articles based on these and other publicly available materials, including Connor (2007, 2008), Marshall, Marx, and Raiff (2008), and Marshall and Marx (2014). These studies constitute our secondary source of data, which fill the gaps of the primary ones and supplement institutional contexts for the correct interpretation of the data.

4.2 Prices, Costs, and Outputs

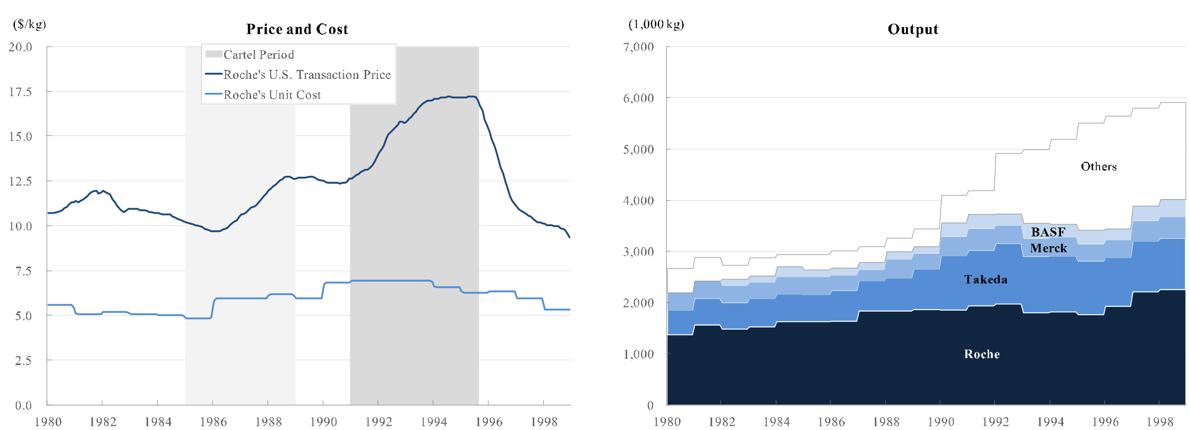
Bernheim's (2002) expert report contains the following information, mainly based on Roche's Data Book for its internal administration, but also supplemented by other cartel members' internal documents including BASF, RP, and Takeda.

First, Bernheim's (2002) section 9 shows prices at the monthly frequency for the U.S. market in dollars, both at the "concentration-adjusted" aggregate level for each of the 14 vitamin categories (e.g., vitamin C) and at the product-specific level (e.g., Ascorbic Acid Compressible, which is one of the particular physical forms in which vitamin C is traded). Such varieties of physical forms notwithstanding, bulk vitamins are homogeneous commodity for all practical purposes, and firm-level price differences are minimal. Nevertheless, the report contains firm-level prices for a subset of the vitamin categories (vitamins B2, B5, C, and E, and beta carotene) in its section 10.

Second, Appendix F of the expert report reveals firm-specific global unit production costs at the annual frequency in dollars at the product level for many categories. Roche's data are the most detailed with plant-specific unit costs although their costs are often similar across plants across different countries.

Third, information on sales quantities is relatively sparse because Bernheim's (2002) empirical analysis focused efforts on time-series regressions of prices on costs and other covariates but did not estimate a demand function or any other objects that would require the use of quantity data. Nevertheless, section 9 and Appendix E contain the world production data and all of the major producers' market shares at the annual frequency in dollars.

Figure 2: Price, Cost, and Quantity of Vitamin C



We combine these information with other supplementary data (e.g., Connor 2008) to construct our final dataset. Figure 2 summarizes basic data patterns for vitamin C as an example (see Figure 12 in Appendix for the corresponding data displays for beta carotene, vitamin A, and vitamin E). Price increased rapidly from 1991, the first year of the vitamin C cartel, despite virtually flat unit cost. Aggregate output exhibits an upward trend through the sample period, including those periods of rapid price increases in the early 1990s, which suggests a secular growth of demand. The four cartel makers' outputs moved harmoniously, but the expansion of fringe is conspicuous. We use these data and other institutional knowledge (from section 3) for empirical analysis in the next section.

5 Empirical Analysis

The goal of our empirical analysis is to estimate the cartel members' incentive to collude and assess the effects of demand, supply, and a hypothetical merger on the cartel's breakdown. We proceed in three steps. First, we estimate demand and costs in each period by using the firms' first-order conditions. Second, we calculate hypothetical market outcomes (i.e., price, outputs, and profits) in each period under static Nash equilibrium, the cartel's quota scheme, and unilateral deviations from it. Third, we calculate the discounted present values of collusion and defection to evaluate the incentive compatibility condition, which can then be used to assess whether the cartel could have survived under different circumstances (i.e., more favorable demand conditions, less aggressive expansion of fringe supply, and an earlier consummation of the BASF-Takeda merger) in section 6.

Our exposition in main text focuses on the vitamin C market but Appendix contains similar analysis for three other markets (beta carotene, vitamin A, and vitamin E) for which comparable data are available.

5.1 Demand and Costs

Vitamins are simple, homogeneous goods and many small buyers exist, so a linear demand model is a natural starting point:[18]

$$Q_t^D = \alpha_0 + \alpha_1 P_t + \alpha_2 X_t + \varepsilon_t, \tag{4}$$

where Q_t^D is quantity demanded, P_t is price, X_t is demand shifter, ε_t is unobserved demand shocks, αs are demand parameters, and t is time subscript.

[18] See section 5.4 and Appendix for a robustness check with a differentiated-product demand model.

A standard approach is to estimate αs by regressing Q_t^D on P_t and X_t, preferably with some instruments for P_t to address the endogeneity problem due to possible correlation between P_t and ε_t (i.e., the firms could be responding to demand shocks). Potential IVs include supply-shifters such as costs and the degree of competition or cartelization, both of which happen to be available in our data. However, the gradual increase of P_t coincided with that of Q_t^D during the cartel period (see Figure 2), which implies a secular growth of X_t. This collinearity between P_t and X_t makes parameter estimates highly unreliable and sensitive to small changes in specification.

Consequently, instead of searching for *ad hoc* specifications, we have chosen to exploit the strength of our empirical context, that is, the exact time period of the actual competitive/collusive regime is known as a result of the criminal investigations and the subsequent civil litigations. The vitamin C cartel was in effect between January 1991 and August 1995.[19] Thus it is natural to assume static Nash equilibrium before and after the cartel period. From the fact that the producers of these homogeneous goods seemed to earn positive profits even during the non-cartel period, Cournot model seems to approximate the actual mode of competition,[20] in which the first-order condition (FOC) of profit maximization with respect to output is

$$P_t + \frac{\partial P}{\partial Q} q_{i,t} = c_{i,t}, \tag{5}$$

where $\frac{\partial P}{\partial Q} = \frac{1}{\alpha_1}$, $q_{i,t}$ is firm i's output, and $c_{i,t}$ is firm i's marginal cost. Our dataset contains the firms' internal documents concerning unit production costs. In particular, Roche was the leader of most vitamin cartels, and its cost data are the most comprehensive and reliable according to the plaintiffs in the civil litigations. Hence we can use data on $(P_t, q_{roche,t}, c_{roche,t})$ to infer the price coefficients before and after the cartel (solid lines), and interpolate its values during the cartel (dashed lines) in Panel A of Figure 3.[21]

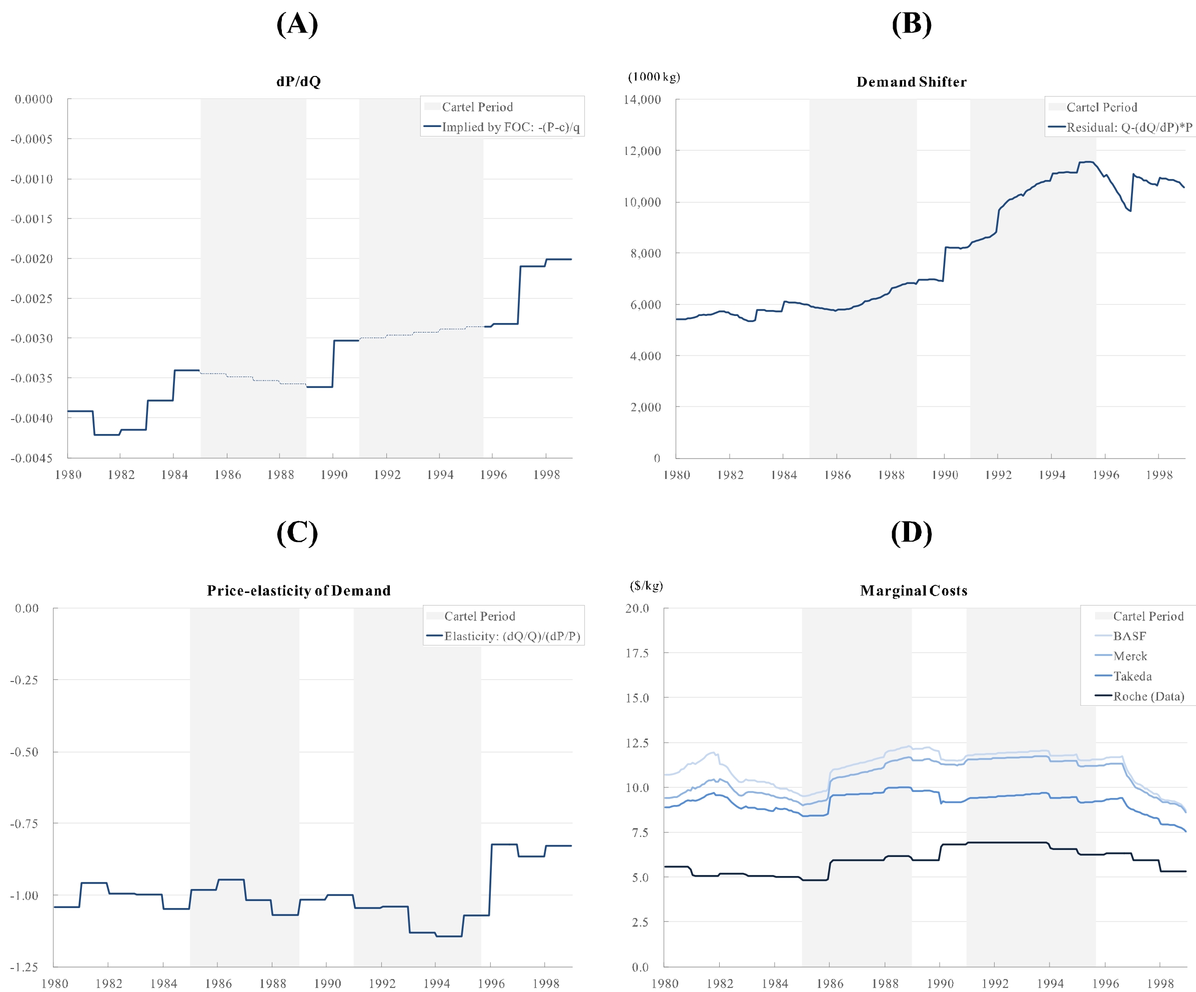
Note that we have not yet relied on specific functional forms of demand or cost except for additive separability of the price term in the demand function. Under this assumption,

[19] The plaintiffs in the civil litigations claimed the existence of cartel schemes from as early as 1985. We can use this alternative date in a sensitivity analysis. However, our preliminary analysis suggests limited market power between 1985 and 1990 anyway. Thus the results of our main analysis concerning the 1990s are not sensitive to this choice of dates.

[20] In section 5.4 and Appendix, we show a robustness check with a differentiated-product Bertrand model.

[21] We allow $\frac{\partial P}{\partial Q}_t$ to change over time and recover it at annual frequency because q_t and c_t are recorded annually.

Figure 3: Demand and Cost Estimates for Vitamin C



all of the non-price terms in (4) can be collectively inferred as an *effective* demand shifter,

$$\tilde{X}_t \equiv \alpha_0 + \alpha_2 X_t + \varepsilon_t, \tag{6}$$

by subtracting $\hat{\alpha}_{1t} P_t$ from Q_t.[22] Panel B shows this effective demand shifter, $\tilde{X}_t$, exhibits a secular, upward trend as we suspected earlier. Court documents and other antitrust reports state that the demand for vitamins generally increases with population and income, as well as the general public's awareness of the health benefits of vitamins, all of which seem to suggest a gradual, increasing time trend. Our estimates of $\tilde{X}_t$ confirms these expert opinions. Panel

[22]See Appendix Figure 13 for the corresponding demand estimates for beta carotene, vitamin A, and vitamin E.

