

# Measuring the Incentive to Collude: The Vitamin Cartels, 1990–99

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Do mergers help or hinder collusion? This article studies the stability of the vitamin cartels in the 1990s and presents a repeated-games approach to quantify “coordinated effects” of a merger. We use data and direct evidence from American courts and European agencies to show the collusive incentive of the short-lived vitamin C cartel was likely to be negative when it actually collapsed in 1995, whereas the incentives of the long-lived cartels (vitamins A and E, and beta carotene) were unambiguously positive until the prosecution in 1999. Simulations suggest some mergers could have prolonged the vitamin C cartel, but others could have further destabilized it, because both the direction and magnitude of coordinated effects depend not only on the number of firms but also on their cost asymmetry.

*Key words:* Antitrust, Cartel, Collusion, Coordinated effect, Merger, Repeated game.

*JEL Codes:* D43, L13, L41.

## 1. INTRODUCTION

One of the most fundamental ideas of repeated-game theory is that cooperation is sustainable if and only if it is self-enforcing or incentive compatible. That is, the long-term gains from cooperation must be greater than the short-term gains from cheating on it. Theory provides a “checklist” of relevant factors that affect the sustainability of collusion, including the number of competitors, the degree of symmetry among them, demand growth, and fringe supply. However, predicting the likelihood of collusion on this basis alone would be difficult, because a given market will have some characteristics that facilitate collusion and others that hinder collusion.<sup>1</sup> In particular, a merger poses a practical challenge because it affects many of these factors at the same time (*e.g.*

1. Ivaldi et al. (2003) summarize the theoretical “checklist.” Their report to the European Commission (EC) explains why mergers’ effects on collusion are ambiguous, and advocate for a structural analysis to quantify the effects of these factors. Levenstein and Suslow (2006) and Harrington (2006) summarize stylized facts.

reducing the number of firms may facilitate collusion, but a merger can also make the remaining firms more asymmetric, which would hinder collusion), which makes its impact theoretically ambiguous.<sup>2</sup> For these reasons, both academics and practitioners have recognized the need for a quantitative analysis of “coordinated effects” (*i.e.* the effects of mergers on the possibility and durability of collusion) based on a structural model and prospective merger simulations.<sup>3</sup>

This article presents a structural analysis of coordinated effects with a concrete example of the vitamin cartels in the 1990s, which are one of the largest antitrust cases in history.<sup>4</sup> We quantify the cartel firms’ incentives to collude in a model of collusion by using data and direct evidence from American courts and European agencies. In the theory of collusion, a collusive agreement is enforceable (incentive compatible) when the short-run gains from cheating are less than the discounted value of the forgone future profits obtained from adhering to the agreement.<sup>5</sup> The measurement of collusive incentives allows us to assess the empirical relevance of this theory more directly than in the existing research. Moreover, the econometric estimates help us disentangle various factors that affect the sustainability of collusion, and address an important policy question: will a merger create a situation in which collusion is significantly easier to sustain? Our results suggest the combination of a simple model and “typical” data that are available to antitrust agencies can both (1) explain what happened to the vitamin cartels and (2) provide an analytical tool to predict coordinated effects of mergers.

The vitamins case is like a laboratory of cartel stability. Roche, a Swiss drug company, cooperated with 20 other vitamin makers around the world and cartelized 16 different product categories at the beginning of the 1990s. Some cartels collapsed internally in 1994 or 1995 (*e.g.* vitamin C) allegedly because of a slowdown of demand growth and a sudden expansion of fringe supply; others survived until prosecution in 1999 (*e.g.* vitamins A and E, and beta carotene). Figure 1 summarizes the price trends in the four largest categories.

Evidence from American courts and European agencies suggests each cartel used a quota agreement (based on percentage shares of the global market on a tonnage basis in the pre-cartel period). They met every three months to verify each other’s self-reported sales quantity by checking government statistics on imports and exports. Their communication record indicates they shared an understanding that the violation of the quota would terminate the agreement and bring back competitive prices for the foreseeable future. They seemed successful in predicting the steady growth of world demand, but failed to predict a sudden expansion of fringe supply in some categories (*e.g.* vitamin C).

Based on this documented evidence, we characterize the spot market of each vitamin as a quantity game, and use quantitative information in Bernheim (2002a) to estimate its key parameters, in the four markets for which the data quality is the highest: vitamins A, C, and E, and beta carotene. Following the details in the European Commission’s report (EC, 2003), we model the cartel agreement as a quota system to maximize the collective profits (given the

2. Compte et al. (2002) and Vasconcelos (2005) study these theoretical relationships.

3. Merger simulations to assess coordinated effects have been proposed by economists at the UK Competition Commission (Davis and Huse, 2010) and the Italian Competition Authority (Sabbatini, 2006), as well as Kovacic et al. (2009) in the American context.

4. See <https://www.justice.gov/atr/sherman-act-violations-yielding-corporate-fine-10-million-or-more>.

5. A formal definition is provided in inequalities 13 and 14 in Section 5.1. The literature refers to this condition as “enforcement constraint” or “incentive compatibility constraint (ICC).” For example, see Porter (2020) for an introduction and a review, in which he uses these terms interchangeably. Outside this literature, however, they are used with different meanings in a variety of contexts (*e.g.* “enforcement” also refers to law enforcement in antitrust, and the exact content of ICCs depends on application topics). Consequently, we have chosen to stick with “incentive to collude” or “collusive incentives” to avoid confusion to readers familiar with the terminology in other fields. When we have to refer to the inequality constraint 13 or 14, we call it “enforcement/incentive constraint” to minimize ambiguity.

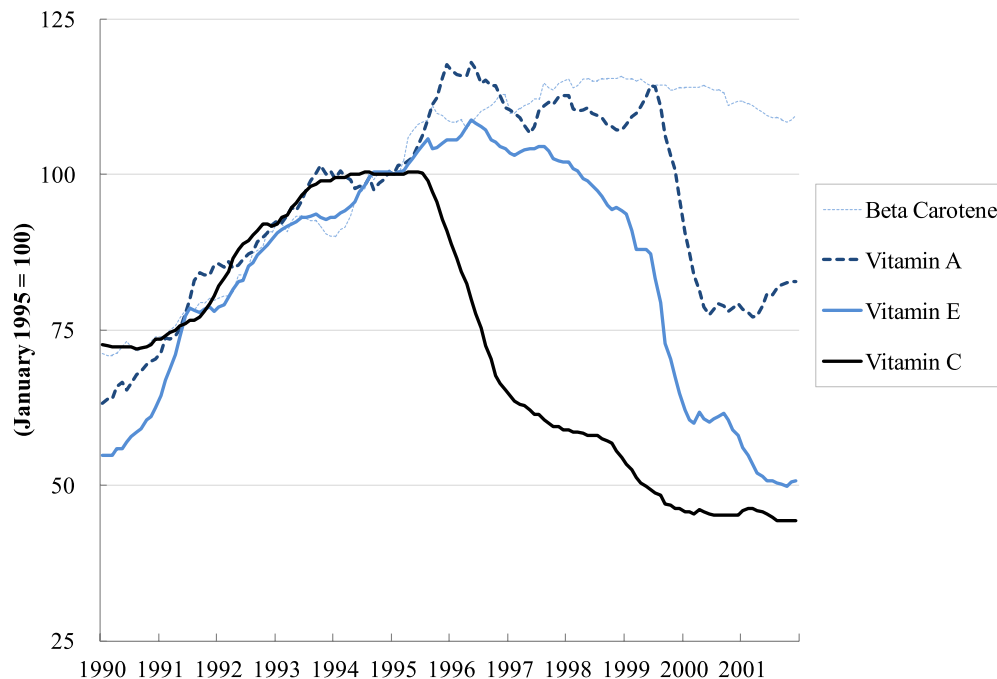


FIGURE 1

**Cartels and vitamin prices**

*Notes:* Roche's monthly average U.S. transaction prices (\$/kg) are rescaled with January 1995 as the base period. The vitamin C cartel collapsed internally in August 1995, whereas the other three cartels continued operations until 1999, when the U.S. government prosecuted them.

*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.

demand curve, fringe supply, and the leading firm's cost), and assume the firms use trigger strategies with the threat of reversion to static Nash if someone's non-compliance is confirmed by trade statistics at the quarterly meetings (*i.e.* "perfect" monitoring with a three-month delay). We conduct sensitivity analysis with alternative model specifications concerning fringe supply, quotas, cartel pricing, monitoring lag, expectations, demand, and long-term contracts.

We present three sets of results. First, under a reasonable assumption about the firms' annual discount factor (at or near 0.8), the collusive incentive of the short-lived vitamin C cartel was likely to become negative (*i.e.* the enforcement/incentive constraint was likely to be violated) at the time of its actual collapse in 1995, whereas the collusive incentives of the long-lived cartels for vitamins A and E and beta carotene were unambiguously positive (*i.e.* the constraints were slack) through 1999. Thus, we show evidence in support of the theory of collusion regarding its central prediction that if a cartel collapses internally, it does so because the environment has changed so that the enforcement/incentive condition is no longer satisfied. We use this argument and counterfactual simulations to quantify the effects of demand growth and fringe supply on the stability (or collapse) of the vitamin C cartel.

Second, we measure the impact of a merger on cartel stability, by simulating a hypothetical situation in which BASF's acquisition of Takeda's vitamin assets (which actually happened in 2001) had been consummated before the beginning of the vitamin C cartel in 1991. We show this merger would have increased the incentive to collude. However, simulations with varying degrees of synergy suggest coordinated effects could be negative when a merger generates efficiency gains.

Even though mildly positive synergies, such as a 5% reduction in BASF-Takeda's marginal cost, would have increased the incentive to collude, larger efficiency gains (*e.g.* over 25%) would have destabilized the cartel, because synergies make the merged entity's collusive incentive more aligned with those of low-cost rivals but less aligned with those of high-cost rivals.

Third, although mergers reduce the number of firms and increase market-share concentrations, which are usually associated with *less competitive* market structures, our simulations suggest mergers (from four to three or two firms) could also simultaneously lead to *less collusive* incentive structures. Mergers that eliminate the highest-cost firms make the remaining firms' cost profiles more symmetric, whereas mergers that eliminate medium-cost firms polarize the cost profile. Asymmetries generally destabilize collusion, because even if some firms have higher incentives to collude, others end up with reduced incentives (relative to a situation with symmetric firms). Note a stable collusive agreement must satisfy all members' enforcement/incentive constraints, and hence the fact that at least one member has lower incentives to collude means the collusive agreement as a whole becomes less stable. Thus, concentration may increase market power in terms of "unilateral effects" (*i.e.* the static Nash outcomes become less competitive after mergers), but both the sign and the magnitude of coordinated effects critically depend on cost asymmetry. These findings highlight the feasibility and desirability of quantitative analysis to inform merger enforcement with respect to coordinated effects.

This article relates to three literatures. First, the game-theoretic literature on collusion has developed and tested the predictions of repeated-game theory. Many papers focused on the timing of price wars, including [Porter \(1983\)](#), [Green and Porter \(1984\)](#), [Rotemberg and Saloner \(1986\)](#), [Bresnahan \(1987\)](#), [Slade \(1987, 1992\)](#), [Haltiwanger and Harrington \(1991\)](#), [Ellison \(1994\)](#), and [Borenstein and Shepard \(1996\)](#). By contrast, we study cartel stability in the longer run in terms of the incentive to collude and its determinants. We clarify conditions under which collusion is sustainable in a structural empirical model, and present more direct evidence in support of the theoretical prediction by quantifying collusive incentives.

Second, a large literature exists on the internal operations of cartels.<sup>6</sup> More recently, [Asker \(2010\)](#) studied the bidding ring of stamp dealers in the 1990s; [Harrington and Skrzypacz \(2011\)](#) explain stylized facts by a new theoretical model; and [Clark and Houde \(2013\)](#) studied the retail gasoline cartels in Quebec (2005–06). Our work is similar to these papers in studying a relatively recent case and in using a structural model but diverges from them with our focus on the measurement of collusive incentives and coordinated effects of mergers.<sup>7</sup>

Third, coordinated effects of mergers have been an active area of antitrust policy discussion, but empirical evidence has been scarce, with the notable exception of [Miller and Weinberg's \(2017\)](#) study of a beer merger case. We complement their retrospective merger analysis by showcasing a prospective merger simulation, which has become common in quantifying unilateral effects of mergers (*e.g.* [Werden and Froeb, 1994](#); [Nevo, 2000](#)) but not for coordinated effects. We extend these efforts by using a repeated-games framework. Although the analysis becomes inherently dynamic, our data requirement is similar to that of usual (static) merger analysis and does not impose an additional burden. The [Supplementary Appendix](#) includes a "practitioner's guide" to highlight key aspects of our framework that are more generally applicable beyond the specific context of vitamins.

6. For example, [Porter \(1983\)](#) and [Ellison \(1994\)](#) studied the 19th-century U.S. railroad cartel; [Levenstein \(1997\)](#) studied the U.S. bromine cartel (1885–1914); [Scott Morton \(1997\)](#) studied British shipping cartels (1879–1929); [Genesove and Mullin \(2001\)](#) documented the U.S. sugar cartel (1892–1914); [Röller and Steen \(2006\)](#) studied the Norwegian cement cartel in the mid-20th century.

7. Our work is also categorically related to [Fershtman and Pakes \(2000\)](#), who proposed a Markovian dynamic oligopoly model with collusion, and [de Roos \(2006\)](#), who applied their model to the lysine cartel.

## 2. THE VITAMIN CARTELS, 1990–1999

The vitamins case has been studied extensively, and we refer the reader to excellent books by [Connor \(2007\)](#) and [Marshall and Marx \(2014\)](#) for its general background. This section focuses on more specific features of the cartels that are essential for our modelling purposes. [Supplementary Appendix A](#) provides further details on the institutional background.

