ANNUAL REVIEWS

Annual Review of Resource Economics

Concentration in Seed and Biotech Markets: Extent, Causes, and Impacts

Koen Deconinck

Organisation for Economic Co-Operation and Development (OECD), 75775 Paris Cedex 16, France; email: Koen.Deconinck@oecd.org

Annu. Rev. Resour. Econ. 2020. 12:5.1–5.19

The *Annual Review of Resource Economics* is online at resource.annualreviews.org

https://doi.org/10.1146/annurev-resource-102319-100751

JEL codes: L11, L40, L65, O30, Q16

Keywords

seed industry, seed markets, agricultural biotechnology, concentration, market power, competition

Abstract

The merger of Dow and DuPont, the acquisition of Syngenta by ChemChina, and the acquisition of Monsanto by Bayer have recently reshaped the global seed and biotech industry and caused concern about growing market concentration. This review documents market concentration in seed and agricultural biotech markets and discusses its causes and impacts. The available evidence suggests that concentration in seed markets varies strongly by crop and by country, while markets for biotech traits are considerably more concentrated. Complementarities between seed, biotech, and crop protection chemicals explain much of the observed structural changes in the industry, and new complementarities may be emerging with digital agriculture. Although growing concentration might in theory lead to higher prices and less innovation, evidence on this is currently limited; this tendency is also in part offset by the remedies imposed by competition authorities.

INTRODUCTION

Between 2015 and 2018, the global seed and crop biotechnology industry underwent important structural changes. The merger of Dow and DuPont (and the subsequent spinoff of its agricultural division as Corteva Agrisciences) and the acquisition of Monsanto by Bayer reduced the number of major players in the sector from six to four, while the fourth player, BASF, acquired divested Bayer businesses. At the same time, the acquisition of Syngenta by ChemChina put one of the four players under control of a Chinese state-owned firm.

These developments have reignited long-standing concerns over market concentration and corporate power in seed and biotechnology (Bonny 2017, ETC Group 2013, Philpott 2016). To assess the potential impacts of the recent mergers requires information on the extent of market concentration as well as an understanding of the underlying causes driving consolidation in the industry. A body of literature has studied these topics, but academic research and public debate have generally been hampered by a lack of information on the actual extent of market concentration (Fernandez-Cornejo & Just 2007, Mammana 2014).

In this article, I review the evidence on market concentration in seed and crop biotechnology. After briefly introducing these markets, I discuss the extent of concentration, its drivers and potential impacts, and avenues for further research.[1] Recurring themes are the heterogeneity of the sector across countries and crops (which cautions against broad generalizations) and the importance of innovation, both as a driver of consolidation and as a valuable outcome of the competitive process in the sector, which ought to be safeguarded.

FIRST THE SEED: A SHORT INTRODUCTION TO GLOBAL SEED AND BIOTECHNOLOGY MARKETS

Plant breeding is essential to long-run agricultural productivity growth.[2] Improved varieties introduced during the Green Revolution were responsible for 40% of the growth in crop production in developing countries between 1981 and 2000 (Evenson & Gollin 2003). Likewise, genetic improvement accounted for 60–80% of the sevenfold increase in US corn yields since the 1930s (Smith et al. 2014). Even where yields are stagnant, plant breeders often play a crucial role in preventing declines caused by pests (Olmstead & Rhode 2008). In the future, plant breeding may further support agricultural productivity; recent work has, for instance, shown that tweaking the photosynthesis process could lead to important yield increases for crops such as soybean, rice, and wheat (South et al. 2019).

Historically, farmers used seed saved from previous harvests or exchanged with neighbors. Farm-saved seed is still important in the developing world and for some crops (e.g., wheat) in

[1]This review builds on an OECD report by the author (Deconinck 2019, OECD 2018). For reviews of concentration in agricultural input industries, see Bonanno et al. (2017), Fuglie et al. (2011), Hernandez & Torero (2013), and Wesseler et al. (2015). Related topics surveyed elsewhere include the broader literature on competition issues in food and agriculture (MacDonald 2017, OECD 2014, Sexton & Xia 2018, Sheldon 2017), the role of intellectual property rights and proprietary innovation in agriculture (Campi & Nuvolari 2015, Clancy & Moschini 2017), and the role of public and private R&D in agricultural productivity growth (see e.g., Alston et al. 2010, Heisey & Fuglie 2018). A large literature explores the issues related to genetically modified (GM) crops; see Barrows et al. (2014), Bennett et al. (2013), and Qaim (2009) for introductions to the economic, health, environmental, and ethical aspects; Herring & Paarlberg (2016) on the political economy of GM crops; and Bonny (2017) on the differing philosophies that underlie the heated debates over GM crops and corporate power.