C shows the implied price-elasticity of demand exhibits a stable time path near -1.

The estimates of α_{1t} and $\tilde{X}_t$ relied on internal cost data of Roche. Bernheim's (2002) report contains cost data of Takeda and BASF as well, but not for the entire sample period. Merck's data are missing. Moreover, the exact definition and recognition of costs may vary across firms, currencies, and countries. Thus we have chosen to estimate the three non-Roche firms' costs by using their respective FOCs during the non-cartel period, instead of relying on incomplete records that may not be comparable across firms. For the cartel period, we use interpolation based on the estimates for the non-cartel period under an additional assumption of constant differences with Roche's cost.[23] Panel D shows the four firms' marginal costs exhibited relatively small changes compared with the drastic rise and fall of output prices.

These cost estimates assume constant marginal cost across output levels, which might appear restrictive. We can relax this assumption by estimating the slope of marginal cost as a function of output. However, our investigation of Roche's cost curve yielded no discernible patterns and a virtually flat slope, despite the fact that Roche's output level exhibited ample variation over the sample period. Thus we have concluded that, despite its simplicity, the constant marginal cost specification reasonably approximates the production technology, at least for the relevant levels of output.

5.2 Profits under Static Nash, Cartel, and Unilateral Deviation

Recall that we assume static expectation of $Q_{fri,t}$. For each period t, given the expectation $Q_{fri,\tau} = Q_{fri,t-3}$ for all $\tau \geq t$, these demand and cost estimates allow us to calculate equilibrium prices and each firm's period profits in all periods,

$$\pi_{i,\tau|t} = \left(P_{\tau|t} - c_{i,t}\right) q_{i,\tau|t}, \tag{7}$$

both under the cartel and in a static Nash equilibrium.[24] Figure 4 (left) plots three different prices for each t and $\tau = t$ (that is, the price in period t given period-t belief about $Q_{fri,t}$). The top, dotted line is the hypothetical monopoly price given fringe supply, whereas the bottom, dashed line reflects the static Nash price. The solid line is the actual price in the data and fluctuates between the two hypothetical prices. The actual price did not switch immediately between the monopoly and the Nash levels because the cartel needed to act

[23]Specifically, we calculate each non-Roche firm i's average difference from c_t^{roche} in the non-cartel period, $\gamma_i = \bar{c}_i - \bar{c}_{roche}$, and use this γ_i and c_t^{roche} to calculate c_t^i in the cartel period. An alternative specification with constant ratios (i.e., $\gamma_i = \bar{c}_i / \bar{c}_{roche}$) does not significantly alter the estimates.

[24]See Appendix Figure 14 for corresponding analysis for beta carotene, vitamin A, and vitamin E.

covertly to avoid detection by the authority. Additionally, typical contracts covered three to 12 months of delivery at fixed prices, and hence a complete turnover of existing contracts would take at least a year. For these reasons, the vitamin C cartel started in January 1991 but most of the actual price increases took place in 1992, after which it approached the theoretical monopoly price and stayed there. Likewise, the breakup in August 1995 did not immediately result in the Nash price. Court documents suggest another full year was needed for the downward adjustment at the industry level. These gradual transition dynamics are difficult to model convincingly, and hence we simply take such time for adjustments as facts.

Figure 4: Prices and Profits under Cartel and Static Nash

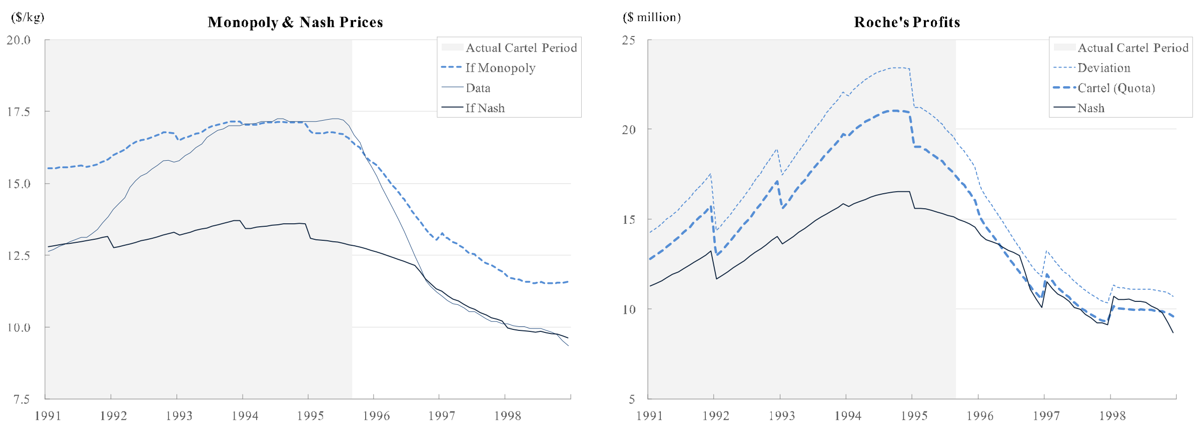


Figure 4 (right) displays Roche's equilibrium profits (again, the profit in period t given period-t belief about $Q_{fri,t}$). The dashed line at the bottom is the static Nash profit; the dotted line in the middle is Roche's profit under the cartel's quota scheme (based on the historical market shares before the cartel); and the top line reflects what Roche may earn temporarily if it unilaterally deviates from the quota. The gap between the first two (i.e., Nash and cartel) occasionally reversed after 1995 because the quotas were based on pre-cartel market shares and did not necessarily align well with the subsequent evolution of Roche's cost-competitiveness against the other members.[25] These subtleties notwithstanding, the three lines share the overall trajectories. Profits increased most of the time between 1991 and 1995 because the market size (i.e., the effective demand shifter, $\tilde{X}_t$) was increasing even though fringe players were increasing exports from China and buyers were becoming slightly more price-sensitive. The tipping point came sometime in 1995 or 1996, and the latter two negative forces (i.e., the increases of $Q_{fri,t}$ and $\frac{\partial P}{\partial Q}_t$) started dominating the positive impact

[25] See section 5.4 and Appendix for the possibility of renegotiation.

of demand growth. Unfortunately (for Roche), the upward trend in $\tilde{X}_t$ came to a halt in 1995 and the demand growth was practically zero or slightly negative for a few years (see Panel B of Figure 3).

These developments of $\tilde{X}_t$, $Q_{fri,t}$, and $\frac{\partial P}{\partial Q}_t$ are foreshadowing our main results on the incentive to collude, but we need one more layer of theory-based empirical analysis (in section 5.3) to translate these data patterns into a useful measure of cartel survival. Then, in section 6.1, we will conduct comparative statics (or more precisely, comparative dynamics) to quantify the impacts of these demand/supply factors on the cartel's eventual fate.

5.3 Expected Values and Incentive Compatibility

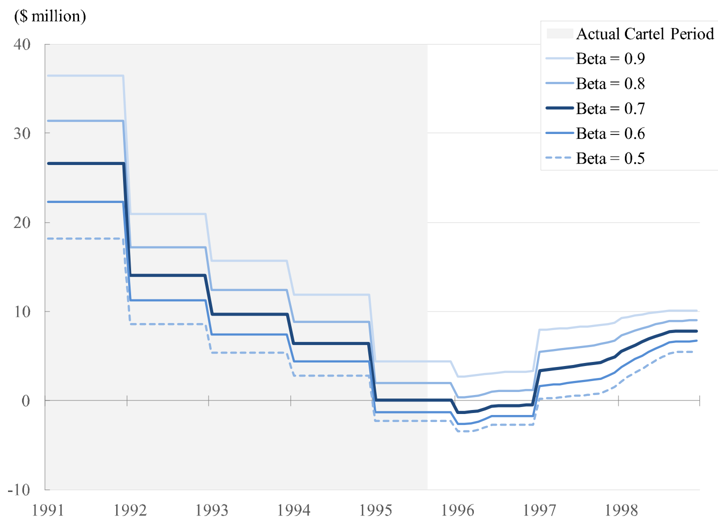
These estimates of period profits under Nash, cartel, and deviation form the basis for calculating the discounted present values of collusion and defection, $V^C_{i,\tau|t}$ and $V^D_{i,\tau|t}$, for each t and $\tau \geq t$, given the belief about $Q_{fri,\tau}$ formed in period t: $Q_{fri,\tau} = Q_{fri,t-3}$ for each $\tau \geq t$. Their difference, $\Delta V_{i,\tau|t} \equiv V^C_{i,\tau|t} - V^D_{i,\tau|t}$, represents the firm's incentive to collude. Note that, simply checking whether $\Delta V_{i,t|t} > 0$ holds in each period would be missing the forward-looking nature of collusion, as we explained in section 2. If someone's $\Delta V_{i,\tau|t}$ is expected to be negative in some future period $\tau > t$, the cartel would find itself in a finitely repeated game at the end of which someone would defect, and the entire scheme unravels. That is, even if $\Delta V_{i,t|t} > 0$ for all i in the current period t, the cartel should break down at t (rather than at $\tau > t$) as long as $\Delta V_{i,\tau|t} < 0$ for some $\tau \geqslant t$ and i. Thus, for the purpose of evaluating the cartel's incentive compatibility, the most relevant measure is the *minimum* of the expected values *across all future* τ given the information set at each point in time t,

$$\Delta \underline{V}_{i,t} \equiv \min_{\tau \geq t} \Delta V_{i,\tau|t}. \tag{8}$$

The incentive to collude becomes negative when $\Delta \underline{V}_{i,t}$ is lower than zero or some fixed cost of coordination, ϕ.

Figure 5 plots Roche's incentive compatibility, $\Delta \underline{V}_{roche,t}$ (multiplied by $1-\beta$ for normalization), for five different levels of discount factor, β. Regardless of the specific calibration of β, $\Delta \underline{V}_{roche,t}$ reaches its lowest point at the beginning of 1996. The actual vitamin C cartel had its last meeting on August 24, 1995, when the members decided to abandon the quota scheme. The level of β that is the most consistent with this historical timing is 0.7 because it sets $\Delta \underline{V}_{roche,t}$ to approximately zero, thereby perfectly rationalizing the cartel's collapse in the middle of 1995. But a higher discount factor such as 0.9 or 0.8 may also