### 2.1. *The Cartels*

[EC's \(2003\)](#) judgment provides detailed information on the internal organization of the vitamin cartels. The EC assesses the quality of the evidence is high.<sup>8</sup>

Before the beginning of collusion, the prices of most vitamins were low. Firms blamed each other's "price offensive" and "aggressive pricing policy" in vitamins A and E. In its invitation to the vitamin C cartel, Roche explained to BASF that "it had been attempting to raise the price level for the past 4 or 5 years" with little success.<sup>9</sup> In the summer of 1989, the heads of the vitamins divisions of Roche and BASF, as well as Rhône-Poulenc's (RP) head of the Animal Nutrition division, met in Basel and Zurich to start cartels for vitamins A and E. They agreed to freeze market shares at the 1988 levels for the foreseeable future: "The market for 1990 was estimated and the forecast agreed; the percentage quotas for each company were then converted into sales allocations on a tonnage basis for the world, the region and each national market."<sup>10</sup> This "budget" exercise was repeated in the fall of each year. In 1990, they recruited Eisai, Hoechst, Daiichi, E. Merck, and Takeda to cartelize a dozen other vitamins markets. By early 1991, most of the Roche-led cartels were successfully raising prices.

Regular meetings took place. At the annual "budget" meetings, the divisional heads of the vitamins business decided on the quotas and overall strategy. The managers of specific vitamins met four times a year to monitor the implementation of the quota systems. Regarding the monitoring structure, bulk-vitamins contracts are private and prices are not completely transparent, although firms learned general industry trends through customers.<sup>11</sup> A more objective source was the customs clearance data in the international trade statistics. The ultimate confirmation of each member's adherence to the quota relied on cross-validation of self-reported sales with trade statistics at the quarterly meetings. The geography of vitamins production facilitated the identification problem, because each firm operated only one or two plants for each vitamin, usually in its home country, and their nationality varied.<sup>12</sup>

Throughout the 1990s, nothing like a full-blown price war was observed, except when several of the cartels ceased operations permanently. The firms did not formally specify contingency plans for adverse events, which is typical of cartel agreements in practice. Nevertheless, [EC \(2003\)](#) reveals they were occasionally expressing their shared belief that the end of agreements would bring back competitive behaviours and low prices. Given the importance of off-equilibrium beliefs in the theory of collusion, we quote three such occasions in the vitamin C cartel.<sup>13</sup>

8. See [Supplementary Appendix A.1](#), "(a) The Nature and Reliability of the Evidence."

9. See [Supplementary Appendix A.1](#), "(b) Competition before and after the Cartels."

10. See [Supplementary Appendix A.1](#), "(c) Volume-Control Mechanism: 'Budgets.'"

11. See [Supplementary Appendix A.1](#), "(d) Meetings" and "(e) Price Increases."

12. See [Supplementary Appendix A.1](#), "(f) Monitoring" and "(g) World-Wide Markets and Production Locations."

13. Curiously, we found no indication of contingency plans ("punishment") connecting multiple vitamin markets, despite theoretical possibilities that such arrangements could have improved the incentive conditions of each cartel (e.g. [Bernheim and Whinston, 1990](#)). See [Supplementary Appendix A.1](#), "(h) (Lack of) Interaction between Different Cartels" and "(i) Adjustments."

- “Takeda complained that (...) if it did not get evidence that the European producers were following its price in May and June, it would ‘react’ against them” (recital 425);
- “According to BASF however, 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. Takeda relented and new lower vitamin C volume allocations were agreed among the four companies” (recital 442); and
- “Takeda returned to its favourite theme that it was ‘unreasonable to ensure the continuation of 1990 shares (...)’ Roche replied that if allotment cuts were mentioned to BASF and Merck they would stop following the scheme and bring chaos to the market with their low prices” (recital 444).

The 16 cartels that Roche helped organize across different vitamin categories ended in one of two ways. Six of them fell apart in 1994 or 1995, allegedly because of the entry and expansion by fringe producers and/or slowdown of demand growth. By contrast, the 10 other cartels were operating smoothly until prosecutions became imminent in the United States. In January 1999, RP applied for (and was granted) amnesty under the Department of Justice (DOJ)’s relatively untested Corporate Leniency Program. Within two months, both Roche and BASF pled guilty and agreed to pay record-breaking fines of \$725 million in total.<sup>14</sup>

The industrial landscape completely changed after 1999, as drug makers shed non-drug operations. RP’s application for amnesty coincided with its drugs division’s proposal to merge with Hoechst, a German rival. Regulators in America and Europe approved this merger, which created Aventis (currently Sanofi). Takeda sold its vitamin business to BASF in 2001. Roche sold its Vitamins and Fine Chemicals division to DSM, a Dutch chemicals firm, in 2003.

## 2.2. *Competitive fringe in China*

Chinese producers played a major role as the competitive fringe in the vitamin C market. In the mid-1980s, researchers at a government laboratory discovered and patented a new method to manufacture vitamin C at a lower cost and smaller scale than the existing technology. Nevertheless, “Chinese vitamin C production had been of little importance internationally” because “during the 1980s, exports were closely controlled by the state.”<sup>15</sup>

In the mid-1990s, however, an abrupt policy change occurred and “the Chinese central government had encouraged the improvement of the two-step process and its commercialization at various production sites.”<sup>16</sup> Figure 2 shows the sudden growth of fringe supply in 1992, when the Bosnian war disrupted the Eastern European supply of vitamin C for the former socialist bloc (Li, 2002). The government encouraged SOEs to increase production and supported the entry of private firms. More than 20 firms had entered by 1995. Nevertheless, EC (2003) suggests that even after three years of China’s rapid growth, the vitamin C cartel was allocating its 1995 quotas based on the premise that fringe supply would stop growing from its 1994 level.

The competitive fringe expanded in several other vitamin markets albeit at much slower rate than in the case of vitamin C. Chinese producers’ market entry and expansion were closely related to China’s economic liberalization in the 1990s, such as Deng Xiaoping’s official endorsement of private enterprises in 1992 and the liberalization of prices and commerce in 1994. [Supplementary Appendix A.2](#) summarizes key historical events and the profile of major producers in China. For the members of the respective cartels, obtaining correct, timely information on the growth

14. See [Supplementary Appendix A.1](#), “(j) Six ‘Natural Deaths’” and “(k) Ten ‘Antitrust Deaths.’”

15. UKCC (2001, p. 179).

16. UKCC (2001, p. 99).

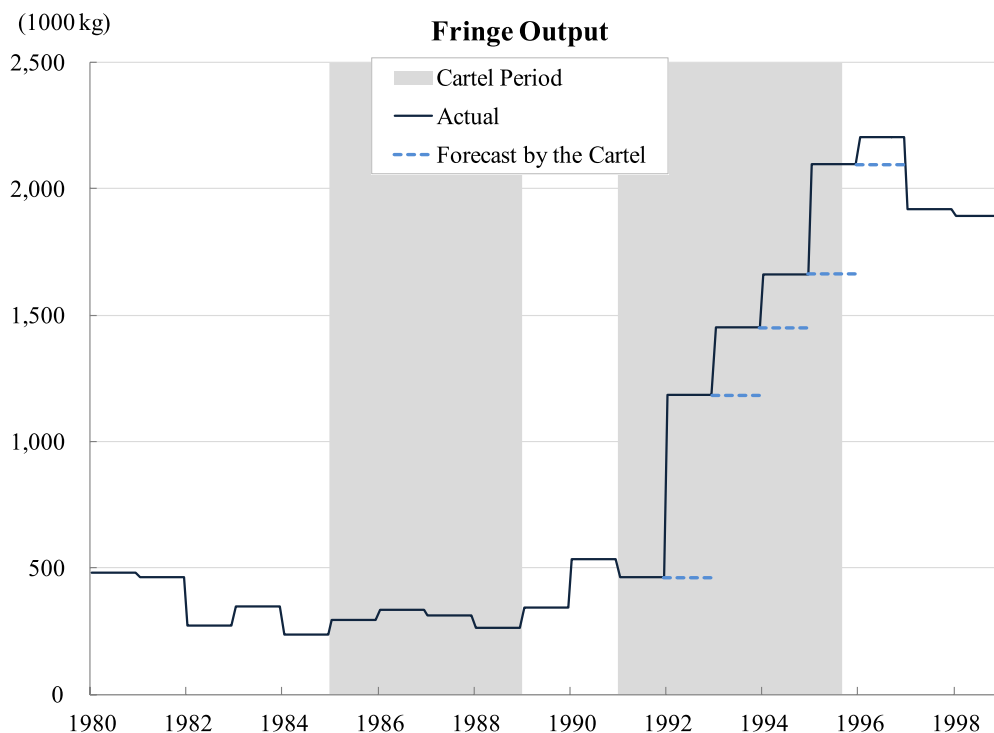


FIGURE 2

**Sudden growth of fringe supply (vitamin C)**

Notes: The dashed lines represent the cartel firms' static predictions, as suggested by EC (2003).

Source: Bernheim (2002a) and EC (2003).

trajectory of fringe seems difficult, as underestimation and staggered revisions were common in other vitamin markets as well.<sup>17</sup>

### 2.3. Product characteristics

We use the following basic features of the industry to guide our modelling choice. Each vitamin is used for its specific biochemical functions.<sup>18</sup> Production of each vitamin required its own specific plant. Both UKCC (2001) and EC (2003) determined that “there was neither demand-side nor supply-side substitutability for individual vitamins.”<sup>19</sup> The underlying production technologies of vitamins had matured by the 1980s and were common across firms. The only exception was

17. See [Supplementary Appendix A.1](#), “(l) Repeated Failures to Predict the Growth of Fringe.” The cartels for vitamins B1, B6, and B9 repeatedly failed to achieve the “budgets” because of Chinese exports. The vitamin B2 cartel failed to predict the output growth of Coors/ADM in America.

18. See [Supplementary Appendix A.1](#), “(m) Health Benefits of Vitamins.” Other benefits for humans have not been proven.

19. See [Supplementary Appendix A.1](#), “(n) Substitutability between Vitamins,” and Appendix A.3 (production technology).



the invention of a new method to produce vitamin C in China. No major entry or exit occurred during the cartel period except for fringe firms.<sup>20</sup>

Each vitamin has a different demand base. More than 90% of vitamin C and beta carotene are for human use, whereas 87% of vitamin A and 73% of vitamin E are for animals. All vitamin markets experienced a steady growth of demand during the 1980s and the 1990s. Buyers of bulk vitamins include farmers, their co-operatives, local blenders who produce pre-mixed vitamin cocktails, manufacturers of foods and beverages, drugs and cosmetics firms, and other firms that use vitamins for miscellaneous technical purposes. Bernheim was engaged on behalf of more than 9,100 purchasers. EC (2003) recognizes a few “large” buyers, primarily in the vitamin C market, but even Coca-Cola, one of the world’s largest buyers, accounted for only 2.14% of the aggregate sales. Thus, buyer concentration is generally low.

Bulk vitamins are sold in different forms according to the product and the application: crystalline, in oil, with a protective coating, or in a powder matrix. Nevertheless, each cartel used a single target price and tonnage-based sales allocation, by converting diluted products into the equivalent of 100% product. UKCC (2001) observes that customers shop around and switching is easy, because “as vitamins are chemical products, once they meet specified standards of purity, physical form, packaging and so on, it becomes difficult for a producer to differentiate its product from competitors.”<sup>21</sup> Vitamin sales can be made either through long-term contracts or spot sales, but typical supply agreements last for only three months. Transportation costs and tariff barriers play minor roles: “The worldwide character of the markets” is confirmed by the internal organization of the cartels, as well as the presence of third-party arbitrage traders.<sup>22</sup>

### 3. DATA

#### 3.1. Sources and variables

As part of their investigation in 1999, the Federal Bureau of Investigation (FBI) and the DOJ obtained data on production and sales, personal records of cartel meetings, and individual depositions. These antitrust enforcements were followed by the purchasers’ multi-district litigation, which were consolidated at the U.S. District Court for the District of Columbia. Some of the expert reports (Bernheim, 2002a, 2002b; Landes et al., 2002) were included in jury trials in 2003 and became publicly available.<sup>23</sup>

Bernheim (2002a) relied primarily on the internal data from Roche, the cartel leader. He also had customer-specific transaction-level data from various plaintiffs and defendants. From his report, we build our dataset on the following variables between 1980 and 1998. Table 1 reports their summary statistics by subsample: non-cartel period ( $I_t = 0$ ), cartel period ( $I_t = 1$ ), and full sample.

**Prices.** Bulk vitamins are homogeneous goods within each category, but multiple grades of concentration exist. Roche’s dataset (ROVIS) contained “monthly weighted average prices (aggregated over customers) for a collection of vitamin products.” Following the cartel’s own

20. “Pink carotinoid,” or astaxanthin, was an exception. BASF was building a new plant and coordinating with Roche (the only producer of astaxanthin) for “controlled entry.” But the plant “did not come on stream until 1999” and the agreement was never implemented (EC, 2003, recital 527).

21. See Supplementary Appendix A.1, “(o) Bulk Vitamins are Commodities,” and Appendix B.1 (firm-level prices).

22. See Supplementary Appendix A.1, “(g) World-Wide Markets and Production Locations.”

23. A new round of antitrust cases emerged in the late 2000s and early 2010s when the Chinese firms, which had become dominant global players by then, restricted their export volumes (e.g. Bernheim, 2008). We do not study this episode, because most of the main players in the 1990s had already exited, and the existence of export quotas (set by the Chinese Ministry of Commerce) complicated its legal characteristic.



TABLE 1  
Summary statistics (Vitamin C)

Variable	Mean (and standard deviation)					
	Non-cartel period ( $I_t = 0$ )		Cartel period ( $I_t = 1$ )		Full sample	
Price (US\$/kg)	11.21	(0.88)	13.61	(2.70)	12.43	(2.35)
Roche's unit cost (US\$/kg)	5.55	(0.60)	6.28	(0.64)	5.93	(0.71)
Aggregate output (1,000 MT)	44,570	(15,553)	51,393	(13,245)	48,161	(14,404)
of which Roche	20,967	(3,795)	21,744	(1,407)	21,376	(2,748)
of which Takeda	8,609	(2,942)	10,622	(3,092)	9,668	(3,113)
of which E. Merck	4,262	(438)	4,057	(621)	4,154	(537)
of which BASF	2,078	(1,497)	2,663	(745)	2,386	(1,167)
of which fringe	8,654	(8,141)	12,308	(9,443)	10,577	(8,807)
Number of months	112		116		228	

Notes: The full sample period is January 1980–December 1998. The main cartel period is January 1991–August 1995. We also set  $I_t = 1$  for an earlier (suspected) cartel episode between 1985 and 1988 as well as the 12 months after August 1995 to define the non-cartel period conservatively. Cost and output data are annual, and we treat 1985–1988 and 1991–1996 as the cartel period for these variables. MT (metric ton) is equal to 1,000 kg.

practices, Bernheim converted them to “100% basis” and aggregated the product-level sales to a single price index.