Figure 5: Roche's Incentive to Collude



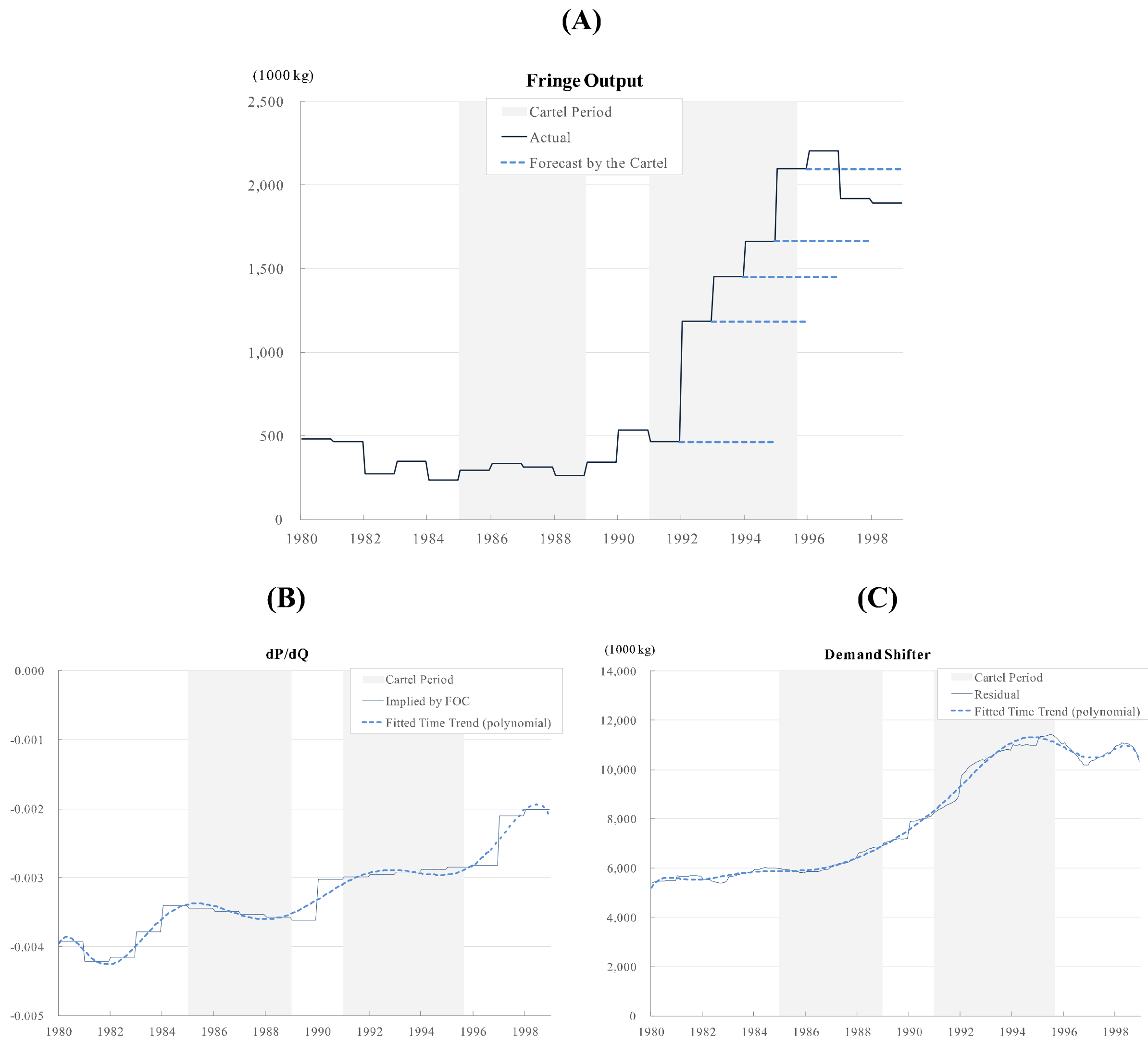
rationalize the data if we allow some fixed cost of operating the cartel, ϕ, such as the costs of communication, coordination, and other logistics issues. A few million dollars of ϕ per month could easily set $\Delta \underline{V}_{roche,t}(\beta)$ to zero even if $\beta > 0.7$. Thus we regard 0.7 as the lower bound of β.[26]

Another important specification issue is the firms' expectations on the future market environment. Specifically, the determinants of future profits include (i) the supply from fringe competitors, (ii) the demand parameters and growth, and (iii) the technologies of the cartel members. The fringe supply consisted mostly of Chinese exports. Figure 6 (Panel A) shows fringe supply was negligible during the 1980s but suddenly increased in the mid 1990s, more than quadrupling between 1991 and 1996. Chinese state-owned enterprises

[26] Although theoretically inclined readers or macroeconomists might find 0.7, 0.8, or even 0.9 to be a very low discount factor, we regard these results on β sensible for two reasons. First, the cartel was designed and operated by the division managers of vitamin business at each member firm. These managers' personal time horizon was presumably shorter than that of shareholders because their perceived benefits such as bonuses and promotions cannot extend beyond their careers and retirement. In other words, the β in our model is conceptually different from the macroeconomic discount factors such as those implied by the real interest rate.

Second, the discovery of criminal activities by the antitrust authority is a rare event but always a possibility, and its consequences fall on the individual managers (e.g., prison sentences) as well as their firms' finances (e.g., fines). Moreover, the cartel might collapse due to other exogenous reasons (e.g., sudden deaths of key officers). Let us denote by δ the probability of such exogenous termination. Our β is the effective discount factor that incorporates such possibilities, that is, $\beta = \tilde{\beta}(1-\delta)$, where $\tilde{\beta}$ represents the intrinsic discount factor. To the extent that δ is positive and perceived as such by the managers, β becomes lower than $\tilde{\beta}$. We do not attempt decomposing β into $\tilde{\beta}$ and $(1-\delta)$ because these are highly subjective parameters and not systematically recorded.

Figure 6: Cartel's Expectations on Fringe and Demand



(SOEs) led this output growth by building large plants and exporting through the traders of bulk chemicals. The success of these SOEs was then followed numerous smaller Chinese firms, which together constituted a sizable new entrant to the global vitamins market. Many vitamin categories witnessed such aggressive expansions of Chinese exports, but the vitamin C market was the most affected because the Chinese exports of vitamin C happened to come with a production process (i.e., a two-step fermentation method) that is fundamentally new and different from the one used by the established manufacturers in Europe and Japan (i.e., a one-step synthetic method). This process innovation gave a significant cost advantage to the Chinese producers and reduced the minimum efficient scale of production, both of which lowered the barriers to entry. Chinese firms did not enjoy such a definitive cost advantage in other vitamin markets.

Initially, the cartel members did not understand what was going on, then they learned about the wide-spread introduction and improvement of the new process in China, but the Chinese government and SOEs restricted foreign firms' access to the new technology. The UKCC's (2001) report on the BASF-Takeda merger suggests that, even in 2001, reliable information hardly existed on the Chinese producers of vitamin C. Thus the cartel members were making predictions in the dark when they tried to forecast future fringe supply and allocate quotas accordingly. More specifically, EC's (2003) criminal investigation reveals that the cartel formed and shared static expectations at each meeting, whereby its members assumed the future Chinese exports would stabilize at the latest record in reality. For example, at its January 1995 meeting, the cartel's quota allocation assumed the 1995 fringe supply to be equal to the actual 1994 level. However, at the final meeting in August 1995, the January forecast turned out to be too optimistic, and the revised, more realistic forecast seemed to persuade the cartel to abandon the quota scheme. We use this historical evidence and specify the cartel's expectation on fringe output to be static, as illustrated by dashed lines in Panel A of Figure 6.

By contrast, the cartel's expectation about demand seemed to involve less surprises. The UKCC's (2001) report reveals that BASF predicted a secular growth trend for the overall market size of vitamin C, based on the growth of the dietary supplement market in North America, Japan, and Europe, as well as the growth of GDP in the emerging countries of Asia and South America. The litigation documents of Bernheim (2002) and EC (2003) further suggest that these basic growth trends are interwoven with fluctuations in the general public's perceived health benefits of vitamins. To capture these patterns of trends and fluctuations, we fit a time trend with polynomials (10th-order polynomials in the baseline specification) and assume rational expectations.[27]

Finally, the court documents suggest the technologies of the cartel firms were practically common knowledge, including each firm's production process, manufacturing facilities, and costs of inputs. The four incumbents used the conventional method, whose physical properties were well understood and did not experience any major changes during the sample period. Figure 3 (Panel D) shows the data on Roche's unit cost as well as our estimates of the marginal costs of the three other firms exhibit only small changes over time. Moreover, these firms were exchanging detailed information on a continual basis throughout the

[27] Changes to the specification of time trend do not meaningfully affect our main results.

cartel period. Thus we assume the cartel members shared information on the production technologies and a perfect foresight over their time paths.

These are the specifications we used for our baseline estimates of the incentive to collude. In section 5.4 and Appendix, we show the results of robustness checks using alternative specifications.

5.4 Robustness

5.4.1 Renegotiation and Endogenous Fringe

As mentioned above, we fix the quota of each firm at the level of pre-cartel periods. One may wonder if it was possible to renegotiate and come up with new quotas with which the incentive compatibility constraint is satisfied. In addition, from the data, it seems that the Chinese firms react to previous high prices by increasing their production. As time goes on and the cartel members figure out the reaction, they may be able to come up with a better production level to suppress the Chinese firms' production.

To make sure our analysis is robust to those considerations, we consider the following model: Suppose the fringe supply in period t is determined by the past K-period prices: $Q_{fri,t} = \alpha_{fri} + \sum_{k=1}^{K} \beta_{fri,k} P_{t-k}$.[28] We specify $K = 2$ and regress $Q_{fri,t}$ on P_{t-2} and P_{t-1} to estimate the fringe supply function. The idea is to capture the notion that Chinese SOEs were building new plants and entering the international market for the first time, partially as an endogenous response (albeit delayed) to the high prices in the international vitamin C market. Now that the past prices $\{P_{t-k}\}_{k=1}^{K}$ affect the fringe supply, the optimal quantity to maximize the discounted sum of the cartel members' profits is a function of $\{P_{t-k}\}_{k=1}^{K}$, denoted by $\bar{Q}\left(\{P_{t-k}\}_{k=1}^{K}\right)$. Let $P\left(\{P_{t-k}\}_{k=1}^{K}\right)$ be the associated prices. Recall that we fix $\tilde{X}_t$ and c_t at the level of 1998. Compared to the myopic optimal quantity (not taking into account the fringe's reaction), the optimal price will be lower since the higher price will enhance the future entry of the Chinese firms.

In addition, since $\{P_{t-k}\}_{k=1}^{K}$ affects the fringe supply, the natural counterpart of the static Nash equilibrium is a Markov perfect equilibrium with state $\{P_{t-k}\}_{k=1}^{K}$. We show in Appendix A that there exists a linear Markov perfect equilibrium, where each firm i produces $q_i\left(\{P_{t-k}\}_{k=1}^{K}\right)$ given the state $\{P_{t-k}\}_{k=1}^{K}$.

Suppose that the firms interact without cartels for a while, and they reach the stationary quantity and price of the Markov perfect equilibrium $\bar{P}$. Then, given the state $P_{t-k} = \bar{P}$

[28] Here we did not allow the Chinese firms to join the cartel, because even in the UKCC's report written in 2001, the incumbent firms in Europe and Japan characterized them as aggressive and untamable fringe.

for each k, we calculate the sequence of cartel quantities and prices, $Q_t = \bar{Q}\left(\bar{P}, ..., \bar{P}\right)$, $P_t = P\left(\bar{P}, ..., \bar{P}\right)$, $Q_{t+1} = \bar{Q}\left(\bar{P}, ..., \bar{P}, P_t\right)$, $\bar{P}_{t+1} = P\left(\bar{P}, ..., \bar{P}, P_t\right)$, $Q_{t+2} = \bar{Q}\left(\bar{P}, ..., \bar{P}, P_t, P_{t+1}\right)$, $\bar{P}_{t+2} = P\left(\bar{P}, ..., \bar{P}, P_t, P_{t+1}\right)$, and so on.

Suppose firm i obtains the market share α_i. Then its on-path profit is $(P_t - c_i)\,\alpha Q_t$, $(P_{t+1} - c_i)\,\alpha Q_{t+1}$, and so on. On the other hand, the optimal deviation in period t' is calculated as follows: given on-path price $\{P_{t'-k}\}_{k=1}^{K}$, the other firms will produce the quantity according to $(1-\alpha)\,\bar{Q}\left(\{P_{\tilde{t}-k}\}_{k=1}^{K}\right)$ for next L periods $\tilde{t} = t', ..., t'+L-1$, and then will switch to the Markov perfect equilibrium $q_i\left(\{P_{\tilde{t}-k}\}_{k=1}^{K}\right)$ from $\tilde{t} \geq t'+L$. Taking into account the effect of deviations in future variables through $\{P_{\tilde{t}-k}\}_{k=1}^{K}$, we calculate firm i's largest deviation gain.

Since "the value under cooperation minus that under deviation" is increasing in α_i, for each firm i, there exists a lower bound $\underline{\alpha}_i$ of the share such that, if and only if firm i's share is no less than $\underline{\alpha}_i$, firm i's incentive is satisfied for all t.

We solve for $\underline{\alpha}_i$ for each firm i, and then add them up: $\sum_i \underline{\alpha}_i$. Since we have $\sum_i \underline{\alpha}_i > 1$ for each $\beta \leq .9$, it is impossible to find the share to satisfy all the firms' incentive compatibility constraint. Therefore, the renegotiaton is impossible.

5.4.2 Differentiated-product Demand and Bertrand Competition

Virtually all government reports and court documents characterize bulk vitamins as commodity chemical goods with little room for product differentiation (UKCC 2001, Bernheim 2002, EC 2003). The vitamin cartels employed simple quotas and uniform target prices across firms, which are also consistent with the homogeneous nature of goods. Nevertheless, the vitamin producers have headquarters, marketing offices, and manufacturing plants in different countries, employ different sales personnel, and offer slightly different after-services, all of which could theoretically be considered as a source of differentiation.

Fortunately, Bernheim (2002) contains firm-level prices for certain products, which help us identify a standard model of differentiated-product demand system. The estimation results are broadly consistent with those in our baseline model. Specifically, our alternative marginal-cost estimates from the Bertrand FOCs show patterns that are similar to our Cournot-based estimates in Figure 3 (Panel D). See Appendix for further details.

5.4.3 Adaptive Expectations on Future Demand

In section 5.3 we assumed rational expectations for the firms' forecast of future demand. This assumption is consistent with the court documents and other reports, in which the cartel firms and industry experts shared a view that the vitamin demand was growing with a secular trend over a relatively long time horizon such as a decade. Nevertheless, we can still ask what our model would predict if firms adjusted their views based on their recent observations.

We conducted a series of sensitivity analyses with multiple different specifications in the spirit of adaptive expectations but obtained quantitatively similar outcomes on the predicted timing of the cartel's breakup. In fact, as we make the firms' demand forecast more sensitive to their contemporaneous observations, our model's prediction moves closer to the historical timing of the collapse in August 1995. Moreover, the prediction becomes less sensitive to the calibrated level of discount factor, β. Thus the alternative assumption of adaptive expectations would make our model's prediction more accurate in terms of timing and more robust with respect to β. See Appendix for further details.

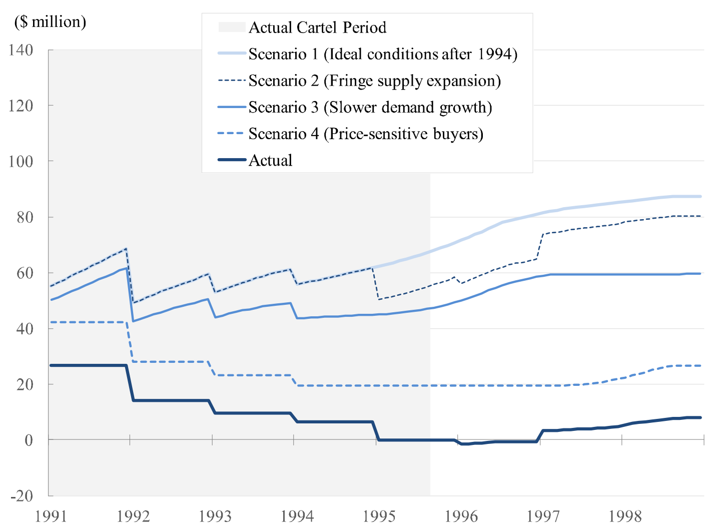
6 Counterfactual Simulations

Having estimated demand, supply, and the dynamic incentive to collude, we are now ready to answer our main, substantive questions. Section 6.1 explains the causes of the vitamin C cartel's collapse in 1995 by quantifying the effects of demand and supply factors. Section 6.2 evaluates the impact of a hypothetical merger on the incentive to collude (i.e., its "coordinated effects").

6.1 Who Killed the Cartel?

Why did the vitamin C cartel collapse so much earlier than those in the markets for vitamin A, vitamin E, and beta carotene? The latter three cartels were busted by the criminal investigation in 1999 and therefore experienced "unnatural" deaths due to exogenous reasons. The vitamin C cartel, by contrast, collapsed in 1995, independently of the antitrust enforcement. Its members quoted the rapid expansion of fringe players in China as the main reason (UKCC 2001, Bernheim 2002, EC 2003), but records suggest some confusions among the market participants regarding the exact mechanism through which the prices fell and the cartel collapsed. For example, UKCC (2001) reports that "BASF, and some other producers, told us that the reason for the breakdown of the cartels was emerging competitive pressure and the desire of certain companies to respond aggressively to these rather than surrender market share (. . .) However, a premixer, Trouw, said that it thought the breakup of the cartel was itself the major cause of the subsequent decline in vitamin prices rather than the entry of the Chinese" (p. 66). Moreover, BASF suggested "part of the fall in prices accounted for changes in market conditions" (p. 101) other than the Chinese entry or the cartel's collapse. Thus the government investigators faced a classical "chicken-or-egg-first" inference problem in which market prices were determined simultaneously by the economic fundamentals including demand shocks, fringe supply, and the endogenous breakdown of the cartel. Fortunately, this is exactly the kind of problem that our structural model can disentangle through comparative static analyses (or more precisely, comparative dynamics, because the entire time paths affect the collusion incentives).

Figure 7: Effects of Demand and Supply on Roche's Incentive to Collude



Three suspects emerge from our reading of the antitrust investigations as well as our data and estimates in the previous sections. First, the entry and rapid expansion of the Chinese fringe producers represent an obvious competitive pressure (Panel A of Figure 6). Second, our demand estimates suggest the demand shifter experienced a few years of slow or negative growth after 1994 (Panel C of Figure 6). Third, the price coefficient of demand is a more subtle but potentially important factor because it directly affects the extent to which the cartel can raise price profitably. Our estimates show an increasing time trend of $\frac{\partial P}{\partial Q}_t$ (Panel B of Figure 6), which implies the buyers became increasingly more price-sensitive over time. To isolate the impact of each factor on the incentive to collude, we conduct three comparative dynamic analyses corresponding to the three determinants and a fourth one that incorporates all of them.

Figure 7 summarizes the evolutions of Roche's incentive to collude under the actual market conditions (i.e., fringe supply expansion, demand growth slowdown, and increasingly price-sensitive buyers), along with four counterfactual scenarios. We show results based on $\beta = 0.7$ because it breaks the incentive compatibility constraint in 1995 (with $\phi = 0$) and therefore matches the actual timing of the cartel's breakup, but other levels of β do not alter the overall patterns. Scenario 1 is the polar opposite of the actual case and represents an ideal development for the cartel, in which Chinese exports had stopped growing after 1994, the demand shifter had remained at the high level of 1994, and $\frac{\partial P}{\partial Q}_t$ had stopped deteriorating from its 1994 level. We allow the firms to rationally expect such favorable conditions.[29] Not surprisingly, Roche's incentive to collude would have been considerably higher and the cartel could have survived at least until the antitrust investigation in 1999.

We use Scenario 1 as an idealistic benchmark (from the cartel's perspective) and compare other, less rosy scenarios against it. Scenario 2 modifies Scenario 1 by incorporating the actual expansion of fringe supply from China after 1994, which lowers Roche's incentive by 18% as of August 1995. This is an economically important impact but far from busting the cartel by its own weight alone. Scenarios 3 and 4 alter Scenario 1 by using the actual (i.e., deteriorating) time paths of $\tilde{X}_t$ and $\frac{\partial P}{\partial Q}_t$ after 1994, and lead to 30% and 71% declines in Roche's incentive, respectively. Again, neither of them alone could break the cartel, but the effects of these demand-side factors appear quantitatively at least as important as the Chinese entry. This is a surprising result in consideration of the cartel members' statements on record that largely attributed the collapse of the cartel to the Chinese export. China was probably the most conspicuous factor that everyone could point their fingers at. In our view, China was an important factor but not the only one; its *interaction* with the demand-side factors turned out to be a powerful combination that busted the cartel.

6.2 Merger Helps Collusion

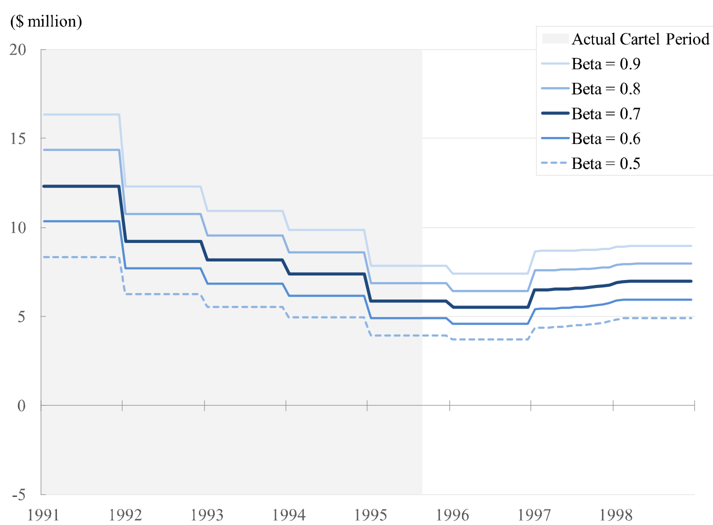
In 2001, Takeda sold almost all of its vitamin businesses to BASF, including vitamin C, and the antitrust authorities across the globe eventually approved this transaction. Mergers affect competition through two channels, "unilateral" and "coordinated" effects. The former refers to the changes in market outcomes due to the changes in observed market structure (including ownership patterns, product portfolios, and costs, but excluding potential changes in the degree of collusion), whereas the latter refers to the effect of the reduced number of players on the probability and the extent of potential collusion. The former has been studied

[29] Regarding fringe supply, we maintain the specification of static expectations as in the baseline model to ensure comparability. When we fix fringe output at its 1994 level, static expectations turn out to be correct and coincides with rational expectations.

extensively in the literature, but the latter has not, because of the covert and illegal nature of collusions and the methodological difficulty of measuring the incentives to collude.[30] Our model and empirical context makes such an analysis feasible.

Does a merger significantly increase the incentive to collude? More specifically, would a merger have prolonged the life of the vitamin C cartel? We answer these questions by simulating an earlier merger between Takeda and BASF, the second and the fourth largest producers, before 1991. This merger scenario has a historical basis in its actual consummation in 2001. In particular, the UK Competition Commission closely investigated the deal and published a 190-page report entitled "BASF AG and Takeda Chemical Industries Ltd: A report on the acquisition by BASF AG of certain assets of Takeda Chemical Industries Ltd" (2001). The only departure from reality in our simulation is that we hypothetically assume the BASF-Takeda merger had materialized by 1991, a decade earlier than in reality, and calculate the counterfactual incentive compatibility conditions, thereby simulating the vitamin C cartel under a three-firm oligopoly instead of four.

Figure 8: If BASF Had Acquired Takeda's Vitamin C Business by 1991



We rely on the details that the UKCC (2001) disclosed, and specify the BASF-Takeda merger as follows. Although BASF was a major supplier in many vitamin markets, its presence in the vitamin C market was the smallest of the four cartel members. Moreover, Takeda had a clear advantage over BASF in production technology and cost-competitiveness.

[30] Exceptions include Selten's (1973) theoretical analysis of symmetric Cournot oligopolists, and Miller and Weinberg's (2015) empirical account of tacit collusion among beer manufacturers after a recent merger.

For these reasons, BASF quietly phased out production at its own vitamin C facilities after the merger, and retained or reinforced the more efficient facilities it acquired from Takeda. We capture this aspect of the transaction by (i) modeling the merged entity (call it "BASF-Takeda") to inherit Takeda's superior cost structure rather than BASF's and (ii) eliminating what used to be BASF's vitamin C business from the market. Thus this merger simply amounts to the exit of pre-merger BASF as an independent producer.

Such a merger to kill competition and scrap old assets might appear crude and extreme, but this paper is studying mature, commodity chemical markets with little room for technological "synergies." Although BASF carefully chooses its words to avoid any impression of reducing competition, restricting outputs, or raising prices, what BASF euphemistically calls "an alternative capacity swap involving the purchase of Takeda's assets" (UKCC 2001, p. 111) clearly involves the retirement and withdrawal of its own existing facilities. Thus consolidation and rationalization appear to be the main characteristics of this horizontal merger.

How should we design the cartel's quota scheme in this counterfactual simulation? The actual cartel used pre-cartel market shares under oligopolistic competition as a basis for the quota agreement. In the same spirit, we can calculate hypothetical market shares in 1990 under the assumption that Roche, Merck, and BASF-Takeda play the Cournot game of our model, and use their market shares in static Nash equilibrium to determine the counterfactual quotas. The rest of the model remains the same as in our baseline model, including the demand function, the fringe supply, and the informational assumptions.

The results in Figure 8 suggest Roche's incentive compatibility constraint would have been satisfied throughout the sample period for all plausible levels of discount factor, β. The merger eliminates the fourth player and helps create a triopoly, thereby increasing each firm's quota and relaxing their constraints. Thus merger helps collusion and we may quantify its extent. At $\beta = 0.7$, for example, the merger improves Roche's $\Delta \underline{V}_{roche,t}$ by approximately \$5.8 million per month (or \$70 million per year) as of August 1995, which would have helped the cartel avoid a breakup.[31]

[31] Given that our study focuses on cartels, or *explicit* collusion, we interpret our estimates of the coordinated effects as a lower bound. If we consider *tacit* collusion, we suspect a merger could help eliminate other intangible costs of coordination as well.