**Production.** Bernheim (2002a) shows aggregate outputs and each firm’s percentage market shares at the annual frequency, from which we calculate firm-level outputs. Similarly to the price indexes, all outputs are converted to 100% basis and aggregated at the vitamin level (*i.e.* the level at which the cartels defined and allocated quotas).

**Costs.** Bernheim (2002a) computes unit costs by using the 100% basis price indices and the annual worldwide “contribution margins” (*i.e.* profit margins) for each vitamin family in the Roche Data Books. These costs are accounting measures based on engineering estimates, not economic marginal costs. Despite this limitation, we have chosen to use these unit-cost data for the following reasons. First, Roche’s unit-cost measure consists of labour, raw materials, and other intermediate inputs such as electricity (*i.e.* variable costs). Second, Roche used this measure for its own production decisions.<sup>24</sup> Third, Roche and other firms’ unit costs seem constant at any quantity or “nameplate capacity utilization rates” (see [Supplementary Appendix B.2](#)), which would limit the scope of divergence between average variable costs and marginal costs. Physical capacities at the facility level were far from binding during the sample period (see below), which would make the shadow price of capacity less of a concern.

**Capacities.** Although Bernheim (2002a) had “nameplate capacity utilization” data on multiple firms at the vitamin level, he did not use them, because “nameplate capacity” corresponds to neither the long-run capacity (defined by the physical sizes of production facilities) nor the short-run capacity (in terms of weekly or monthly production schedules, such as work shifts and procurement plans for raw materials).<sup>25</sup> Thus, we follow Bernheim and several other experts in *not* using this ambiguous measure, and interpret the actual production as a reflection of the firms’ short-run production plans.

24. Bernheim (2002a) notes, “since Roche apparently used this information when making contemporaneous business decisions, it is appropriate for my current purpose to take the data at face value” (p. 123).

25. See [Supplementary Appendix B.3](#) for further details on capacities. Nameplate capacities do not have an objective definition; they are medium-run production plans that are occasionally reported (*e.g.* in the firms’ financial statements) based on various assumptions on work schedules.

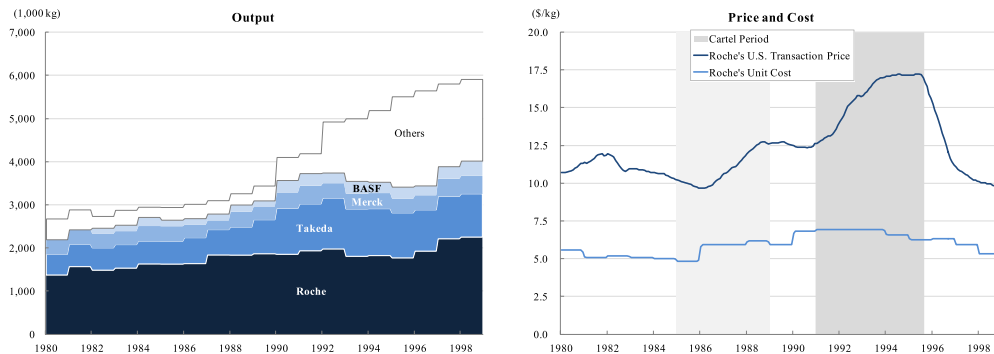


FIGURE 3

### Output, price, and cost (vitamin C)

Notes: Shaded areas indicate cartel periods (January 1985–December 1988 and January 1991–August 1995). The first spell was not the target of the official investigation or litigation (and hence we do not have evidence on this suspected earlier episode); the second one corresponds to the main cartel episode.

Source: Bernheim (2002a) and EC (2003).

**Cartel periods.** We use EC (2003) to determine collusive periods and cross-check with Bernheim (2002a), Connor (2007, 2008), and Marshall and Marx (2014): January 1990–February 1999 for vitamins A and E, January 1991–August 1995 for vitamin C, and January 1991–February 1999 for beta carotene. As a precaution against a “false negative,” we also treat 1985–1988 and the first 12 months after the main cartel’s breakup as collusive periods.<sup>26</sup>

### 3.2. Data patterns and key observations

Figure 3 (left) shows the worldwide production of vitamin C increased throughout the sample period. The four cartel members (Roche, Takeda, E. Merck, and BASF) restricted outputs between 1991 and 1995,<sup>27</sup> but the competitive fringe in China started expanding in 1992. The right panel shows the price soared by more than 30% during the cartel period (January 1991 through August 1995) despite a virtually flat trajectory of unit cost.

Figure 4 shows similar pictures for vitamins A and E, and beta carotene. The prices were significantly higher in the 1990s than in the 1980s despite virtually flat costs. The total outputs were steadily increasing because the world demand was growing for each vitamin. A closer look at the output graphs reveals two differences across markets. One is the variation in market structure: Beta carotene is a duopoly, vitamin A is a triopoly, and vitamin E is a quadropoly. Another difference is the size of the competitive fringe. None existed in beta carotene; vitamins A and E had some small suppliers.

Three data patterns inform our subsequent analysis. First, both the price and the aggregate output increased between 1990 and 1994, which suggests a steady growth of demand.<sup>28</sup> Second, the markup was sizeable even outside the cartel period (*e.g.* early 1980s), despite the experts’ view that bulk vitamins are commodities and the geographic market is global. Third, all firms made

26. Bernheim (2002a) mentions earlier attempts of collusion in the mid-1980s. He notes the price data take a year to reflect the cartel’s breakup (due to the lagged turnover of individual contracts).

27. See Supplementary Appendix B.4 for their within-cartel market shares, which closely followed the allocated quotas.

28. Nevertheless, vitamin prices exhibit trend-stationarity in the pre-cartel sub-samples. See Supplementary Appendix C.1.

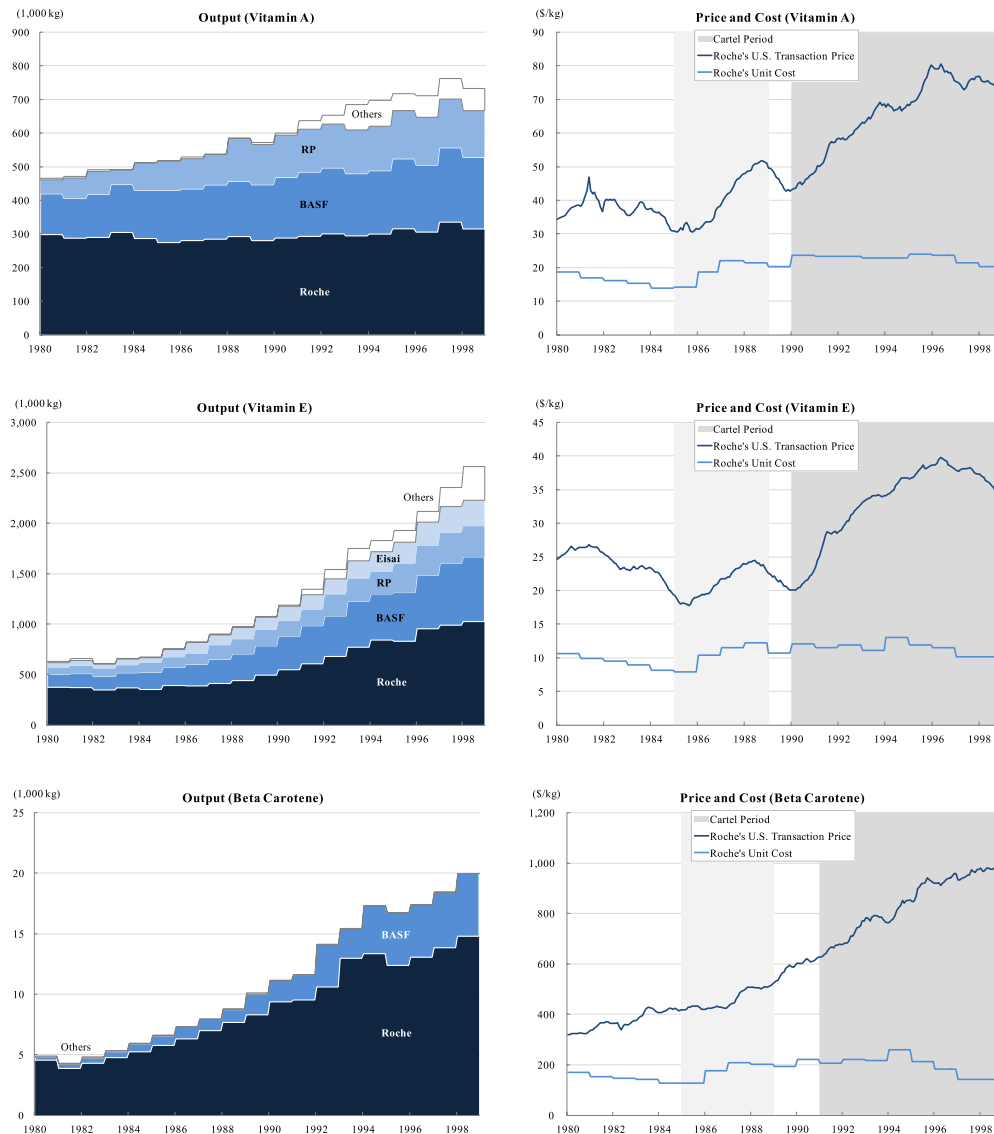


FIGURE 4

Output, price, and cost (vitamins A and E, and beta carotene)

non-negligible sales, even though long-run physical capacities were not binding at low-cost firms. The latter two observations are more consistent with the Cournot model than Bertrand, because Bertrand competition among 2–4 firms with homogeneous goods would lead to much lower markups, whereas Cournot competition could reconcile these facts. Hence, we use a quantity game to characterize the stage game.<sup>29</sup>

29. We revisit this modelling choice in Section 6.1.

## 4. EMPIRICAL ANALYSIS OF DEMAND AND COSTS

Sections 4 and 5 integrate the institutional details and the data in a structural model, and quantify the incentives for collusion. Our exposition focuses on the vitamin C market, but we conduct the same analysis of the three other markets (*i.e.* vitamins A and E, and beta carotene) as well.

4.1. *Specification*

We specify a linear demand model for a bulk vitamin product in each month  $t$ ,

$$Q_t^D = \alpha_0 + \alpha_1 P_t + \alpha_2 X_t + \varepsilon_t, \quad (1)$$

where  $P_t$  is the “100% basis” price index,  $X_t$  is a demand shifter (the logarithm of population in high-income countries), and  $\varepsilon_t$  is a non-systematic component of demand.<sup>30</sup>

On the supply side,  $n$  firms belong to the cartel and collectively produce  $Q_{car,t}$ , whereas the competitive fringe supplies  $Q_{fri,t}$ . We assume the vitamin spot market clears in each  $t$ ,

$$Q_t^D = Q_{car,t} + Q_{fri,t}. \quad (2)$$

We model the fringe supply in three different ways:

$$Q_{fri,t} = \kappa_t, \quad (3)$$

$$Q_{fri,t} = \lambda_t P_t, \text{ and} \quad (4)$$

$$Q_{fri,t} = \kappa + \lambda_t P_t. \quad (5)$$

The first specification (3) assumes fringe output is completely exogenous to the rest of the model, given by a time-varying intercept term,  $\kappa_t$ . The second model (4) assumes the fringe output is a linear function of the world price, in which a time-varying slope coefficient,  $\lambda_t$ , reflects the growing production capacity in China. The third specification (5) is a hybrid of the two, with a time-invariant intercept  $\kappa$  (which reflects the small but consistent output level before China’s explosive growth since 1992) and the time-varying slope  $\lambda_t$ . Every month, the  $n$  cartel firms take the fringe supply function at  $t$  as given and face the residual demand function. Regarding the future trajectory of  $Q_{fri,\tau}$  (where  $\tau > t$ ), we assume they hold static expectations about the time-varying component of fringe supply (*i.e.*  $\kappa_t$  in model 1, and  $\lambda_t$  in models 2 and 3).<sup>31</sup>

In the competitive periods ( $I_t = 0$ ), we assume a static Nash equilibrium of the quantity game played by these  $n$  firms. Each firm’s first-order condition (FOC) is

$$P_t + \frac{dP}{dQ_t} \times q_{i,t} = c_{i,t} \quad \text{if } I_t = 0, \quad (6)$$

where  $\frac{dP}{dQ_t}$  is the slope of the residual demand curve (net of  $Q_{fri,t}$ ),<sup>32</sup> and  $q_{i,t}$  and  $c_{i,t}$  are firm  $i$ ’s output and marginal cost. Given the cartel firms’ relatively stable market shares, we assume

30. We also consider the log–log specification in Section 6.2.

31. This assumption does not affect the estimation of demand and costs in section 4 but plays a central role in Section 5.

32. The fringe model in (3) implies  $\frac{dP}{dQ_t} = \frac{1}{\alpha_1}$ , whereas  $\frac{dP}{dQ_t} = \frac{1}{\alpha_1 + \lambda_t}$  under (4) and (5).

constant gaps exist between their true (unobserved) marginal costs  $c_{i,t}$ s and Roche's (observed) unit cost in the data  $c_{roche,t}^{obs}$ ,

$$c_{i,t} = c_{roche,t}^{obs} + \gamma_i + \eta_{i,t}, \quad (7)$$

where  $\gamma_i$  is the mean difference between  $c_{i,t}$  and  $c_{roche,t}^{obs}$ , and  $\eta_{i,t}$  is the measurement error.<sup>33</sup> Combining (6) and (7), we obtain the main supply-side equations for estimation

$$P_t + \frac{dP}{dQ_t} \times q_{i,t} = c_{roche,t}^{obs} + \gamma_i + \eta_{i,t} \quad \text{if } I_t = 0 \quad (8)$$

for all  $i = 1, 2, \dots, n$ .

Note we use only the data from the competitive periods ( $I_t = 0$ ) for estimation purposes. We defer the modelling of the firms' behaviours in the cartel periods ( $I_t = 1$ ) to section 4.4, and study their dynamic implications in Section 5.

#### 4.2. Identification and Estimation

Equilibrium price and quantities are determined simultaneously in the demand-and-supply model of Section 4.1. To address the associated endogeneity problem, we construct a generalized method of moments (GMM) estimator of the parameters  $\theta \equiv (\alpha_0, \alpha_1, \alpha_2, (\gamma_i)_{i=1}^n)$  by combining moments from (1) and (8).