7 Conclusion

This paper aims to explain why some cartels collapse and others survive, by estimating an empirical model of endogenous cartel breakdown. Normally, repeated games and collusion are difficult to identify from observational data, but the global vitamins cartel case provide us with direct evidence on the internal working of the quota scheme as well as its member firms' expectations about market conditions and potential punishment. Our analysis of the vitamin C market suggests the interaction between increasing fringe supply and unfavorable developments on the demand side caused the cartel to collapse long time before the antitrust enforcement. An earlier consummation of the BASF-Takeda merger could have helped prolong the life of the vitamin C cartel by relaxing the quota allocation and hence the incentive compatibility constraints. Thus we demonstrate the possibility of measuring the incentive to collude and quantifying its structural determinants. Future research could potentially expand such an analysis to more complicated theoretical settings such as private monitoring and tacit collusion, which would be challenging but not impossible if suitable empirical contexts are found.

Appendix

A. Endogenous Fringe Supply and Renegotiation

Model

The model is the same as in section 2 except that players rationally expect that the fringe supply depends on past prices linearly:

$$Q_{fri,t} = Q_{fri}\left(P_{t-1}, ..., P_{t-K}\right) = \alpha_{fri} + \sum_{k=1}^{K} \beta_{fri,k} P_{t-k}.$$

We assume that the demand shifter is fixed at $\tilde{X}_t = x$ and $\frac{\partial P}{\partial Q} = \psi$, and so the inverse demand function for the total output by the players, $Q = \sum_{i \in I} Q_i$, is

$$P = -\psi \times \left(x - Q_{fri}\right) + \psi \times Q, \text{ or } Q = x - Q_{fri} + \frac{P}{\psi}. \tag{9}$$

We also assume that the marginal cost is constant $c_{i,t} = c_i$ for each $i \in I$.

Optimal Cartel Supply

We first derive the optimal cartel supply, where the players jointly maximize the cartel profit (assuming that $c_i = c$ for each i; in the cartel decision making, Roche is the leader, and so we assume that the cartels target the total quantity, as if each firm has the marginal cost equal to Roche's).

Since the environment is stationary, the state variable for calculating the optimal cartel profit is $(P_{-k})_{k=1}^{K}$, where P_{-k} is the price k periods before. In particular, the value function $V((P_{-k})_{k=1}^{K})$ satisfies that the cartel picks Q (given (9), equivalent to picking P) to maximize

$$V\left(P_{-1:-K}\right) = \max_{P}\left(P - c\right)\left[x - Q_{fri} + \frac{P}{\psi}\right] + \delta V\left(P, P_{-1:-K+1}\right), \tag{10}$$

where $P_{-l:-k} = (P_{-l}, P_{-l-1}, ..., P_{-k})$. Note that Q_{fri} depends on $(P_{-k})_{k=1}^{K}$. The first order condition is

$$x - Q_{fri} + \frac{2P - c}{dpdq} + \delta V_1\left(P, P_{-1:-K+1}\right) = 0,$$

where V_k is the derivative of the kth argument. By the envelope theorem, we have

$$V_k\left(P_{-1:-K}\right) = -\left(P-c\right)\beta_{fri,k} + \delta V_k\left(P, P_{-1:-K+1}\right)$$

and so

$$V_k\left(P_{+k-1:+1}, P, P_{-1:-K+k}\right) = -\left(P_{+k}-c\right)\beta_{fri,k} + \delta V_{k+1}\left(P_{+k:+1}, P, P_{-1:-K+k+1}\right),$$

where P_{+k} means the price k periods after. Hence we have

$$\delta V_1\left(P, P_{-1:-K+1}\right) = -\sum_{k=1}^{K}\delta^k\left(P_{+k}-c\right)\beta_{fri,k}. \tag{11}$$

Given (11), the first order condition can be written as

$$x - Q_{fri} + \frac{2P-c}{\psi} - \sum_{k=1}^{K}\delta^k\left(P_{+k}-c\right)\beta_{fri,k} = 0,$$

or

$$P = \frac{|\psi|\left(x - \alpha_{fri} - \sum_{k=1}^{K}\beta_{fri,k}P_{-k}\right) - |\psi|\sum_{k=1}^{K}\delta^k\left(P_{+k}-c\right)\beta_{fri,k} + c}{2}. \tag{12}$$

We prove that there is a linear optimal solution:

Lemma 1 *There exists a linear solution for (10):* $P = \alpha_{cartel} + \sum_{k=1}^{K}\beta_{cartel,k}P_{-k}$.

Proof. With discounting, it suffices to guess that the solution takes the form

$$\alpha_{cartel} + \sum_{k=1}^{K}\beta_{cartel,k}P_{-k} \tag{13}$$

and verify it. Given the guess, repeatedly substituting (13), we have

$$P_{+k} = \alpha_{cartel}\left(1 + \sum_{l=1}^{k}\beta_{cartel,l}\sum_{m=1}^{l}\left(\beta_{cartel,1}\right)^{m-1}\right) + \sum_{l=0}^{k}\left(\left(\sum_{m=1}^{k-l}\left(\beta_{cartal,m}\right)^{k-m}\right)\left(\sum_{n=1}^{K-l}\beta_{cartel,n+l}P_{-n}\right)\right)$$

with $\sum_{m=1}^{0}\left(\beta_{cartal,m}\right)^{k-m} \equiv 1$. Putting them back into the first order condition (12) and matching the coefficient give us the linear solution, and so the guess is verified. ■

MPE

Suppose there is no cartel. Then each firm would like to maximize its profit by changing q_i

$$P = -\psi \times (x - Q_{fri}) + \psi \times (Q_{-i} + q_i),$$

taking the other firm's output as given. In other words, rationally expecting that the other players produce Q_{-i}, firm i who wants to target the price P produces

$$q_i = x - Q_{fri} + \frac{P}{\psi} - Q_{-i}.$$

Lemma 2 *There exists a linear MPE: each firm i produces $q_i (P_{-1:-K}) = \alpha^i_{MPE} + \sum_{k=1}^K \beta_{MPE,k} P_{-k} + \gamma^i_{MPE} c_i$.*

Note that the reaction to the price, $\beta_{MPE,k}$, does not depend on the index of the player.
Proof. Suppose the other players follow an MPE, and so Q_{-i} is determined by $P_{-1:-K}$. Then the optimal cartel supply q_i given Q_{-i} is to maximize

$$V^{MPE,i} (P_{-1:-K}) = \max_P (P - c_i) \left[x - Q_{fri} + \frac{P}{\psi} - Q_{-i} \right] + \delta V^{MPE,i} (P, P_{-1:-K+1}).$$

We guess $q_i (P_{-1:-K}) = \alpha^i_{MPE} + \sum_{k=1}^K \beta_{MPE,k} P_{-k} + \gamma^i_{MPE} c_i$ for each i, and verify this strategy satisfies this value function.

The first order condition is

$$x - Q_{fri} - Q_{-i} + \frac{2P - c_i}{\psi} + \delta V_1^{MPE,i} (P, P_{-1:-K+1}) = 0.$$

By the envelope theorem, we have

$$\begin{aligned} V_k^{MPE,i} (P_{-1:-K}) &= (P - c_i) \left(-\beta_{fri,k} - \frac{dQ_{-i}}{dP_{-k}} \right) + V_{k+1}^{MPE,i} (P, P_{-1:-K+1}) \\ &= (P - c_i) \left(-\beta_{fri,k} - (N-1) \beta_{MPE,k} \right) + V_{k+1}^{MPE,i} (P, P_{-1:-K+1}) \end{aligned}$$

and so

$$\delta V_1^{MPE,i} (P, P_{-1:-K+1}) = -\sum_{k=1}^K \delta^k (P_{+k} - c_i) \left(\beta_{fri,k} + (N-1) \beta_{MPE,k} \right). \tag{14}$$

Hence the first order condition is equivalent to

$$P = \frac{|\psi|\left(x - Q_{fri} - Q_{-i}\right) + c_i - |\psi| \sum_{k=1}^{K} \delta^k \left(P_{+k} - c_i\right)\left(\beta_{fri,k} + (N-1)\,\beta_{MPE,k}\right)}{2}.$$

Adding them up with respect to i, we have

$$\begin{aligned} P &= \frac{|\psi|\left(x - Q_{fri} - \frac{N-1}{N}Q\right) + \bar{c}}{2} \\ &\quad - \frac{|\psi|}{2} \sum_{i \in I} \sum_{k=1}^{K} \delta^k \left(P_{+k} - \bar{c}\right)\left(\beta_{fri,k} + (N-1)\,\beta_{MPE,k}\right) \end{aligned} \tag{15}$$

where $\bar{c} = \frac{1}{N}\sum_i c_i$ is the average marginal cost.

Substituting (15) into $Q = x - Q_{fri} - \frac{P}{|\psi|}$, we have

$$Q = \frac{N}{N+1}\left(x - Q_{fri}\right) - \frac{\sum_i c_i}{|\psi|\,(N+1)} + \frac{\sum_{n=1}^{k} \delta^n \left(NP_{+n} - \sum_i c_i\right)\left(\beta_{fri,n} + (N-1)\,\beta_{MPE,k}\right)}{N+1}. \tag{16}$$

and

$$P = |\psi|\left(x - Q_{fri} - Q\right).$$

The rest of the proof (matching the coefficient) is the same as Lemma 1, and so is omitted.

■

Optimal Deviation

Suppose that the on-path cartel agreement is determined by Lemma 1; and after a deviation is identified with lag L, then the players switch to the MPE specified by Lemma 2. For each past prices $(P_{-1:-k})$ (which determines fringe output Q_{fri} and cartel output Q_{cartel}), we can derive the optimal deviation by backward induction.

Suppose firm i has deviated $L-1$ periods ago, and so this is the last period before switching to MPE. Given that firm i has α_i share in the cartel agreement, we have

$$P = -\psi\left(x - Q_{fri}\right) + \psi\left(\alpha_{-i}Q_{cartel} + q_i\right)$$

with $\alpha_{-i} = 1 - \alpha_i$. In other words,

$$q_i = (x - Q_{fri}) + \frac{P}{\psi} - \alpha_{-i} Q_{cartel}.$$

The optimal cartel supply q_i given Q_{cartel} is to maximize

$$V^{i,L}(P_{-1:-K}) = \max_P (P - c_i) \left[x - Q_{fri} + \frac{P}{\psi} - \alpha_{-i} Q_{cartel} \right] + \delta V^{i,MPE}(P, P_{-1:-K+1}).$$

From (14), we know $V_1^{i,MPE}(P, P_{-1:-K+1})$. Hence the first order condition becomes

$$\begin{aligned} P &= \frac{|dpdq|(x - Q_{fri} - \alpha_{-i} Q_{cartel}) + c_i}{2} \\ &\quad - \frac{|\psi| \sum_{k=1}^{K} \delta^n (P_{+k} - c_i) \left(\beta_{fri,k} + (N-1) \beta_{MPE,k} \right)}{2}. \end{aligned} \tag{17}$$

Since we know the law of motion of $\{P_{+K:+1}\}$ from Lemma 2, we can solve P as a function of Q_{fri}, that is, a function of $P_{-1:-K}$.

Importantly, by the envelope theorem, we have

$$V_1^{i,L}(P_{-1:-K}) = (P - c_i) \left(-\beta_{1,fri} - \alpha_{-i} \frac{d}{dP_{-1}} Q_{cartel} \right) + \delta V_2^{i,MPE}(P, P_{-1:-K+1}). \tag{18}$$

Since $\frac{d}{dP_{-1}} Q_{cartel}$ and $V_2^{i,MPE}(P, P_{-1:-K+1})$ are known from Lemma 2, we know $V_1^{i,L}(P_{-1:-K})$.

In the previous period, firm i wants to maximize

$$V^{i,L-1}(P_{-1:-K}) = \max_P (P - c_i) \left[(x - Q_{fri}) + \frac{P}{\psi} - \alpha_{-i} Q_{cartel} \right] + \delta V^L(P, P_{-1:-K+1}).$$

By (18), we can solve for the optimal P as a function of Q_{fri}, Q_{cartel}, and $P_{-1:-K}$. Since the former two are functions of $P_{-1:-K}$, we can solve for the optimal P as a function of $P_{-1:-K}$. By backward induction, we solve for optimal deviation prices and quantities.

Possibility of Renegotiation

We consider the following counterfactual question: if the cartel members know the law of motion of Q_{fri}, then can they renegotiate and come up with shares $(\alpha_i)_{i \in I}$ with which each player's incentive is satisfied?

To answer this question, we first set $K = 2$ and estimate α_{fri}, $\beta_{fri,1}$, and $\beta_{fri,2}$. Then we verify that the MPE specified by Lemma 2 converges to the unique stationary price

P^{MPE}. Suppose the economy is settled in this stationary price. That is, the initial state is $P_{-1} = P_{-2} = P^{MPE}$.

Suppose the cartel calculates the path of $P, P_{+1}, ...$ and $Q, Q_{+1}, ...$ (we write P, Q as P_0, Q_0 for the notational convenience) from this initial state. For each market share $\alpha_i \in [0, 1]$ of firm i, we can calculate the on-path profit for firm i from each period $t \geq 0$ on.

Then, for each $t \geq 0$, given P_{t-1}, P_{t-2}, we can calculate the optimal deviation gain from the cartel from period t to period $t + L - 1$, given that the continuation play from period $t + L$ on is the MPE specified by Lemma 2. We say the incentive compatibility is satisfied if there is no $t \geq 0$ such that the value from the deviation is higher than the value from the cartel.

Since "the value from the deviation minus the value from the cartel" is decreasing in α_i, we can derive the lowest $\underline{\alpha}_i$ with which firm i's incentive is satisfied. Then we calculate $\sum_{i \in I} \underline{\alpha}_i$.

Given our data, for each $\delta \leq .9$, to maintain Roche's incentive, we have to give $\underline{\alpha}_i > .8$ to Roche (that is, with $\alpha_i = .8$, its incentive compatibility is violated). At the same time, to maintain Takeda's incentive, we have to given $\underline{\alpha}_i > .2$ to Takeda (that is, with $\alpha_i = .2$, its incentive compatibility is violated). These are incompatible. Hence, we conclude that, even if cartel members have perfect foresight of fringe supplies, the cartel renegotiation is impossible.

B. Differentiated-product Demand and Bertrand Competition

Consider a discrete-choice model of demand for differentiated products. Buyer i's utility from purchasing a unit of firm j's product is

$$u_{ij} = \alpha p_j + \xi_j + \varepsilon_{ij}, \tag{19}$$

where α is price coefficient, p_j and ξ_j are price and perceived quality of firm j's product, respectively, and ε_{ij} is buyer i's idiosyncratic taste for firm j's product, which we assume is iid type-1 extreme value. Firms $j = 1, 2, ..., J$ supply branded products, whereas competitive fringe ($j = 0$) collectively supplies unbranded products, the utility from which is normalized to $u_{i0} = \varepsilon_{i0}$. The Bertrand FOC implies

$$\alpha = \frac{-s_j}{(p_j - c_j)\, M\, (1 - s_j)\, s_j}, \tag{20}$$

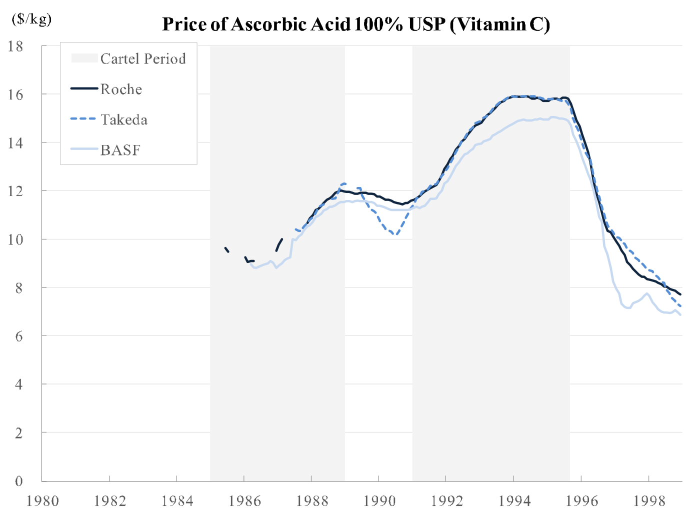
where s_j and c_j are market share and marginal cost of product j, respectively, and M is market size. Berry's (1994) inversion suggests

$$\xi_j = \ln\left(\frac{s_j}{s_0}\right) + \alpha p_j. \tag{21}$$

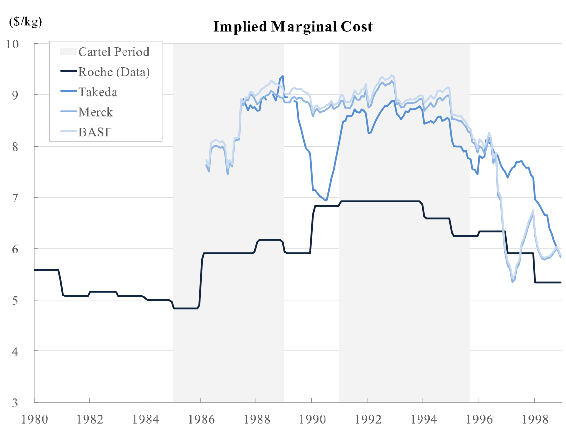
Following the identification strategy for our baseline model, we use Roche's cost data to recover α in (20), which in turn allows us to identify the other firms' c_j's. In addition, we use each firm's price data (Panel A of Figure 9) to recover ξ_j in (21). Panels B and C show such estimates of c_j and ξ_j. The main difference is that these two variables rationalize each firm's p_j and s_j in the data, whereas our baseline model with homogeneous goods and Cournot competition recovered c_j to rationalize q_j. Nevertheless, the alternative marginal-cost estimates exhibit broadly similar patterns with our baseline estimates in Figure 3 (Panel D). The differences between the three non-Roche firms' c_j are now less pronounced. Such heterogeneity among the non-Roche firms manifests itself in terms of unobserved quality or "brand" effects, ξ_j. Note that we normalized $\xi_0 = 0$, so that the branded products' ξ_j's are all expressed relative to the perceived quality of Chinese exports, which is the reason ξ_j's exhibit a declining trend in the mid 1990s when the fringe sales increased. Thus the differentiated-product version of estimates capture some additional nuances that were absent in our baseline estimates, but the overall results seem to agree with the latter mainly because prices in the data are quite similar across firms.

Figure 9: Differentiated-product Bertrand Estimates for Vitamin C

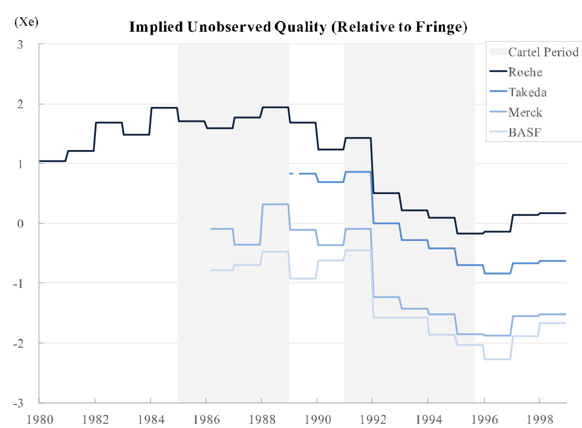
(A)



(B)



(C)



C. Adaptive Expectations on Future Demand

In section 5.3, we showed the estimates of Roche's incentive to collude under the assumption of rational expectations. We conducted a series of sensitivity analyses with multiple different specifications in the spirit of adaptive expectations but obtained quantitatively similar outcomes on the predicted timing of the cartel's breakup.

Figure 10: Roche's Incentive under Adaptive Expectations

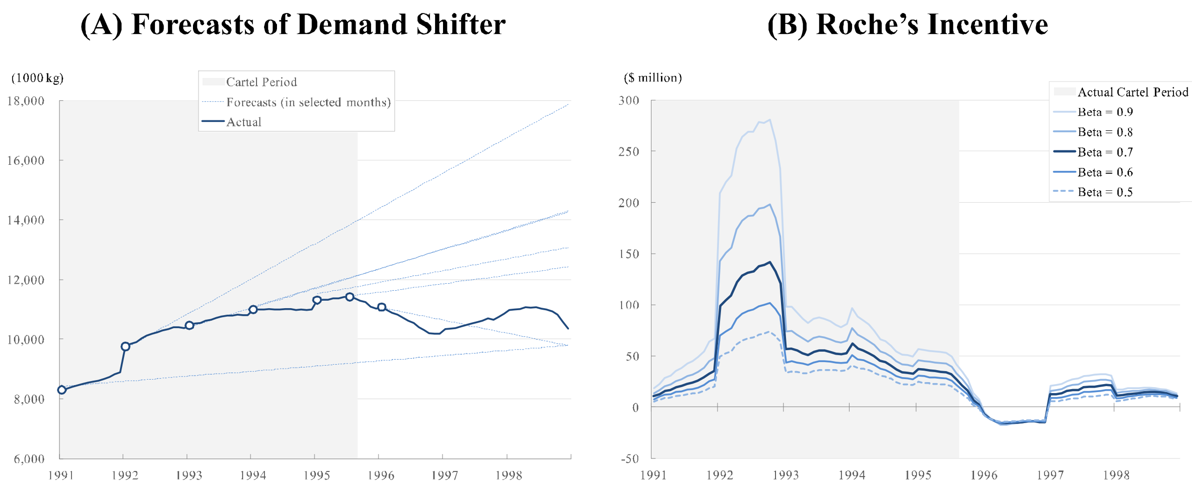


Figure 10 shows additional results under the adaptive expectations setting with one-year window (i.e., $K = 13$), which makes the firms' demand forecast highly sensitive to their contemporaneous observations. Our model's prediction moves closer to the historical timing of the collapse in August 1995. Moreover, the prediction becomes less sensitive to the calibrated level of discount factor, β. Thus the alternative assumption of adaptive expectations would make our model's prediction more accurate in terms of timing and more robust with respect to β.

The reason is that the demand $\left(\tilde{X}_t\right)$ stops growing and starts declining in the middle of 1995. Firms with rational expectations would correctly foresee the temporary nature of such a downturn and keep colluding for a while, but adaptive expectations (with reasonably short memories) would place higher weights on such declining trends and make the firms more pessimistic about the net gains from collusion, which breaks the incentive compatibility condition exactly at the time when the cartel collapsed in the data. This is the mechanism through which adaptive expectations make our results stronger and more precise. Despite such favorable results under adaptive expectations, however, we still prefer rational expectations as our baseline specification on the factual grounds. Historical evidence suggests the firms expected a secular growth trend with at least five to ten years of time horizons.

D. Additional Facts and Data

In section 1, we said the international vitamin cartels are among the largest antitrust cases in history. Table 2 ranks the top-10 antitrust cases in America by the amount of fine.

Table 2: Top-10 Sherman Act Violations and Corporate Fines

Rank	Product	Defendant	Country	Fiscal year	Geographic scope	Fine (million)
1	Vitamins	Roche	Switzerland	1999	International	\$500
1	LCD panels	AU Optronics	Taiwan	2012	International	\$500
3	Car parts	Yazaki	Japan	2012	International	\$470
4	Car parts	Bridgestone	Japan	2014	International	\$425
5	LCD panels	LG Display	Korea	2009	International	\$400
6	Air Transport	Air France & KLM	France & Netherlands	2008	International	\$350
7	Air Transport	Korean Air	Korea	2007	International	\$300
7	Air Transport	British Airways	UK	2007	International	\$300
7	DRAM	Samsung	Korea	2006	International	\$300
10	Vitamins	BASF	Germany	1999	International	\$225

Note: Ranking as of September 12, 2016. *Source*: U.S. Department of Justice, Antitrust Division.

In section 3.1, we discussed the production processes of vitamins. Table 3 lists raw materials and intermediates for each vitamin.