The first set of moment conditions comes from the demand equation (1):

$$\bar{m}_1(\theta) = \sum_y \bar{\varepsilon}_y \cdot Z_y,$$

where  $y$  indexes a year,  $\bar{\varepsilon}_y = Q_y - \alpha_0 - \alpha_1 \bar{P}_y - \alpha_2 \bar{X}_y$ , and  $Z_y = (1, \bar{X}_y, c_{roche,y}^{obs})$ .  $P_t$  and  $X_t$  are observed at a monthly frequency, which we convert to annual averages (*i.e.*  $\bar{P}_y = \frac{1}{12} \sum_{t \in y} P_t$  and  $\bar{X}_y = \frac{1}{12} \sum_{t \in y} X_t$ ). We construct  $\bar{m}_1(\theta)$  at an annual frequency, because  $Q_y$  and  $c_{roche,y}^{obs}$  are recorded only annually. As the composition of the instrument vector  $Z_y$  suggests, we are using Roche's unit cost as an excluded instrumental variable (IV) to identify the demand function.

The second set of moments comes from the supply relations (8):

$$\bar{m}_{2,i}(\theta) = \sum_y \bar{\eta}_{i,y} \cdot W_{i,y},$$

where  $\bar{\eta}_{i,y} = \bar{P}_y + \frac{dP}{dQ_t} q_{i,y} - c_{roche,y}^{obs} - \gamma_i$  and  $W_{i,y} = (1, \bar{X}_y)$ . Thus, we are using the demand shifter as an excluded IV to identify marginal costs.<sup>34</sup> Pooling  $\bar{m}_{2,i}(\theta)$ s across firms,

$$\bar{m}_2(\theta) = \sum_i \bar{m}_{2,i}(\theta),$$

we construct the set of aggregate moments  $\bar{m}_2(\theta)$ .

33. An alternative specification with constant ratios (*i.e.*,  $c_{i,t} = c_{roche,t}^{obs} \times \gamma_i + \eta_{i,t}$ ) generates similar results. Bernheim (2002a) contains data on a few other firms' costs as well, but they are incomplete. See [Supplementary Appendix C.2](#) for non-Roche firms' cost data and our estimates.

34. Population is a valid IV in our context, because the Cournot equilibrium implies that prices and outputs depend on the demand intercept (*i.e.* the maximum willingness to pay), which is likely to increase with population. The connection between population and the intercept would become less obvious if buyers were completely homogeneous with identical demand schedules, but such a situation seems unlikely. Buyer concentration is low, and the demand comes from diverse channels (see Section 2.3).

The third set of moments builds on both the demand side and the supply side:

$$\bar{m}_3(\theta) = \sum_t \bar{\eta}_t \cdot X_t,$$

where  $\bar{\eta}_t = P_t + \frac{1}{n} \frac{dP}{dQ_t} (\alpha_0 + \alpha_1 P_t + \alpha_2 X_t - Q_{fri,t}) - c_{roche,t}^{obs} - \frac{1}{n} \sum_i \gamma_i$ , which averages the FOCs (8) across firms and uses the market clearing condition (2). Both  $\bar{m}_2(\theta)$  and  $\bar{m}_3(\theta)$  use similar variation in the data, but  $\bar{m}_3(\theta)$  exploits monthly variation in  $P_t$  and  $X_t$  as well.

These three sets of moments  $\bar{m}(\theta) = (\bar{m}_1(\theta), \bar{m}_2(\theta), \bar{m}_3(\theta))$  lead to an over-identified model. We use them with equal weights in one-step GMM,

$$\hat{\theta}_{gmm} = \arg \min_{\theta} \bar{m}(\theta)' I \bar{m}(\theta),$$

where  $I$  is a conformable identity matrix.<sup>35</sup>

The GMM procedure takes the fringe supply parameters as given, which we calibrate directly from the data before the main estimation step. Specifically, we set  $\hat{\kappa}_t = Q_{fri,t}$  in model 1, and  $\hat{\lambda}_t = Q_{fri,t}/P_t$  in model 2. In model 3, we set  $\hat{\kappa} = \max_{t < 1992} Q_{fri,t} = Q_{fri,1990}$  and then compute  $\hat{\lambda}_t = (Q_{fri,t} - \hat{\kappa})/P_t$ .

#### 4.3. Estimates of demand and costs

Table 2 reports the GMM estimates of demand and costs under the three different fringe supply models. Model 1 exhibits the lowest price coefficient  $\alpha_1$ , whereas models 2 and 3 lead to less negative slopes because  $\lambda_t$  alters the slope of the residual demand curve.<sup>36</sup> The demand-shifter coefficient  $\alpha_2$  is positive, which is intuitive.<sup>37</sup>

The difference  $\gamma_{roche}$  between Roche's true (unobserved) marginal cost and its (observed) unit cost is negligible and statistically indistinguishable from zero, which suggests its internal cost data are reliable. The other firms' costs are estimated to be approximately \$3–\$5 higher than Roche's cost. These cost gaps are relatively large in comparison with the output price (\$9–\$18), which seems surprising when the firms are using the same technology to produce homogeneous goods. Nevertheless, our assessment of auxiliary data on labour cost and other factors suggests such gaps are realistic (see [Supplementary Appendix C.2](#)).<sup>38</sup>

35. We experimented with the two-step GMM procedures as well, but the results are highly volatile, because the covariance matrix of the error term is close to singular.

36. We slightly change the choice of moments across models 1, 2, and 3. We use all moments  $\bar{m}(\theta) = (\bar{m}_1(\theta), \bar{m}_2(\theta), \bar{m}_3(\theta))$  for estimating model 1, whereas we use only  $\bar{m}(\theta) = (\bar{m}_1(\theta), \bar{m}_2(\theta))$  for models 2 and 3 because the use of  $\bar{m}_3(\theta)$  in the latter two destabilizes the estimates.

37. We use the logarithm of population in high-income countries based on the definition and data from the World Bank. High-income countries are the most relevant demand base for vitamins, because both the general public's health consciousness and the sophistication of animal husbandry tend to increase when countries reach a relatively high level of gross domestic product (GDP) per capita. We also experimented with other demand shifters, such as high-income countries' GDP per capita and the number of livestock. Their fit with  $Q_t$  is slightly inferior, and using their combinations lead to noisy, counter-intuitive estimates due to high collinearity.

38. While the underlying chemical processes are common across firms (e.g. the hybrid Reichstein vitamin C production process explained in [Supplementary Appendix A.3](#)), many cost components are location-specific, such as wages and other input prices. Cost differences could be large even within the same firm: the maximum difference between Roche's high-cost plant in Grenzach, Germany and its low-cost plant in Belvidere, USA is \$4.64, which is comparable to  $\gamma_{e,merck}$  (\$4.47) and  $\gamma_{basf}$  (\$4.88). [Supplementary Appendix C.2](#) examines the magnitude of these cost differences, where we find that our cost estimates are consistent with the non-Roche firms' accounting profit margins, and that the differences in local labour costs and foreign exchange rates could explain most of these cost gaps.

TABLE 2  
GMM estimates of demand and costs (vitamin C)

Model	(1)	(2)	(3)
Specification of fringe	Time-varying intercept (Baseline)	Time-varying slope	Time-invariant intercept and time-varying slope
	$Q_{fri,t} = \kappa_t$	$Q_{fri,t} = \lambda_t P_t$	$Q_{fri,t} = Q_{fri,1990} + \lambda_t P_t$
$\alpha_0$	-0.434 (3.375)	0.066 (2.313)	-0.068 (2.330)
$\alpha_1$	-0.330 (0.002)	-0.248 (0.002)	-0.312 (0.005)
$\alpha_2$	0.391 (0.011)	0.323 (0.007)	0.364 (0.009)
$\gamma_{roche}$	0.011 (2.597)	-0.188 (4.400)	0.107 (11.813)
$\gamma_{takeda}$	3.194 (0.626)	3.136 (0.925)	3.262 (2.263)
$\gamma_{e.merck}$	4.474 (0.168)	4.426 (0.234)	4.485 (0.580)
$\gamma_{basf}$	4.882 (0.152)	4.880 (0.157)	4.914 (0.300)
Moment conditions	$\bar{m}_1, \bar{m}_2, \bar{m}_3$	$\bar{m}_1, \bar{m}_2$	$\bar{m}_1, \bar{m}_2$
Number of months	112	112	112

Notes: Standard errors in parentheses are based on 1,000 block-bootstrap samples, where each block consists of 12 consecutive months of a calendar year. See [Supplementary Appendix C.3](#) for vitamins A and E, and beta carotene.

For reasons we explain in section 4.4, we use model 1 as our baseline result in Sections 5–7, but the coefficient estimates are mostly similar across models. The estimates for vitamins A and E, and beta carotene are reported in [Supplementary Appendix C.3](#).

#### 4.4. Stage-game profits

We calculate each firm's stage-game profits for all  $t$ ,

$$\pi_{i,t} = (P_t - c_{i,t}) q_{i,t}, \quad (9)$$

in three different cases:  $(\pi_{i,t}^C, \pi_{i,t}^D, \pi_{i,t}^N)$ . Note we assume a constant marginal cost with respect to output level, because our data on cost, output, and “nameplate capacity” exhibit such patterns (see [Supplementary Appendix B.2](#)).

First,  $\pi_{i,t}^C$  denotes the profit under the cartel agreement. We assume the cartel's collective output  $Q_{car,t}$  maximizes its total profit,

$$\sum_{i \in \mathcal{I}} \left( \frac{dP}{dQ_t} \times (Q_{car,t} + Q_{fri,t} - \tilde{X}_t) - c_{i^*,t} \right) \times q_{i,t}, \quad (10)$$

where  $\mathcal{I} = \{1, \dots, n\}$  denotes the fixed set of cartel firms,  $\tilde{X}_t \equiv \alpha_0 + \alpha_2 X_t + \varepsilon_t$  is the effective demand intercept/shifter, and  $i^*$  is the cartel leader (Roche, which is also the lowest-cost producer in most vitamin markets). This assumption is based on our finding that the cartel did achieve high prices that are statistically indistinguishable from theoretical monopoly prices (see [Figure 5](#) below).

Regarding the individual output levels, the cartel agreement used percentage quotas based on the member firms' within-cartel market shares in the pre-cartel period (e.g. 1990 in the vitamin C cartel).<sup>39</sup> These shares were applied to the collective output  $Q_{car,t}$  and converted into sales

39. [Supplementary Appendix B.4](#) shows within-cartel market shares are stable over time.



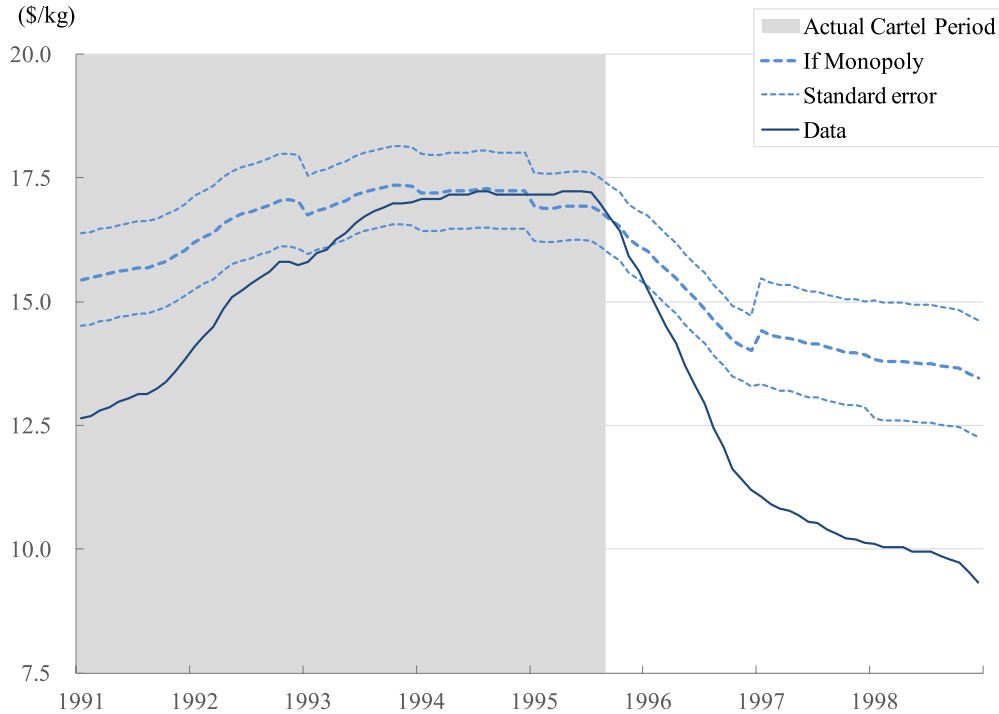


FIGURE 5

**Actual and monopoly prices (vitamin C)**

Notes: The hypothetical monopoly price is based on the estimates of demand and Roche's cost in column 1 of Table 2. The thin dashed lines indicate standard errors based on 1,000 block-bootstrap samples.

allocations on a 100%-equivalent tonnage basis,  $(\bar{q}_{i,t})_{i \in I}$ . Accordingly, we assume the cartel firms are supposed to supply their respective quotas and earn  $\pi_{i,t}^C = (P_t - c_{i,t})\bar{q}_{i,t}$ .

Second,  $\pi_{i,t}^D$  is an individual member's optimal non-compliance profit against  $(\bar{q}_{j,t})_{j \neq i}$ . That is, a cartel firm can maximize its individual profit by secretly increasing its own output beyond its allotment ( $q_{i,t} > \bar{q}_{i,t}$ ) while the other members stick with their quotas.<sup>40</sup> Finally,  $\pi_{i,t}^N$  is the static Nash equilibrium profit.

Figure 5 compares the historical price data and the theoretical cartel/monopoly price that corresponds to  $\pi_{i,t}^C$  (given the actual demand, fringe supply, and cost profile at each  $t$ ) based on model 1 in Table 2. The actual price is low at the beginning of the cartel in 1991, which is not surprising, because our demand estimation assumed the spot market is in Nash equilibrium until December 1990. Subsequently, the actual price converges to the optimal cartel price by the spring of 1993, which is surprising because we do not impose monopoly pricing (or any other restrictions) when  $I_t = 1$ . This pattern agrees with the evidence in EC (2003, recital 432) that the cartel achieved its price target in that year and switched to less aggressive price increases.<sup>41</sup> By contrast, models

40. All cartel firms had sufficient capacities to produce non-compliance outputs. See [Supplementary Appendix B.3](#).

41. The actual and monopoly prices of vitamins A and E, and beta carotene show similar patterns. Our estimates suggest the vitamin C cartel decreased the worldwide social welfare by 13.5% or \$559 million (consumer surplus decreased by \$895 million and producer surplus increased by \$336 million) relative to the Cournot outcomes between January 1991 and November 1995, which is the plea period that [Bernheim \(2002a\)](#) used for calculating overcharges. Based on the U.S.