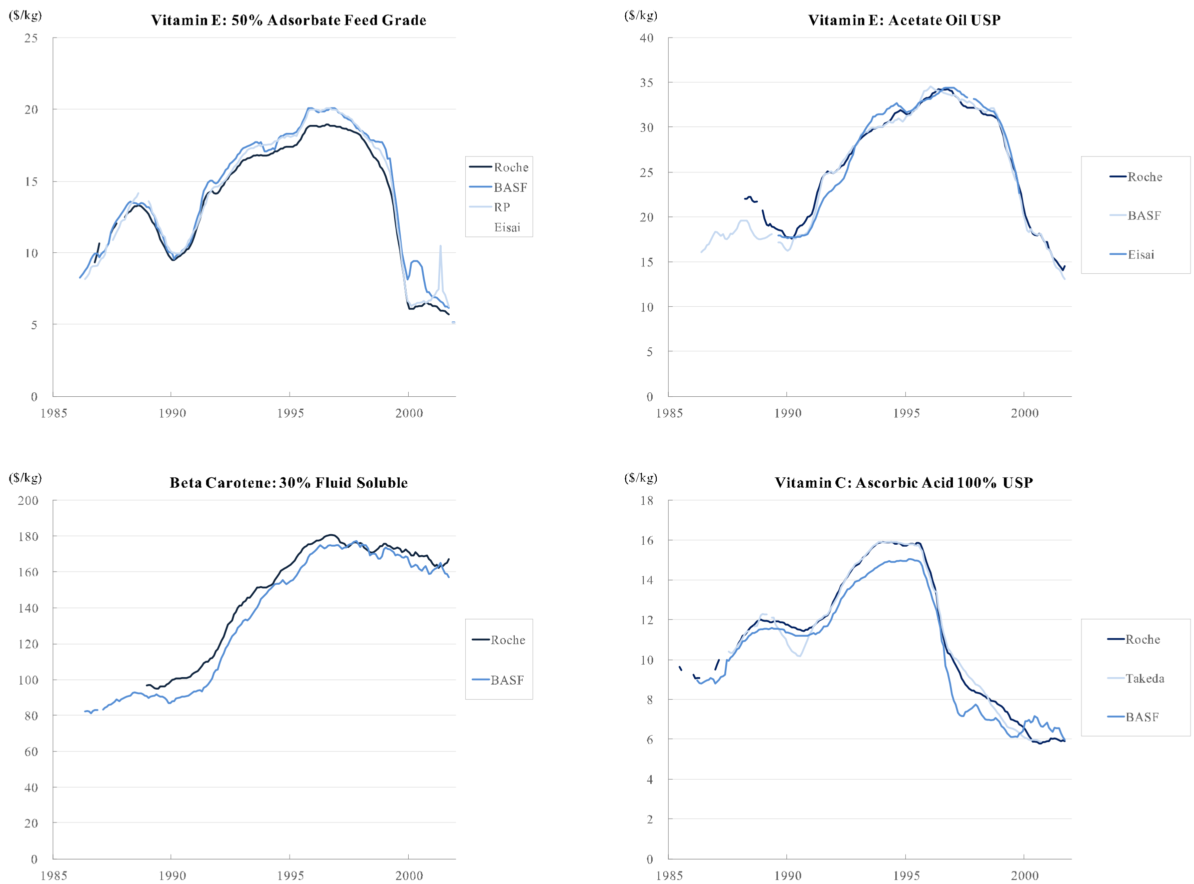
Table 3: Key Chemical Ingredients Required for Vitamin Synthesis

Vitamin	Intermediates	Raw Materials
A	Pseudoionone	Acetone, acetylene, isobutylene, butenediol, formaldahyde
B1	Grewe diamine	Ethylene, Prymidine, malononitrile, acronynitrile, carbon monoxide, cetamidine, butyroloctone, methyl acetate, hydrochloric acid, ammonia, carbon disulphate
B2, synthetic	Ribose	
B2, fermented		Sugars
B3	Methylglutaronitrile, beta picoline, 3-cryanopyridine, methylethylpyridine	Ethylene, nitric acid, farmaldyhyde, ammonia
B4	Trimethylamine	Hydrochloric acid, ethylene oxide
B5	Pantolactone, beta-alanine	Iso butryaldehyde, bydrogen yanide, hydrochloric acid, acrylonitrile, ammonia, caustic soda, calcium hydroxide
B6		Oxazole, dienophile
B9		Acetone or acrolein, chlorine gas, guanadine, cyanoethyl acetate, sodium ethoxide, nitric acid, hydrogen gas, glutamic acid, benzoic acid
B12, fermented		Sugars, nitrogen compounds
C	Sorbitol	Glucose
D3		Cholesterol
E, synthetic	Isophytol, trimethylhydroquinone	Acetone, acetylene, isobutylene, napha, formaldahyde
H	Thiolactone	Furnaric acid or diketene, cysteine, thiophene, phosgene gas
Beta carotene		Acetone, ocetyene, triphenylphosphine
Canthaxanthin	Beta carotene	15-carbon compounds
Astaxanthin	Canthaxanthin	15-carbon compounds

Source: Bernheim (2002), Connor (2007, 2008).

Also in section 3.1, we discussed the similarity of prices across firms and different grades. Figure 11 confirms this observation by showing firm-level prices of four specific vitamin products (Vitamin E 50% Adsorbate Feed Grad, Vitamin E Acetate Oil USP, Ascorbic Acid 100% USP, and Beta Carotene 30% Fluid Soluble), which are highly correlated and close to each other in levels.

Figure 11: Examples of Vitamin Prices by Firm and Grade



In section 3.2, we explained market segments. Table 4 summarizes relative market size by segment.

Table 4: Market Size by Segment (%)

Product	World 1987–98			U.S. 1990–98		
	Feed	Food	Pharma	Feed	Food	Pharma
A	87	6	7	85	7	8
B1	35	16	49	1	24	75
B2	75	8	17	18	31	51
B3	73	11	14	43	25	32
B4	100	0	0	100	0	0
B5	69	3	22	40	9	51
B6	42	8	49	1	14	85
B9	79	17	15	16	44	40
B12	58	2	40	30	3	67
C	8	50	42	1	66	33
D3	93	3	4	43	0	57
E	73	3	23	34	13	52
H	85	4	10	75	7	18
Beta carotene	8	64	28	10	47	44
Other carotenoids	92	7	1	23	77	1
Total	43	26	30	40	24	36

Source: Bernheim (2002), Connor (2007, 2008).

In section 3.3, we explained regional markets. Table 5 summarizes market size by region.

Table 5: Market Size by Region (Million U.S. $)

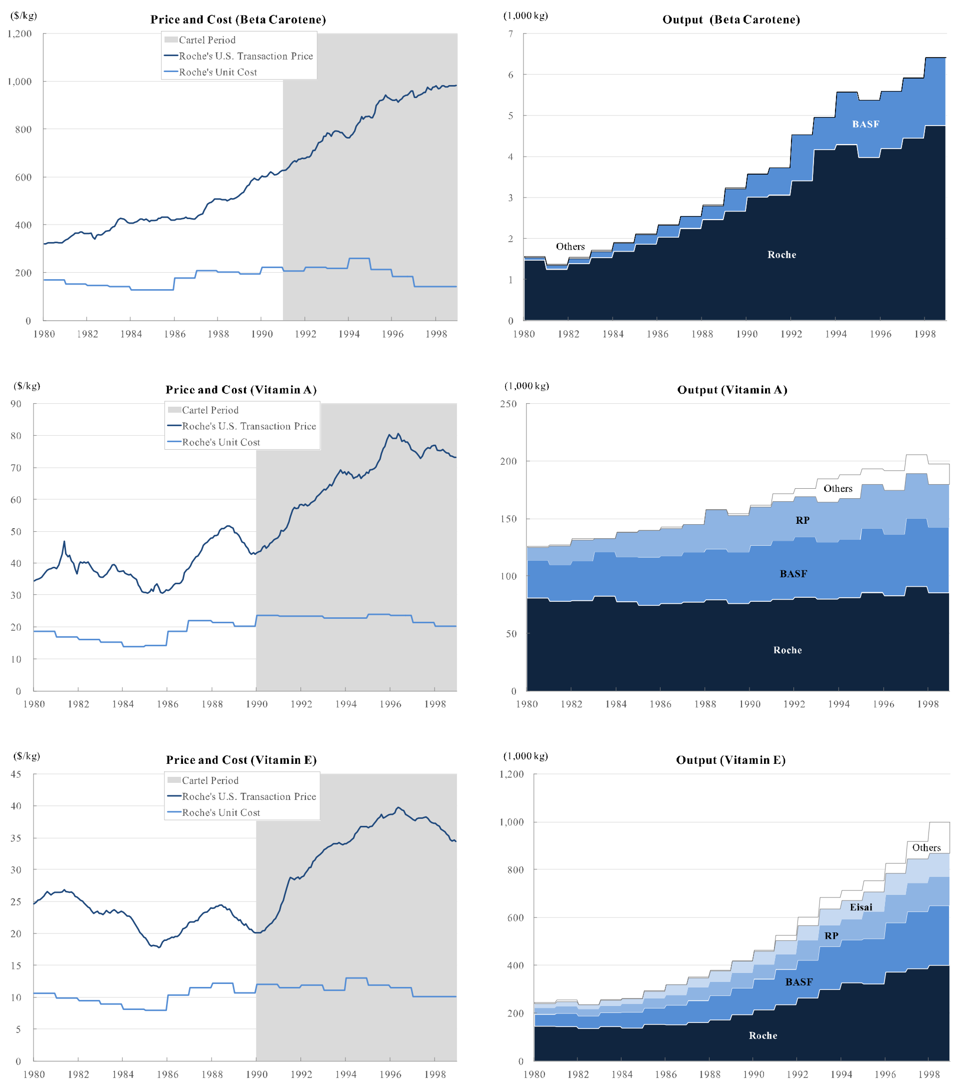
Product	United States	Canada	Western Europe	Restof theWorld	World Total
A	89.6	6.9	159.9	73.6	329.9
B1	14.3	1.8	29.1	22.6	68.0
B2	29.1	2.5	49.3	20.7	100.2
B3	35.6	1.9	33.3	33.9	104.7
B4	43.5	13.7	58.3	20.9	136.4
B5	22.4	1.7	37.6	8.4	70.1
B6	13.5	3.8	20.9	27.1	65.3
B9	3.3	0.6	5.7	1.3	10.9
B12	14.0	0.5	18.8	25.3	58.4
C	205.4	14.4	251.1	293.3	764.2
D3	7.8	0.5	10.7	7.1	26.1
E	180.0	13.0	229.2	87.1	509.3
H	30.3	2.0	26.9	41.8	101.1
Beta carotene	49.0	3.5	89.2	23.3	165.0
Other carotenoids	14.5	0.8	84.5	140.6	240.1
Premixes	291.4	19.3	375.0	355.2	1,040.9
Total	1,044.0	85.5	1,482.8	1,186.5	3,798.8

Source: Connor (2007, 2008).

E. Empirical Analysis of Markets for Beta Carotene, Vitamin A, and Vitamin E

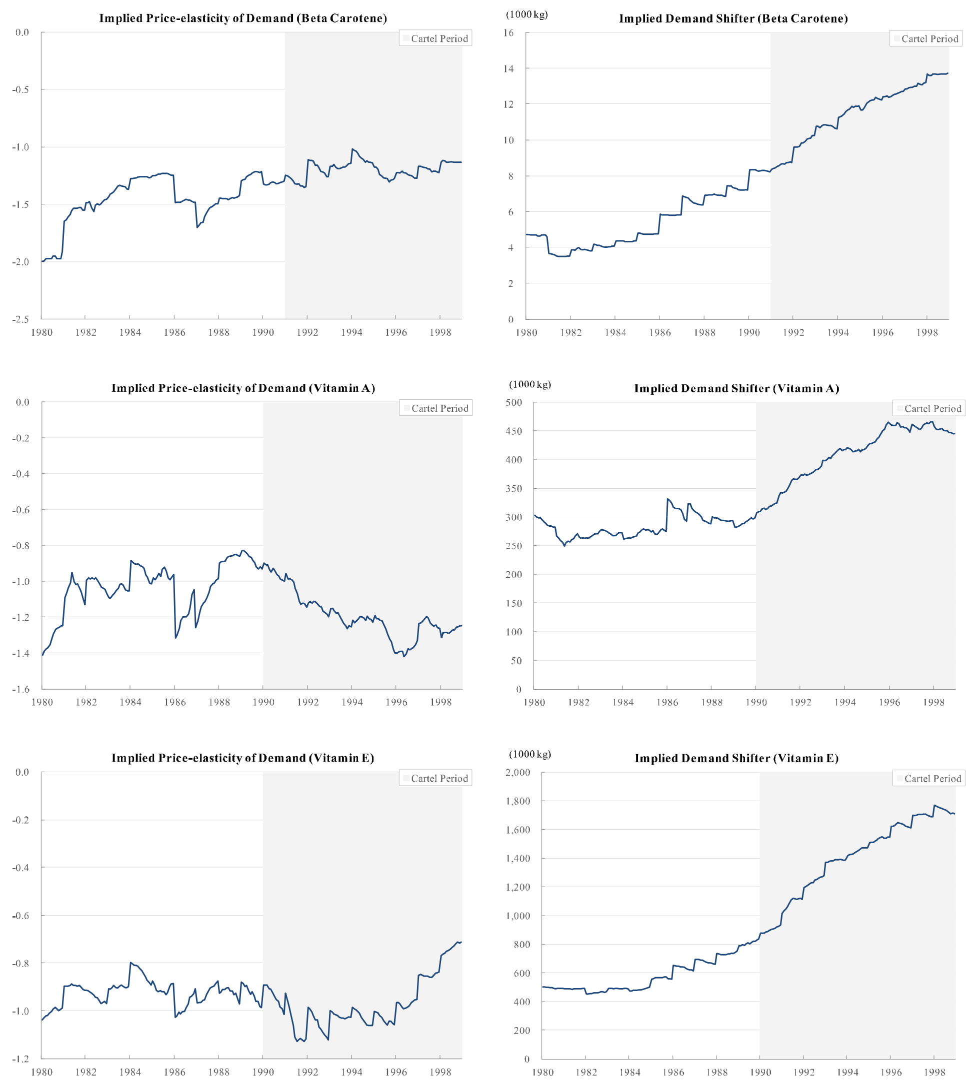
In section 4.2, we showed basic data patterns for the vitamin C market. Figure 12 is the corresponding data displays for beta carotene, vitamin A, and vitamin E.