2 and 3 lead to somewhat higher monopoly prices (see [Supplementary Appendix E.1](#)). Hence, we use model 1 as our baseline model in the following.

The cartel took more than a year to achieve its optimal price. [EC \(2003\)](#) shows the firms took turns announcing small price increases, in an attempt to mimic “natural” price-leadership behaviours.<sup>42</sup> Note the data reflect the average of all transactions at Roche. Although typical contracts spanned three months, some lasted for 6 to 12 months.<sup>43</sup> Hence, after the last documented cartel meeting on 24 August 1995, the price data also took a year to come down to the pre-cartel level. We do not model these sluggish transitions that are driven by such idiosyncratic and mechanical features, and instead focus on more fundamental components of the incentives to collude:  $(\pi_{i,t}^C, \pi_{i,t}^D, \pi_{i,t}^N)$ .

## 5. DYNAMIC IMPLICATIONS ON CARTEL STABILITY

This section studies the dynamic implications of the (static) estimates of demand and costs in the previous section. Section 5.1 presents our repeated-games model, which we specify according to the internal organization of the vitamin cartels in [EC \(2003\)](#). Section 5.2 uses this dynamic model to estimate the firms’ incentives to collude. Section 5.3 assesses the effects of demand slowdown and fringe supply to explain the collapse of the vitamin C cartel in 1995.

### 5.1. A repeated-games framework

We introduce the following repeated-games framework to quantify the incentive for collusion. In each month  $t$ , each cartel firm  $i \in \mathcal{I}$  observes the residual demand (both its slope  $\frac{dP}{dQ}_t$  and effective intercept  $\tilde{X}_t$ ) and the cost profile  $(c_{j,t})_{j \in \mathcal{I}}$ , and decides its output  $q_{i,t}$  conditional on its private history  $h_i^t$  (to be defined). Their total supply  $Q_{car,t} = \sum_{i \in \mathcal{I}} q_{i,t}$ , fringe supply  $Q_{fri,t}$ , and the demand collectively determine the market price  $P_t = \frac{dP}{dQ}_t \times (Q_{car,t} + Q_{fri,t} - \tilde{X}_t)$ .

Based on the monitoring structure of the vitamin cartels in Section 2.1, we assume the quantity profile is observed with  $L$  periods of lag:  $((q_{j,\tau}, Q_{fri,\tau})_{j \in \mathcal{I}, \tau \leq t-L})$ . We set  $L=3$  because most cartels relied on government statistics to verify self-reports at quarterly meetings.<sup>44</sup> Under this institutional setup, firm  $i$ ’s private history at the beginning of month  $t$  is

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

and the public history is

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

share of transaction volumes in 1998 (29.6%), the overcharges to American buyers are \$265 million. Bernheim’s estimate is smaller at \$190 million, presumably because he calculated only damages to the largest buyers (*i.e.* the plaintiffs), and also because his reduced-form regression did not incorporate the buyers’ equilibrium response to lower prices. That is, our model predicts the transaction volume would have been 17.9% higher, which we incorporate as additional gains from competition.

42. See [Supplementary Appendix A.1](#) (e) and [Marshall et al. \(2008\)](#) for the details of these price announcements. [Harrington and Chen \(2006\)](#) propose a model of an endogenously rising price path.

43. Our results are robust to the consideration of long-term contracts (see Section 6.2).

44. We abstract from the exact timing of these quarterly meetings on calendar due to data limitations.

Regarding the cartel firms' beliefs, we assume they held static expectations about fringe output (*i.e.* they expect  $Q_{fri,\tau} = Q_{fri,t-3}$  for each  $\tau \geq t$ ),<sup>45</sup> because Section 2.2 suggests they had limited visibility about the growth of fringe supply. Meanwhile, the industry background in Section 2.3 suggests the evolution of demand and costs,  $(\tilde{X}_\tau, \alpha_1, (c_{j,\tau})_{j \in \mathcal{I}})_{\tau=1}^\infty$ , is common knowledge, and hence we assume rational expectations with perfect foresight about these objects and omit them from the history. Finally, we assume the demand, the costs, and fringe supply after the sample period remain constant at their end-of-sample values in December 1998.<sup>46</sup> Our rationale for this modelling choice is that the industrial landscape completely changed after the prosecution in 1999, to the extent that assuming any prior knowledge or even remotely rational expectations about the subsequent events would seem unrealistic (see the final paragraph of Section 2.1).<sup>47</sup>

We consider the following equilibrium based on trigger strategies. The cartel firms are supposed to supply their respective quota allocations,  $(\bar{q}_{i,\tau|t})_{i \in \mathcal{I}, \tau \geq t}$ , given the rational expectation of demand and costs  $\{\tilde{X}_\tau, \alpha_1, (c_{j,\tau})_{j \in \mathcal{I}}\}_{\tau \geq t}$  and the static expectation of the fringe supply function (*i.e.*  $\kappa_\tau = \kappa_{t-3}$  or  $\lambda_\tau = \lambda_{t-3}$ ) for each  $\tau \geq t$ .

We write  $\tau|t$  to indicate the expected future cartel production plan for period  $\tau \geq t$  conditional on the static expectation  $Q_{fri,\tau} = Q_{fri,t-3}$  (or  $\lambda_\tau = \lambda_{t-3}$ ) formed as of current period  $t$ . We say non-compliance is confirmed in period  $\tau$  if, given the government statistics, it becomes common knowledge that some firm did not produce  $(\bar{q}_{i,s|t})_{i \in \mathcal{I}}$  in period  $\tau - 3$  for the first time (*i.e.*  $q_{i,s|t} = \bar{q}_{i,s|t}$  for each  $s < \tau - 3$  and  $i \in \mathcal{I}$ , but  $q_{i,\tau-3|t} \neq \bar{q}_{i,\tau-3|t}$  for some  $i \in \mathcal{I}$ ).

In each month  $t$ , given the expectation formed at  $t$ , the firms agree to play the following strategy for  $\tau \geq t$ : (1) if no non-compliance is confirmed before month  $\tau$ , then each firm sells  $q_{i,\tau|t} = \bar{q}_{i,\tau|t}$ ; and (2) if some non-compliance is confirmed in some previous month  $s \leq \tau$ , then each firm sells a static Nash equilibrium quantity  $q_{i,\tau} = q_{i,\tau|t}^N$ . Let us call this strategy the “trigger strategy.”<sup>48</sup>

Complying with the cartel agreement from month  $\tau$  on gives firm  $i$  the payoff of

$$V_{i,\tau|t}^C(\beta) = \sum_{s \geq \tau} \beta^{s-\tau} \pi_{i,s|t}^C, \quad (11)$$

where  $\beta \in (0, 1)$  is the discount factor. When firm  $i$  does not comply at  $\tau$ , the optimal deviation payoff is

$$V_{i,\tau|t}^D(\beta) = \sum_{s=\tau}^{\tau+2} \beta^{s-\tau} \pi_{i,s|t}^D + \sum_{s \geq \tau+3} \beta^{s-\tau} \pi_{i,s|t}^N, \quad (12)$$

because no punishment is conducted until the government statistics verify  $i$ 's non-compliance  $L = 3$  months later.

45. This specification corresponds to the baseline model (3). We assume the cartel firms expect  $\lambda_\tau = \lambda_{t-3}$  for each  $\tau \geq t$  in the alternative models (4) and (5).

46. This specification is typical in the empirical dynamic game literature. For example, Igami (2017, 2018) makes similar assumptions. By contrast, Igami and Uetake (2020) explicitly models the end of an industry by specifying a demand shifter that linearly decreases with time.

47. An alternative assumption would be the expectation of continued demand growth after 1998, but that would make the terminal values unrealistically high. By contrast, the correct anticipation of the industry's decline (at least in Europe and Japan) would imply low terminal values and low incentives to collude, which are difficult to reconcile with the existence of successful collusion. Thus, assuming a steady state after 1998 is both simple and reasonable in our context.

48. Note that producing  $q_{i,t}^N$  in each period  $t$  is an equilibrium in the dynamic game as well, because the evolution of demand and costs does not depend on the firms' outputs.

In each  $t$ , given  $V_{i,\tau|t}^C$  and  $V_{i,\tau|t}^D$  for  $\tau \geq t$ , cartel stability requires that each firm's individual incentive to collude is positive,

$$\text{Incentive to collude}_{i,t}(\beta) = \min_{\tau \geq t} (V_{i,\tau|t}^C(\beta) - V_{i,\tau|t}^D(\beta)) \geq 0. \quad (13)$$

If there exist  $i \in \mathcal{I}$  and  $\tau \geq t$  for which  $V_{i,\tau|t}^C < V_{i,\tau|t}^D$ , it becomes common knowledge as of  $t$  that some firm will deviate in month  $\tau$  and the prevailing actions will be a static Nash equilibrium from  $\tau + 3$ . The situation becomes the same as in a *finitely* repeated game, and hence each firm deviates in month  $t$ . Accordingly, the trigger strategy is an equilibrium (given the firms' expectations at  $t$ ) if and only if the collective incentive is positive,

$$\text{Incentive to collude}_t(\beta) = \min_{i \in \mathcal{I}} (\text{Incentive to collude}_{i,t}(\beta)) \geq 0. \quad (14)$$

That is, the cartel's stability at  $t$  requires all of its members to expect positive payoffs at each point in the foreseeable future  $\tau > t$  given the information at  $t$ . This inequality constitutes the “enforcement/incentive constraint” in our model (see footnote 5 in the introduction for the terminology).

Recall that the cartel firms held static beliefs about  $Q_{fri,\tau}$ . The actual  $Q_{fri,t}$  in the data increased from 1992 in a staggered manner in the vitamin C market, which is the only vitamin (among the four vitamins that we scrutinize) in which the cartel collapsed before the prosecution. The firms revise their expectation of  $Q_{fri,\tau}$  more pessimistically over time. Eventually, the cartel becomes unstable in the period in which (14) is violated for the first time.<sup>49</sup>

## 5.2. Estimates of the incentives to collude

This theoretical model is deterministic in the sense that monitoring is “perfect” (albeit with a delay) and there is no uncertainty about demand or costs from the firms' perspectives. From the econometrician's perspective, however, our measure of cartel stability should account for the statistical uncertainty due to sampling error. We used block-bootstrap samples to compute  $\theta^{bs}$  (where  $bs = 1, 2, \dots, BS$ ) and standard errors in section 4.3. We use the same  $BS = 1,000$  parameter estimates to calculate 1,000 sequences of  $\text{Incentive to collude}_t(\theta^{bs}; \beta)$ , based on which we construct confidence intervals for our incentive estimates.

Figure 6 shows our estimates of the vitamin C cartel members' individual incentives (top panel) as well as their collective ones (bottom panel). The top panel suggests Roche's constraint was the least stringent of all members' at the beginning of the cartel, because it is the largest firm with the lowest cost, and the cartel quotas are well aligned with market shares under static Nash (recall quotas are based on competitive market shares in 1990). However, Roche's constraint became more stringent as the negative news on the fringe supply arrived, and was the tightest in 1995 and 1996, coinciding with the cartel's breakup in reality.<sup>50</sup>

49. This setup implies that, for the market in which the cartel collapsed, we do not interpret the entire sequence of the play as part of a *single* equilibrium strategy as in Porter (1983) or Ellison (1994). Instead, we focus on the actual history of bad news (e.g. an unprecedented growth of the vitamin C exports from China) and propose the following interpretation. At the beginning of the cartel, the cartel firms expected the future environment would make the trigger strategy an equilibrium (in particular, that no breakup would happen on the equilibrium path). At some point in the subsequent periods, however, the previously unforeseen negative news about  $Q_{fri,t}$  arrives and forces them to realize the cartel agreement is no longer an equilibrium. The members switch to the repetition of static Nash equilibrium as a consequence.

50. Figure 6 shows the incentive estimates at  $\beta = 0.8$  as the baseline case, because  $\beta < 0.8$  predicts the cartel's instability almost from the beginning in 1991, whereas higher  $\beta > 0.8$  could make it mechanically (and almost arbitrarily) more stable throughout the sample period. Note our notion of  $\beta$  includes the probability of an “exogenous” death of the cartel, and the main decision-makers are divisional heads, which makes  $\beta = 0.8$  a realistic level.