Figure 12: Prices, Costs, and Quantity of Beta Carotene, Vitamin A, and Vitamin E



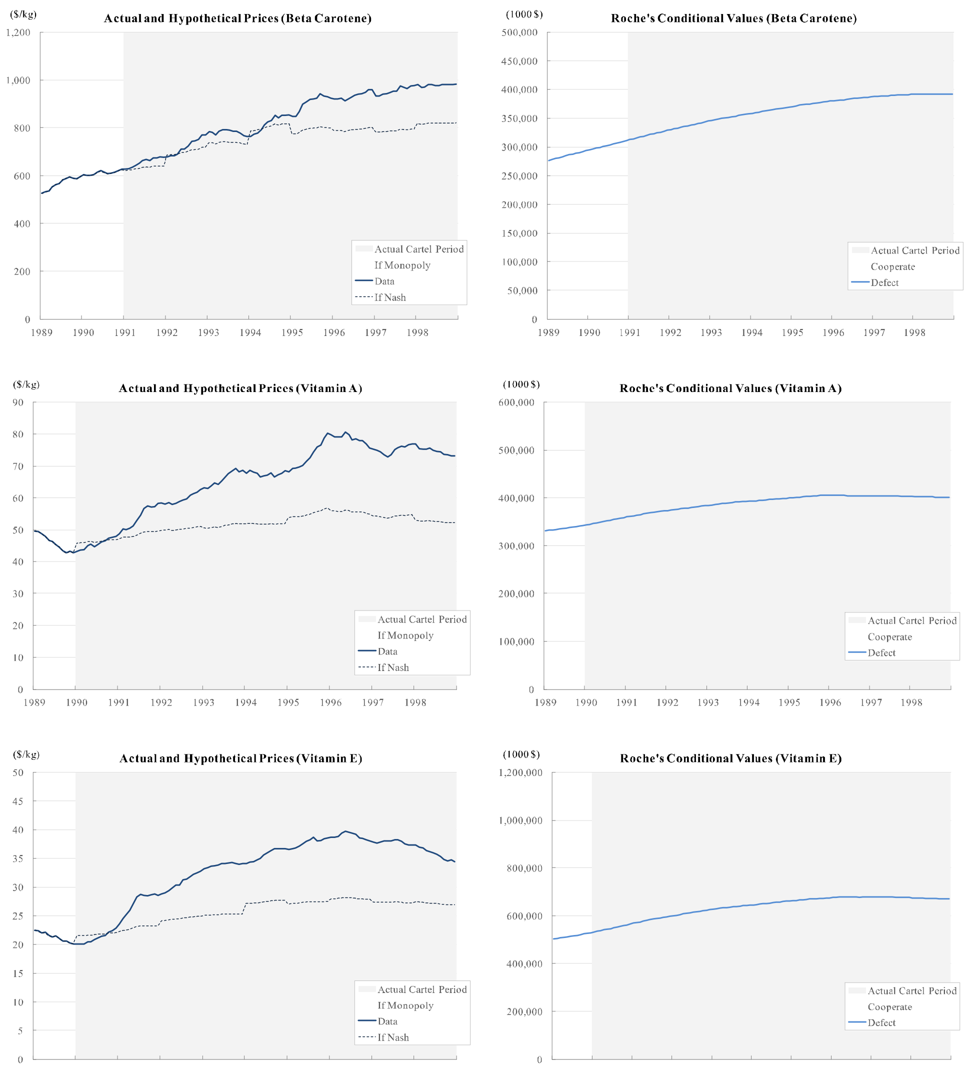
In section 5.1, we showed demand estimates for vitamin C. Figure 13 shows demand estimates for beta carotene, vitamin A, and vitamin E.

Figure 13: Demand Estimates for Beta Carotene, Vitamin A, and Vitamin E



In sections 5.2 and 5.3, we showed hypothetical prices and Roche's incentive to cooperate in the vitamin C market. Figure 14 summarizes the same analysis for beta carotene, vitamin A, and vitamin E.

Figure 14: Collusion Incentives for Beta Carotene, Vitamin A, and Vitamin E



References

[1] Abreu, D. (1986), "Extremal Equilibria of Oligopolistic Supergames," *Journal of Economic Theory*, 39, 191-225.

[2] Abreu, D., D. Pearce, and E. Stacchetti (1986), "Optimal Cartel Equilibria with Imperfect Monitoring," *Journal of Economic Theory*, 39, 251-269.

[3] Abreu, D., D. Pearce, and E. Stacchetti (1990), "Toward a Theory of Discounted Repeated Games with Imperfect Monitoring," *Econometrica*, 58, 1041-1063.

[4] Asker, John. 2010. "A Study of the Internal Organization of a Bidding Cartel." *American Economic Review*, 100 (3): 724–762.

[5] Athey, S. and K. Bagwell (2008), "Collusion with Persitent Cost Shocks," *Econometrica*, 76, 493-540.

[6] Bagwell, K. and R.W. Staiger (1997), "Collusion over the Business Cycle," *RAND Journal of Economics*, 28, 82-106.

[7] Bernheim, B. Douglas. 2002. "Expert Report of B. Douglas Bernheim," *In Re: Vitamins Antitrust Litigation*, MDL No. 1285, Misc 99-0197.

[8] Berry, Steven T. 1994. "Estimating discrete-choice models of product differentiation." *RAND Journal of Economics*, 25 (2): 242–262.

[9] Connor, John M. 2007. *Global Price Fixing*, second edition. Heidelberg: Springer.

[10] Connor, John M. 2008. "The Great Global Vitamins Conspiracies, 1985-1999." SSRN working paper.

[11] de Roos, Nicolas. 2001. "Collusion with a Competitive Fringe: An Application to Vitamin C." Manuscript, Yale University.

[12] de Roos, Nicolas. 2004. "A model of collusion timing." *International Journal of Industrial Organization*, 22: 351–387.

[13] de Roos, Nicolas. 2006. "Examining models of collusion: The market for lysine." *International Journal of Industrial Organization*, 24: 1083–1107.

[14] Ellison, Glenn. 1994. "Theories of cartel stability and the Joint Executive Committee." *RAND Journal of Economics*, 25 (1): 37–57.

[15] European Commission. 2003. "Case COMP/E-1/37.512 – Vitamins," *Official Journal of the European Communities.*

[16] Fershtman, Chaim, and Ariel Pakes. 2000. "A dynamic oligopoly with collusion and price wars." *RAND Journal of Economics*, 31 (2): 207–236.

[17] Fershtman, Chaim, and Ariel Pakes. 2012. "Dynamic Games with Asymmetric Information: A Framework for Empirical Work." *Quarterly Journal of Economics*, 1611–1661.

[18] Fuchs, W. (2007), "Contracting with Repeated Moral Hazard and Private Evaluations," *American Economic Review*, 97, 1432-48.

[19] Fudenberg, D., Y. Ishii, and S. D. Kominers (2014), "Delayed-Response Strategies in Repeated Games with Observation Lags," *Journal of Economic Theory*, 150, 487-514.

[20] Fudenberg, D., D. Levine, and E. Maskin (1994), "The Folk Theorem with Imperfect Public Information," *Econometrica*, 62, 997-1039.

[21] Fudenberg, D. and E. Maskin (1986), "The Folk Theorem in Repeated Games with Discounting or with Incomplete Information," *Econometrica*, 533-554.

[22] Green, Edward J., and Robert H. Porter. 1984. "Noncooperative Collusion under Imperfect Price Information." *Econometrica*, 52 (1): 87–100.

[23] Harrington, Joseph E. 2006. "How Do Cartels Operate?" *Foundations and Trends in Microeconomics*, 2 (1): 1–105.

[24] Harrington, J.E. and A. Skrzypacz (2007), "Collusion under Monitoring of Sales," *RAND Journal of Economics*, 38, 314-31.

[25] Harrington, Joseph E., and Andrzej Skrzypacz. 2011. "Private Monitoring and Communication in Cartels: Explaining Recent Collusive Practices." *American Economic Review*, 101: 1–25.

[26] Kandori, M. (2002), "Introduction to Repeated Games with Private Monitoring," *Journal of Economic Theory*, 102, 1-15.

[27] Kawai, Kei, and Jun Nakabayashi. 2015. "Detecting Large-Scale Collusion in Procurement Auctions." Manuscript, UC Berkeley.

[28] Kovacic, William E., Robert C. Marshall, Leslie M. Marx, and Steven P. Schulenberg. 2009. "Quantitative Analysis of Coordinated Effects." *Antitrust Law Journal*, 76: 397–430.

[29] Levenstein, Margaret, and Valerie Suslow. 2006. "What Determines Cartel Success?" Journal of Economic Literature, 44 (1): 43–95.

[30] Levenstein, Margaret, and Valerie Suslow. 2011. "Breaking Up Is Hard to Do: Determinants of Cartel Duration." Journal of Law and Economics, 54 (2): 455–492.

[31] Levenstein, Margaret, and Valerie Suslow. 2014. "Cartels and Collusion: Empirical Evidence." In Roger D. Blair and D. Daniel Sokol (eds.), The Oxford Handbook of International Antitrust Economics, vol. 2.

[32] Levin, J. (2003), "Relational Incentive Contracts," *American Economic Review*, 93, 835-57.

[33] Mailath, G.J. and L. Samuelson (2006), *Repeated Games and Reputations*, Oxford University Press: Oxford.

[34] Marshall, Robert C., and Leslie M. Marx. 2014. *The Economics of Collusion: Cartels and Bidding Rings*. Cambridge, Massachusetts: The MIT Press.

[35] Marshall, Robert C., Leslie M. Marx, and Matthew E. Raiff. 2008. "Cartel price announcements: The Vitamins industry." *International Journal of Industrial Organization*, 26: 762–802.

[36] Miller, Nathan H., and Matthew C. Weinberg. 2015. "Mergers Facilitate Tacit Collusion: Empirical Evidence from the U.S. Brewing Industry." Manuscript, Georgetown University.

[37] Porter, Robert H. 1983. "A study of cartel stability: the Joint Executive Committee, 1880–1886." *Bell Journal of Economics*, 301–314.

[38] Porter, Robert H., and J. Douglas Zona. 2008. "Collusion." *Antitrust Law Journal*, 2: 1069–1084.

[39] Rotemberg, J.J. and G. Saloner (1986), "A Supergame-Theoretic Model of Price Wars During Booms," *American Economic Review*, 76, 390-407.

[40] Selten, Reinhard. 1973. “A Simple Model of Imperfect Competition where 4 Are Few and 6 Are Many.” *International Journal of Game Theory*, 2 (1): 141–201.

[41] Stigler, George J. 1964. “A Theory of Oligopoly.” *Journal of Political Economy*, 72 (1): 44–61.

[42] The United Kingdom Competition Commission. 2001. *BASF and Takeda Chemical Industries Ltd: A Report on the Acquisition by BASF AG of Certain Assets of Takeda Chemical Industries Ltd.* London: UK Competition Commission.