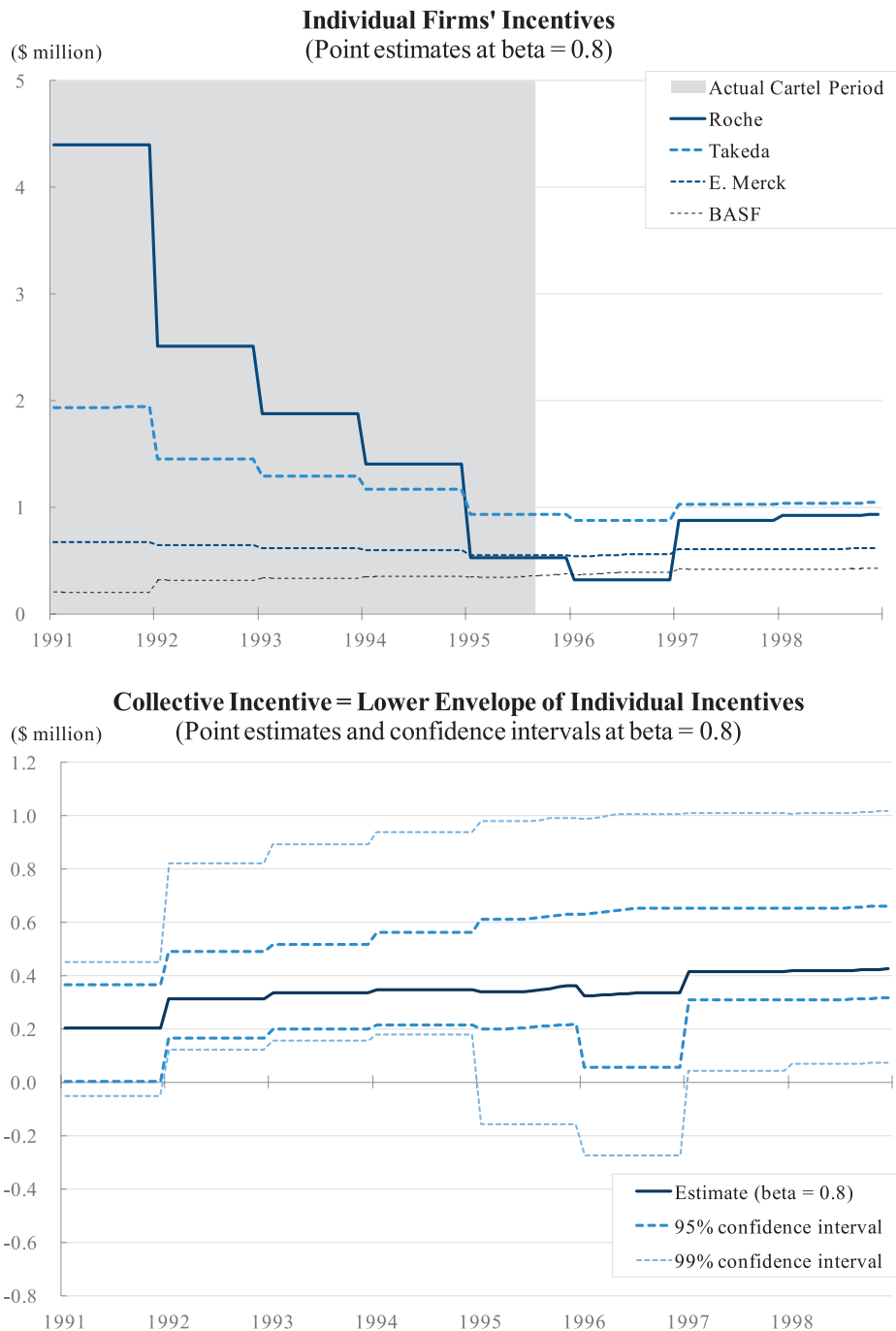


FIGURE 6

**Individual and collective incentives to collude (vitamin C)**

*Notes:* See equations (13) and (14) for the definitions of the “incentives to collude.” All values are rescaled as the average monthly profits (*i.e.* multiplied by  $1 - \beta$ ). We assume the demand, the costs, and fringe supply after the sample period remain constant at their end-of-sample values in December 1998. The confidence intervals in the bottom panel reflect the 99.5th, 97.5th, 2.5th, and 0.5th percentiles of the 1,000 block-bootstrap estimates.

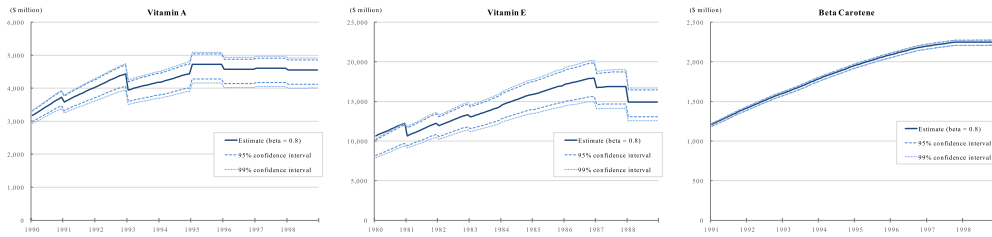


FIGURE 7

### Roche's incentive to collude (vitamins A and E, and beta carotene)

*Notes:* We assume the demand, the costs, and fringe supply after the sample period remain constant at their end-of-sample values in December 1998. We set  $\beta = 0.8$  for these plots. The confidence intervals reflect the 99.5th, 97.5th, 2.5th, and 0.5th percentiles of the 1,000 block-bootstrap estimates. All values are rescaled as the average monthly profits (*i.e.* multiplied by  $1 - \beta$ ).

The finding that the cartel was destabilized by the sudden, unexpected growth of fringe would seem obvious, but note the constraint would never be violated if costs were symmetric. Larger  $Q_{fri,t}$  means smaller residual demand,  $\tilde{X}_t - Q_{fri,t}$ . When the residual demand is small, a low-cost firm such as Roche could win a disproportionately large market share (relative to high-cost rivals) in static Nash,<sup>51</sup> but the quota share is fixed. Hence, as the residual demand shrinks, low-cost firms become increasingly disgruntled.

By contrast, the same analysis yields completely different pictures for vitamins A and E, and beta carotene. Figure 7 shows Roche's incentives are unambiguously positive, suggesting the stability of these cartels throughout the 1990s; they were fully operational until the prosecution in 1999 in reality as well. Hence, our model explains the life and death of all four cartels for which reliable data exist.<sup>52</sup>

### 5.3. Why the vitamin C cartel collapsed

Why did the vitamin C cartel collapse within a few years, whereas the other three survived for a decade? Figure 8 illustrates the effects of demand growth and fringe supply on the cartel's stability, by showing Roche's incentive to collude in four different scenarios. Our counterfactual simulations alter the course of events from 1995, because the actual cartel ended in the middle of 1995, which suggests the environment fundamentally changed around that year.

Scenario 1 at the top is the “dream world” counterfactual for the cartel, in which the demand shifter did not decline after 1994, and the Chinese exports stopped growing after 1994. Under these favourable conditions, Roche's incentive in 1995 would have been greater than that in reality as of 1991. The cartel could have survived throughout the sample period.

51. To verify this claim, suppose the inverse demand function is  $P(Q) = a - bQ$ . Firm  $i$ 's market share in Cournot equilibrium is

$$s_i = \frac{a - (n+1)c_i + \sum_j c_j}{na - \sum_j c_j},$$

where  $c_i$  is firm  $i$ 's marginal cost. As  $a \rightarrow \infty$ ,  $s_i$  converges to  $\frac{1}{n}$ . Hence, cost asymmetry matters less when demand is larger.

52. We do not analyse the suspected cartel spell 1985–88 in the vitamin C market, because neither a static Nash equilibrium or a dynamic-game equilibrium seems to apply. Bernheim (2002a) suggests the plaintiffs suspected anti-competitive behaviours in this period, but EC (2003) suggests Roche's attempts did not succeed, which means the strategy profile was not common knowledge (*i.e.* Roche was trying to coordinate on a repeated-games equilibrium, but BASF and the other firms believed Roche was doing something else and did not quite follow it).

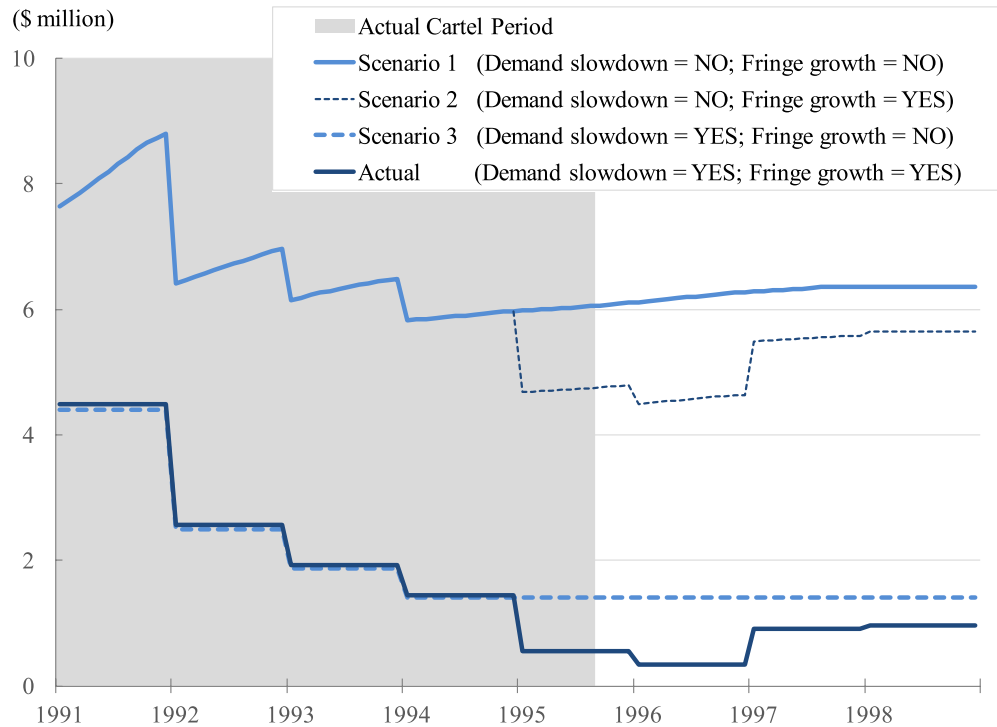


FIGURE 8

### Effects of demand and supply on Roche's incentive (vitamin C)

Notes: Different scenarios about demand lead to different incentive estimates from the beginning, because the firms have rational expectations (perfect foresight) about the growth of demand. By contrast, different scenarios on fringe growth affect the incentives only contemporaneously, because the firms hold static expectations about it, which are updated every year when they observe the actual shipments. We set  $\beta = 0.8$  for expositional purposes, but similar patterns emerge under different values of  $\beta$ .

Scenario 2 is the same as Scenario 1 on the demand side but incorporates the actual path of fringe supply. Hence, their difference reflects the impact of fringe growth in the mid-1990s. Even the lowest part of the incentive in this scenario is greater than the actual level in 1991. Thus, despite the rapid expansion of the competitive fringe, the cartel could have survived beyond 1995 if the market size had not shrunk at the same time.<sup>53</sup>

Scenario 3 is the opposite of Scenario 2, incorporating the slowdown of demand while “freezing” the growth of fringe supply. Hence, we may interpret the difference between Scenarios 1 and 3 as the impact of the demand slowdown after 1994. Roche's incentive in 1995 is still positive but as low as its actual level in 1994.<sup>54</sup>

Finally, the incentive estimate at the bottom is the same one as in Figure 6. It reflects both the slowdown of the demand growth and the final phase of the Chinese supply expansion in the mid-1990s. Thus, our counterfactual simulations suggest neither the slowdown of demand growth nor the sudden expansion of fringe supply alone could explain the cartel's breakup, but the two together could.

53. The magnitude of this finding is sensitive to the way we model the fringe supply. [Supplementary Appendix E.1](#) reports the same analysis under models 2 and 3, where China plays a more important role.

54. See [Harrington et al. \(2015\)](#) for cartel and demand slowdown.



These simulations demonstrate how one can use our framework to measure the effects of various factors on cartel stability. In Section 7, we extend this approach to measuring the effects of mergers (*i.e.* changes in market structure and cost profile). Before proceeding, however, we discuss several theoretical considerations and conduct sensitivity analysis on the key features of the model.

## 6. THEORETICAL CONSIDERATIONS AND SENSITIVITY ANALYSIS

Section 5 showed a simple repeated-games model could explain the life and death of the four vitamin cartels. Section 6.1 considers more complicated theoretical models and discuss the implications of our modelling choices. Section 6.2 reports the results under alternative assumptions.

### 6.1. *Theoretical considerations*

We discuss five important aspects of the model and their background.

**(1) Multi-market contact** Multi-market contact (MMC) is a situation in which firms compete (or collude) in more than one market. Theoretically, MMC could facilitate collusion if firms adopt a scheme that involves punishment in multiple markets, thereby making punishment more severe and the enforcement/incentive constraints less stringent than in the single-market scheme.<sup>55</sup> Curiously, the vitamin cartels did not seem to employ such punishment schemes, nor did the breakup of a cartel trigger punishment in other markets, even when the same members (and the cheating firms) were involved.<sup>56</sup> Accordingly, we model punishment in each market separately, and our incentive estimates represent a lower bound of theoretically possible ones under multi-market punishment schemes.

**(2) Quantity game** We model the stage game as a quantity game, which is a standard model for homogeneous-good industries such as bulk chemicals. A usual criticism of the Cournot model is that real-world oligopolists choose both quantities *and* prices. We have considered alternative specifications including a price game (Bertrand) and a quantity-and-price game (Kreps-Scheinkman). However, the Bertrand model does not match the industry characteristics and the data patterns (Section 3.2), and quantity-and-price games either require data that do not exist or entail multiple equilibria. Hence, we believe the Cournot model is the best available choice that fits our empirical context, is computationally tractable, and generates reasonable estimates. [Supplementary Appendix D.1](#) provides more details.

**(3) Delayed monitoring** In our model, no punishment is conducted until non-compliance is verified with  $L$ -month lag. That is, we assume “perfect” monitoring of sales quantities with a delay, based on the fact that the vitamin cartels relied on government statistics as a source of external verification of self-reported sales, at the quarterly meetings. Two questions arise.

55. [Bernheim and Whinston \(1990\)](#), [Matsushima \(2001\)](#), [Kobayashi and Ohta \(2012\)](#), and [Sekiguchi \(2015\)](#).

56. The EC evidence does not suggest the existence of any contingency plans connecting different cartels. Each cartel had its own protocol, operated separately, and ended at different times between 1994 and 1999. See [Supplementary Appendix A.1](#), “(h) (Lack of) Interaction between Different Cartels” for specific examples. Why did they *not* use multi-market punishment? Our results in Section 4.4 suggest the initial enforcement/incentive constraints were satisfied even under the single-market punishment scheme, which obviates the need for more complicated arrangements. Co-ordinating 21 firms across 16 markets would pose a practical challenge as well.

First, why did firms choose to wait for the government statistics when they might have been able to infer rivals' non-compliance from contemporaneous prices and other (albeit imperfect) monitoring devices? Second, why did firms bother to exchange self-reported sales records when more reliable information would arrive in a few months anyway? We may reconcile the first observation by extending the model to include an additive noise term in the inverse demand function, which will prevent firms from inferring rivals' non-compliance. Regarding the second point, modelling communications is beyond the scope of this paper, but recent theories suggest cheap talks could facilitate collusion. See [Supplementary Appendix D.2](#) for details.

**(4) Static expectations on fringe supply** We assume the cartel firms had static expectations about fringe supply, based on [EC \(2003\)](#). Were they really so “irrational”? One possibility is that they truly lacked precise information about Chinese SOEs and other fringe suppliers, which seems plausible given their record of failed predictions in multiple markets. (As we find in Section 6.2, the cartel could not have even started operations if they had correctly foreseen the growth of fringe.) Another possibility is that they had correct predictions but rationally chose to speak naïvely at the cartel meetings. That is, even if we suppose instead that they had had near-perfect foresight about  $Q_{fri,t}$ , an extended version of our model in the spirit of [Kreps et al. \(1982\)](#) could still rationalize “static expectations.” [Supplementary Appendix D.3](#) explains such an extension and intuition.

**(5) Nash reversion** We specify an infinite repetition of the static Nash equilibrium as the punishment, because [EC \(2003\)](#) reports the cartel members communicated their understanding that someone's withdrawal or non-compliance would bring back competitive behaviours and low prices (without any indication of reverting back to cooperative behaviours subsequently). Theorists have proposed more severe forms of punishment. For example, [Abreu \(1986\)](#) constructs a “stick-and-carrot” equilibrium. [Fudenberg and Maskin \(1986\)](#), [Abreu et al. \(1990\)](#), and [Fudenberg et al. \(1994\)](#) show players can implement a severe punishment incentivized by a continuation payoff. However, the data on vitamin C prices after the cartel's collapse indicate the market was stable, and do not exhibit patterns indicating the movement of continuation payoffs as these advanced theories predict.<sup>57</sup>

## 6.2. Sensitivity analysis

We used as much direct evidence as possible to guide our modelling choices. This subsection considers alternative specifications of the following eight aspects.

**(1) Endogenous fringe** China was a major disturbance to cartel stability.<sup>58</sup> Our baseline model treated its government and SOEs as exogenous fringe players who built new plants for geopolitical reasons and dumped domestic surpluses on the international market. [Supplementary Appendix E.1](#) reports results under alternative models, in which we treat China as endogenous fringe that responds to the international price. Whereas the GMM estimates of demand and costs are broadly similar to the baseline result, the cartel/monopoly prices that these models imply are slightly too high relative to the actual price in the data. The most important difference between model 1 and models 2 and 3 is that the rapid growth of the Chinese exports plays a more important

57. This observation does not preclude the possibility that the distribution of continuation payoffs depends on strategies. Nevertheless, the post-cartel price data exhibit stationary patterns for at least a few years.

58. This analysis applies only to the vitamin C market. The cartel firms' total market shares were close to 100% in the three other markets, as [Supplementary Appendix A.1](#) (h) shows. Vitamin B12 was an exception with a non-cartel share of 31%, most of which is attributed to Glaxo, a British drug maker. A model with a sub-coalition, such as [Decarolis et al. \(2020\)](#) might be useful for studying a situation with partial cartel.

role in the latter two, because the fringe affects the cartel's profitability more dramatically in these models.

**(2) Dynamic limit pricing** In [Supplementary Appendix E.2](#), we also consider the theoretical possibility that the cartel had known the time-invariant fringe supply curve and had rationally played against it. We ask whether the cartel could have kept the price somewhat lower than the actual/monopoly level, so that fringe output would not expand as much as it actually did. Our analysis suggests such a “limit price” would have been too low for the cartel to be meaningful. Hence, we reject this hyper-rational scenario.

**(3) Renegotiating Quotas** We relied on direct evidence from EC (2003) to model the cartel's quotas based on its members' pre-cartel market shares (i.e., under oligopolistic competition). The record indicates that whenever a member proposed a revision of pre-existing quotas, the “Big Three” opposed the idea because they believed negotiations over quotas would never end and would destabilize cartel operations. Such pragmatic considerations notwithstanding, we ask whether the vitamin C cartel could have optimally renegotiated quotas to avoid its collapse in 1995. In [Supplementary Appendix E.3](#), we find some quota reallocation could have improved Roche's incentive sufficiently but would have been impractical.

**(4) Cartel price below monopoly level** Because the actual cartel pricing converged to monopoly levels, our subsequent analysis equated cartel prices with monopoly prices. Appendix E.4 shows alternative cartel prices could not have increased the incentive to collude.

**(5) Monitoring lag** Given the prominent role of monitoring in the theory of repeated games, one may naturally ask how the results change under alternative specifications of monitoring lag,  $L$ . [Supplementary Appendix E.5](#) shows two cases, with  $L = 1$  and  $L = 12$ . We find  $L = 1$  would increase the incentive to collude but only slightly, whereas  $L = 12$  would make collusion unsustainable. The direction of change is not surprising, but its nontrivial magnitude is a potentially policy-relevant finding, because  $L$  is partially determined by national governments who publish international trade statistics.

**(6) Rational, static, and adaptive expectations** Our baseline model assumes the cartel members had rational expectations about demand and costs, as well as static expectations on China, based on the evidence in Section 2. [Supplementary Appendix E.6](#) considers two alternatives. First, we use adaptive expectations on demand growth ( $\tilde{X}_t$ ), in which firms update predictions based on their observations in the recent past. Second, what if the firms had had rational expectations on China? In both cases, we find the enforcement/incentive constraint would have been violated from the beginning of the cartel (i.e.  $Incentive\ to\ collude_{1991} < 0$ ), which is inconsistent with the cartel's existence for more than four years.

**(7) Log-log demand** We used the linear demand model in Section 4, whereas [Supplementary Appendix E.7](#) uses the log-log specification. Neither the identification strategy nor the cost estimates changes materially. However, the log-log estimates suggest inelastic demand. Taken at its face value, this result implies the optimal cartel/monopoly price would be positive infinity. In reality, however, the documents suggest the cartel faced elastic demand and constantly adjusted its target prices both upward and downward. Hence, we prefer the linear specification to the log-log version.

**(8) Long-term contracts** A typical contract is either spot or lasts for three months, but some last six to 12 months ([UKCC, 2001](#)). Our baseline model assumes monthly spot-market transactions and abstracts from multi-period aspects. [Supplementary Appendix E.8](#) shows explicitly incorporating long-term contracts does not alter the incentive to collude in our model.

Three messages emerge from these analyses. First, we find simple theory goes a long way. Our baseline model with a linear demand, Cournot competition, monopoly pricing, and trigger strategy is among the simplest models of collusion. One might think such a textbook model is too stylized for studying antitrust cases in reality; it turned out to be a useful framework. The second takeaway is that certain parts of the model play critical roles—as theory suggests they should—such as the modelling of the outsiders and the length of the monitoring lag. Meanwhile, other theoretical possibilities (*e.g.* dynamic limit pricing and renegotiation) turned out to be less relevant in our context. Finally, static expectations would seem a useful modelling assumption when firms are faced with new challenges like the emergence of strong competitors from China.

## 7. MERGERS, ASYMMETRY, AND COORDINATED EFFECTS

Mergers affect the incentives for collusion, explicit or tacit.<sup>59</sup> “Coordinated effects” refer to this possibility and have been an important issue in antitrust policy. Nearly 60% of challenges filed by the DOJ and FTC over 1990–2014 allege coordinated effects, according to Gilbert and Greene (2015). The central question is whether a merger makes firms more likely to restrict output and raise prices collectively, or (if the market currently has effective existing coordination) whether “it leads rivals to coordinate their strategic choices more perfectly, more completely, or more durably.”<sup>60</sup> Our empirical model makes such coordinated-effects analysis possible. Because we use only such basic data as prices, costs, quantities, and the state of competition, which are often available to the antitrust authority at the time of merger review, our approach does not add extra burden compared with the data requirement for a conventional analysis (*e.g.* prospective merger simulations of unilateral effects).

Section 7.1 explains how the incentive to collude depends not only on the number of firms but also on their cost asymmetry. We then present empirical measures of coordinated effects in Sections 7.2–7.4 by simulating incentives under a series of hypothetical mergers. Results suggest many mergers could make market structure less competitive (in terms of unilateral effects) and *less collusive* (in terms of coordinated effects) at the same time. [Supplementary Appendix F.2](#) offers a “practitioner’s guide.”

### 7.1. *How mergers affect the incentive to collude*

The conventional wisdom since [Stigler \(1964\)](#) is that mergers facilitate collusion, but this conjecture is not always correct. [Rothschild \(1999\)](#) points out that “the stability of a cartel depends not only on the number of members but also on their individual or aggregate costs.” Subsequent theoretical works by [Compte et al. \(2002\)](#), and [Vasconcelos \(2005\)](#) suggest mergers may hurt collusion if firms become more asymmetric after the deal. In particular, [Vasconcelos \(2005\)](#) highlights the role of efficiency gains in reshaping cost asymmetries among firms, which could either help or hinder collusion.<sup>61</sup>

59. We regard our analysis of explicit collusion as a benchmark and an upper bound of what tacit colluders would be able to achieve. Theoretical models usually do not distinguish between explicit and tacit collusion, but see [Awaya and Krishna \(2016\)](#) for one that distinguishes between them. [Kaplow \(2013\)](#) elaborates on exactly what constitutes price fixing in the legal sense.

60. See [Dick \(2003, p. 66\)](#), then acting chief of competition policy at the DOJ’s Antitrust Division.

61. [Vasconcelos \(2005\)](#) considers optimal punishment, and most of his “counter-intuitive” findings come from easing the punishment. Hence, his results are not directly applicable to our context with Nash reversion, for which we present our theoretical analysis in the following.

To develop intuition, first consider a situation with symmetric firms. Then compare it with another in which some firms have lower costs while the others have higher costs. The individual incentives (13) of some firms increase, but those of the others decrease. Because a successful collusion must satisfy all firms, the collective enforcement/incentive constraint (14) becomes more stringent as a result. This is how asymmetries destabilize collusion.

More precisely, let  $s_i$  be firm  $i$ 's market share in the static Nash equilibrium (we omit the time subscript and fringe output for expositional purposes). Its profit under the quota-based cartel is

$$\pi_i^C = s_i (P^m - c_i) Q^m, \quad (15)$$

where  $P^m$  and  $Q^m$  are monopoly price and output based on the cartel leader's cost. Given the inverse demand function  $P = a - bQ$ ,<sup>62</sup> the deviation payoff is

$$\pi_i^D = \max_{q_i} (a - b(q_i + (1 - s_i)Q^m) - c_i) q_i. \quad (16)$$

The punishment (static Nash) payoff is

$$\pi_i^N = s_i (P^N - c_i) Q^N, \quad (17)$$

where  $P^N$  and  $Q^N$  are the price and total output in the static Nash equilibrium. Firm  $i$ 's gains from collusion is proportional to

$$\pi_i^C - \pi_i^N = s_i [(P^m - c_i) Q^m - (P^N - c_i) Q^N], \quad (18)$$

and its opportunity cost (*i.e.* the deviation gain) is proportional to

$$\pi_i^D - \pi_i^C = \max_{q_i} (a - b(q_i + (1 - s_i)Q^m) - c_i) q_i - s_i (P^m - c_i) Q^m. \quad (19)$$

Mergers reduce the number of firms and affect the incentive conditions (13) and (14) through four channels. First, fewer competitors mean a higher market share,  $s_i$ . This *direct market-share effect* increases the gains from collusion (18).

Second, the gains from deviation (19) are decreasing in  $s_i$ :

$$\begin{aligned} & \frac{d}{ds_i} (a - b(q_i + (1 - s_i)Q^m) - c_i) q_i^* - s_i (P^m - c_i) Q^m \\ &= bQ^m q_i^* - (P^m - c_i) Q^m \\ &= -(P^m - c_i - bq_i^*) Q^m < 0, \end{aligned} \quad (20)$$

where  $q_i^*$  is firm  $i$ 's optimal unilateral deviation from the cartel agreement (*i.e.* best response to the other firms that are collectively producing  $(1 - s_i)Q^m$ ). The first equality follows from the envelope theorem. The last inequality follows from firm  $i$ 's profit maximization. In [Supplementary Appendix F.1](#), we show it is suboptimal for firm  $i$  to increase  $q_i^*$  to the level such that  $P^m - c_i - bq_i^* < 0$ . Hence,  $\pi_i^C$  increases more than  $\pi_i^D$  does, as  $s_i$  increases with mergers. This *deviation-mitigating effect* reduces (19) and further increases the incentive to collude.

62. Note  $a$  and  $b$  correspond to  $\tilde{X}_t/|\alpha_1|$  and  $1/|\alpha_1|$  in Sections 4 and 5.

However, the third channel works against these two positive effects. The bracketed term in (18),  $[(P^m - c_i)Q^m - (P^N - c_i)Q^N]$ , decreases with mergers, because  $P^N$  increases and narrows its gap with  $P^m$ . As market structure becomes closer to monopoly, the Nash profit eventually converges to the monopoly level, which obviates the need for collusion. The convergence of market structure decreases the gains from collusion (18). This *convergence effect* would not dominate the first two positive effects (of increasing  $s_i$ ) under symmetric Cournot, but it could under cost asymmetry.<sup>63</sup>

Fourth, mergers alter not only the number of firms but also their *cost profile*. Changing degrees of cost asymmetry affect  $s_i$ , which in turn affects collusive incentives through the three channels in the above. Moreover, if firm  $i$  is merging, efficiency gains could directly affect its incentive by changing  $c_i$  in (18) and (19).

Thus, the enforcement/incentive constraint (14) could become either more stringent or less stringent as a result of mergers. Not only the magnitude of the coordinated effects but also their *direction* depends on market structure, cost asymmetry, and demand conditions. Hence, coordinated effects call for a careful quantitative analysis. Our explanation in the above highlights the intuition; see [Supplementary Appendix F.1](#) for a formal analysis.

## 7.2. The BASF-Takeda merger

We start our empirical merger analysis with the specific case of BASF and Takeda, in which Takeda sold all of its vitamin businesses to BASF in 2001, that is, after the prosecution.<sup>64</sup> Instead of 2001, we simulate the same merger in 1990, a year before the vitamin C cartel started, so that we can study the impact of merger on collusive incentives during the period for which we have detailed evidence on the cartels.

Details are based on the UKCC's 190-page report on the proposed acquisition:

- After the actual transaction in 2001, BASF shut down its own facilities and switched all production to Takeda's plants. Hence, we assume the merged entity inherits Takeda's cost structure, which was superior to BASF's:

$$c_{basf, \tau|t}^{post} = \min \left\{ c_{takeda, \tau|t}^{pre}, c_{basf, \tau|t}^{pre} \right\} = c_{takeda, \tau|t}^{pre} \quad (21)$$

for all  $\tau$  and  $t$ , where  $c_{i, \tau|t}^{pre}$  and  $c_{i, \tau|t}^{post}$  are pre- and post-merger marginal costs, respectively. Other, non-merging firms' costs remain unchanged.

- We assume the existence of ample production capacity, because neither the long-run physical capacities nor the reported "nameplate" capacities were binding at any point during the sample period (see Section 3.1).
- The cartel in reality allocated quotas based on the historical market shares before the cartel (*i.e.* competitive outcomes in 1990). Accordingly, we construct a counterfactual version

63. For example, suppose two low-cost firms (call them L1 and L2) and a high-cost firm (H) exist.  $P^N$  is low when L1 and L2 are independent and compete against each other.  $P^N$  will increase substantially if they merge, because the combination of L1 and L2 creates a near-monopoly player. Hence, the merged entity would not benefit as much from collusion as L1 or L2 independently would.

64. The public-relations disaster due to the cartel scandal was one reason, but a more fundamental reason was that the global pharmaceutical industry was undergoing a period of restructuring in which conglomerates pulled out of non-core, low-margin businesses such as bulk chemicals. See [Yamaguchi \(2000\)](#). We thank Hidemaru Yamaguchi, health care and pharmaceutical research analyst at Citigroup Global Markets Japan, for sharing his knowledge on these transactions and industry history.



TABLE 3  
Cartel stability under hypothetical BASF-Takeda Merger in 1990

Merger scenario	No merger	BASF-Takeda merger								
Synergy ( $\sigma$ )		0	0.05	0.1	0.15	0.2	0.25	0.3	0.4	0.5
Collusive incentive	329	485	512	483	450	411	367	318	202	64
Coordinated effect	0	156	183	154	121	82	38	-12	-127	-264
(% change)	$\pm 0\%$	+47%	+55%	+47%	+37%	+25%	+11%	-4%	-31%	-80%

Notes: The numbers (in thousand dollars) indicate the point estimates of the cartel's collective incentive in equation (14) as of August 1995 under  $\beta = 0.8$ . The first column shows our baseline estimates without merger. The other columns show results under the counterfactual BASF-Takeda merger in 1990 with specific levels of efficiency gain ("synergy"). See equation (22) for the definition of synergy,  $\sigma$ .

of "historical shares" and cartel quotas, by re-computing static Nash outcomes in 1990 between *three* firms (Roche, E. Merck, and the consolidated BASF-Takeda, including the efficiency gains in equations 21 or 22) instead of four in reality.

Under this setup, we recalculate streams of profits under the cartel, unilateral deviation, and static Nash,  $(\pi_{i,\tau|t}^C, \pi_{i,\tau|t}^D, \pi_{i,\tau|t}^N)$ , for each  $i \in \mathcal{I}$ ,  $t \geq 1991$ , and  $\tau \geq t$ .<sup>65</sup> The repeated-games framework of section 5 allows us to convert these profits into the estimates of counterfactual incentive to collude (14). The first two columns of Table 3 suggest the coordinated effect from this merger would be positive. Hence, the cartel's survival is more likely under the hypothetical merger in 1990 than in the actual history without merger.

### 7.3. The role of efficiency gains

Could efficiency gains help? Let  $\sigma \in [0, 1]$  parameterize synergy, and modify the merged entity's cost (21) as follows:

$$c_{basf,\tau|t}^{post} = (1 - \sigma) \times \min \left\{ c_{takeda,\tau|t}^{pre}, c_{basf,\tau|t}^{pre} \right\} = (1 - \sigma) \times c_{takeda,\tau|t}^{pre}. \quad (22)$$

In Table 3, additional columns reflect such synergistic scenarios. The 5%-efficiency-gain ( $\sigma = 0.05$ ) scenario outperforms both the baseline (no merger) and the no-synergy ( $\sigma = 0$ ) cases. However, higher levels of synergy ( $\sigma \geq 0.1$ ) turn out to destabilize the cartel, and the coordinated effects become negative at  $\sigma \geq 0.3$ . Thus, synergies could hinder collusion.

Figure 9 explains the underlying mechanism by comparing individual incentives (13) across these scenarios with different levels of  $\sigma$ . The first set of bar graphs ("Actual") shows the four firms' incentives in August 1995 without merger. The second set of bars labelled "Merger ( $\sigma = 0$ )" represents the three firms' incentives in the no-synergy merger counterfactual. The rest are synergistic mergers (5–50% cost reductions relative to Takeda's pre-merger level).

65. Readers who are familiar with Salant et al.'s (1983) theoretical finding (that *symmetric* Cournot competitors do not have static incentive to merge) might question whether our quantity-game setup is suitable for merger simulations. We believe so for two reasons. First, their "no incentive to merge" results rely on symmetry and do not extend to settings with asymmetric firms. Perry and Porter (1985) showed this limitation in a Cournot game with asymmetric costs, and Deneckere and Davidson (1985) did so for a differentiated-good Bertrand case. Our case involves firms with asymmetric costs as well, and our calculations confirmed BASF and Takeda would have (static) incentives to merge (*i.e.* BASF-Takeda's combined Cournot profits in 1991 would have *increased* by 6% under merger). Second, BASF's closure of its own facilities after the actual merger is indicative of excess capacity. BASF-Takeda's combined outputs decreased after merger. These developments closely match the "rationalization of assets" in Farrell and Shapiro (1990).



Individual firms'  
incentives to collude  
(\$ million)

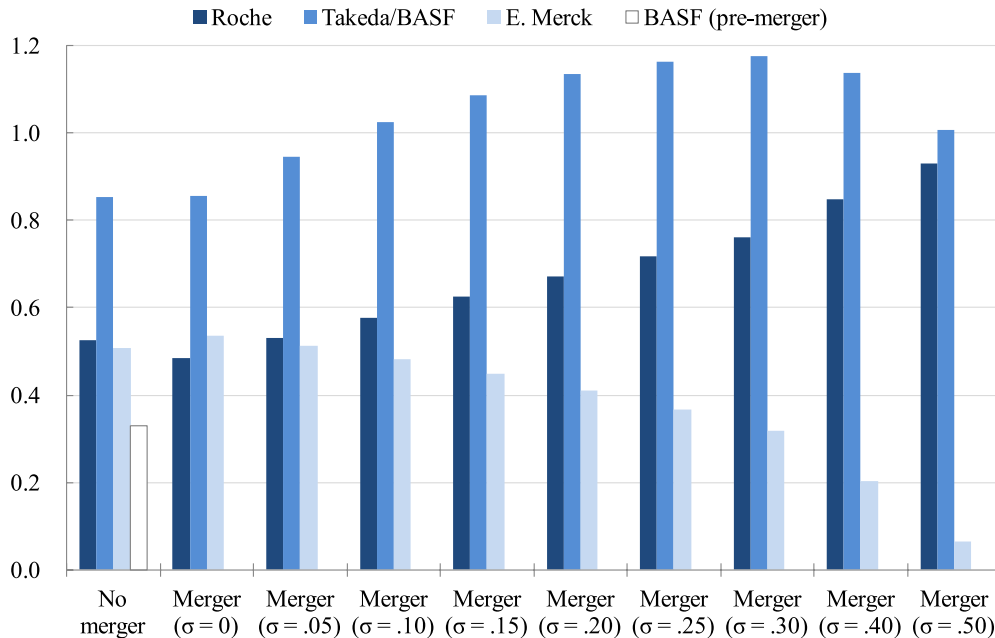


FIGURE 9

**Each firm's incentive at different levels of BASF-Takeda synergy**

Notes: The bars indicate individual firms' incentive estimates in equation (13) as of August 1995 under  $\beta = 0.8$ .

The impact of  $\sigma$  is highly asymmetric across firms. Roche's incentive increases with  $\sigma$ , whereas E. Merck's incentive decreases with  $\sigma$ . The main source of asymmetry is their competitive positions relative to BASF-Takeda. As  $\sigma$  increases, the cost competitiveness of BASF-Takeda becomes more similar to that of Roche (a low-cost rival) but less similar to that of E. Merck (a high-cost rival). Hence, their synergistic merger would facilitate collusion with Roche, but not with E. Merck, and destabilizes the cartel overall.<sup>66</sup> These firm-level asymmetries make the impact non-monotonic in efficiency gains.

Could a cartel-destabilizing merger still be profitable for the merging firms? The answer is "yes," because a sufficiently synergistic merger makes BASF-Takeda's static Nash profit greater than the sum of the constituent firms' collusive profits under the no-merger scenario (in a period-by-period comparison circa 1991). Our calculations suggest BASF and Takeda would want to merge when  $\sigma \geq 0.1$  even if they knew the merger could *destabilize* the cartel. Hence, efficiency gains could be socially beneficial beyond their immediate contribution to cost reduction.

66. Another interesting feature of the firm-level plot is that the incentive of BASF-Takeda changes non-monotonically in  $\sigma$ , with a peak at around  $\sigma = 0.3$ . As  $\sigma$  increases from 0, its cost competitiveness approaches Roche's low cost, which makes its incentives more closely aligned with Roche's. BASF-Takeda's cost matches Roche's at around  $\sigma = 0.3$ , above which it would effectively overtake Roche's lowest-cost position in the industry. Stronger BASF-Takeda would become less fearful about the prospect of breaking the agreement and competing against Roche, and increasingly disgruntled with the Roche-led scheme.

TABLE 4  
*Cartel stability under six different mergers*

Merger scenario	Marginal cost <sup>a</sup> (\$/kg)						Num. of firms <sup>a</sup>	HHI <sup>a</sup>	Collusive incentive <sup>b</sup>	
	Roche	Takeda	E. Merck	BASF	Mean	Std. dev.			(\$ thousand)	(% change)
No merger	6.26	9.44	10.72	11.13	9.39	2.21	4	3,009	329	±0%
Merger 1	6.26	9.44	10.72	—	8.81	2.30	3	3,395	485	+47%
Merger 2	6.26	9.44	—	11.13	8.95	2.47	3	3,519	407	+24%
Merger 3	6.26	—	10.72	11.13	9.37	2.70	3	3,725	213	−35%
Merger 4	6.26	9.44	—	—	7.85	2.25	2	4,273	342	+4%
Merger 5	6.26	—	10.72	—	8.49	3.16	2	4,661	86	−74%
Merger 6	6.26	—	—	11.13	8.70	3.44	2	4,826	8	−98%

Notes: We do not consider synergy in this subsection (*i.e.*  $\sigma = 0$ ).

<sup>a</sup>As of December 1990 (*i.e.* immediately before the beginning of the vitamin C cartel).

<sup>b</sup>Collective incentive to collude as of August 1995 (*i.e.* its final month of operation on record) under  $\beta = 0.8$ .

#### 7.4. Concentration, asymmetry, and coordinated effects

The critical role of cost asymmetry becomes clearer when we consider other hypothetical mergers in 1990. Table 4 lists the six cases we simulate and their key statistics:

- the continuing firms' marginal costs ('—' indicates the firm/plant joins the merger and is subsequently shut down),
- the post-merger number of firms,
- the post-merger Herfindahl–Hirschman Index (HHI), and
- the cartel's collective incentive to collude (14) as of August 1995.

Merger 1 corresponds to the BASF-Takeda merger (without synergy) in Section 7.2, where Roche, Takeda, and E. Merck effectively become the continuing firms. The static Nash equilibrium would have led to the HHI of 3,395, which is higher than 3,009 in the no-merger case. The collective incentive in August 1995 is \$485,000 in our point estimate.

Mergers 2 and 3 lead to triopoly market structures in which E. Merck and Takeda are absent, respectively (we do not consider eliminating Roche, because it is the industry leader with superior cost-competitiveness). The post-merger HHI of 3,519 and 3,725 suggest these mergers would have resulted in a higher concentration of market shares, predicting positive unilateral effects. However, the incentive estimate under Merger 3 (\$213,000) suggests the cartel would have become *less* stable (*i.e.* negative coordinated effects). Thus, a smaller number of firms and higher HHI, which are usually associated with a *less competitive* market structure, could simultaneously be associated with a *less collusive* incentive structure.

Mergers 4, 5, and 6 further illustrate the nuanced relationship between market structure and the incentive to collude. Each of these cases considers transactions that result in a duopoly, and hence the post-merger HHI (4,273–4,826) is generally higher than under Mergers 1, 2, and 3. However, these concentrated market shares do not necessarily translate into greater cartel stability. Merger 4 is the only merger(s) to duopoly in which cartel stability improves, because it creates a relatively symmetric duopoly of Roche and Takeda, the top two firms. By contrast, the coordinated effects of Mergers 5 and 6 are negative, as they lead to highly asymmetric duopoly.

Thus, although concentrated market structures may increase HHI and market power in terms of unilateral effects, both the sign and the magnitude of coordinated effects depend on the cost profile of all firms. The comparison of all scenarios in Table 4 suggests that, for a given number of continuing firms after merger(s), the greater their cost asymmetry (as measured by the standard

deviation of their marginal costs), the lower their incentives to collude. These nuanced, systematic relationships highlight the importance of quantitative analysis.

## 8. CONCLUSION

This paper shows a simple repeated-games model could (1) explain the life and death of the four major vitamin cartels, (2) quantify the effects of demand and supply on the incentive to collude, and (3) allow us to conduct prospective merger simulations of coordinated effects. Such quantification is an important step to complement the unilateral-effect analysis and the theoretical “checklist” of facilitating factors.

In the course of empirical analysis, we also effectively “tested” one of the most fundamental predictions of repeated games—that cooperation breaks down when the incentives are misaligned. Repeated-games theory is known for its conceptual sophistication but is considered difficult for empirical implementation. With suitable data and institutional details, however, the framework is useful for issues of practical importance.

We focused on the vitamins case because of its historical importance and its relatively simple institutional setting. We expect this article’s approach will be useful for studying other markets with similar characteristics, including many industrial markets for relatively homogeneous products.<sup>67</sup> These markets have been prominent on the list of cartel investigations by the antitrust authorities and hence appear immediately relevant.<sup>68</sup> With suitable assumptions, the extension of our method to differentiated-products models would be straightforward as well.

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### Supplementary Data

Supplementary data are available at *Review of Economic Studies* online.

### Data Availability Statement

The data and code underlying this research are available on Zenodo at <https://dx.doi.org/10.5281/zenodo.5104830>. The datasets were derived from sources in the public domain: Bernheim (2002a), EC (2003), and World Bank (2020).

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67. Supplementary Appendix F.2 offers a practitioner’s guide in which we explain the input requirement, deliverable outputs, a summary of procedures, and potential extensions.

68. For example, see <http://ec.europa.eu/competition/cartels/cases/cases.html>.

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