[2]"First the seed" was the slogan of the American Seed Trade Association (ASTA), and the title of Kloppenburg's (1988) history of the development of the American seed sector.

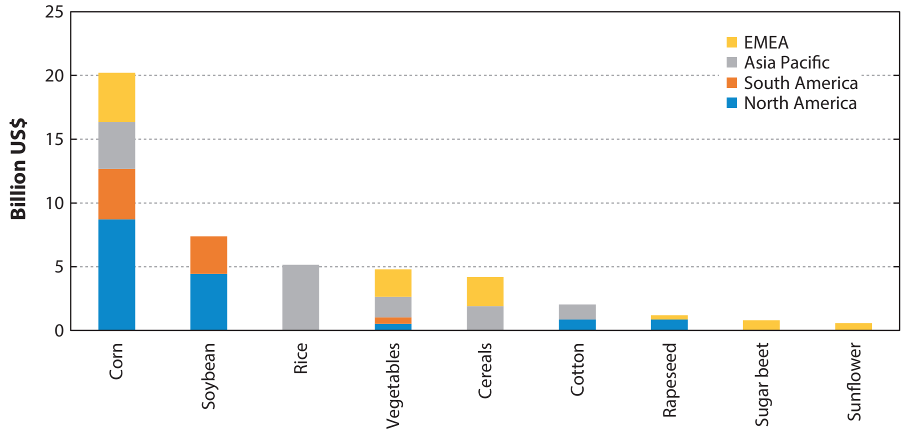

Figure 1

The global market for seed and biotechnology in 2014. Cereals exclude corn and rice. Figures refer only to the commercial seed market. Figure based on data from Syngenta (2016). Abbreviation: EMEA, Europe, Middle East, and Africa.

the developed world, but over time the importance of purchased seed has grown.[3] Public plant breeding has often been an important source of improved varieties, but the role of the private sector has grown and now dominates in high-income countries (Heisey & Fuglie 2011).[4]

The advent of biotechnology in the form of GM seed had a major impact on the industry (Bonny 2014). Specific traits could now be developed, for instance, for herbicide tolerance or resistance to pests or diseases, using genetic material derived from other organisms.[5] While this technology has transformed the sector, its use is concentrated in a limited number of countries, crops, and traits. Four countries in the Americas (United States, Brazil, Argentina, and Canada) account for 85% of the global area of GM crops, nearly all of it devoted to soybean, corn, cotton, and rapeseed (canola), and almost exclusively using insect-resistance and herbicide-tolerance traits. The importance of genetic modification differs by crop; while some 80% of the global soybean and cotton area is planted with GM varieties, this share is closer to one-third for corn and rapeseed. Some important seed markets have been reluctant to allow cultivation of GM varieties. The European Union has only approved one GM variety for cultivation, an insect-resistant corn variety cultivated mainly in Spain (ISAAA 2018).[6]

The global commercial market for seed and biotechnology was estimated at US$52 billion in 2014 (**Figure 1**) and probably reached $70 billion by 2019.[7] In 2014, corn seed accounted

[3]On the importance of farm-saved seed in the developing world, see Spielman & Kennedy (2016) and Van Etten et al. (2017). For several crops including corn, seed is no longer saved because of the use of hybrid seed, developed in the 1930s. Crossing two pure-bred lines can create a seed that leads to a predictable and homogeneous crop. Using the resulting grain as seed, however, leads to heterogeneity and generally lower yields. It is therefore optimal for the farmer to buy new hybrid seed instead.

[4]Historical overviews of plant breeding are provided by Kingsbury (2009), Kloppenburg (1988), and Olmstead & Rhode (2008).

[5]A GM trait is a phenotypic characteristic (e.g., herbicide tolerance); an event refers to the underlying DNA sequence that has been inserted into the host genome and the site(s) where it has been inserted (Mumm 2013). This review uses the terms GM and biotech/biotechnology interchangeably and focuses only on crop biotechnology, excluding other applications (e.g., in animal genetics or medicine).

[6]On the regulatory framework in the European Union, see Beckmann et al. (2006); on the effects of delayed introduction of GM technologies, see Wesseler et al. (2017).

[7]Unless noted otherwise, references to market size refer to the commercial seed market only.

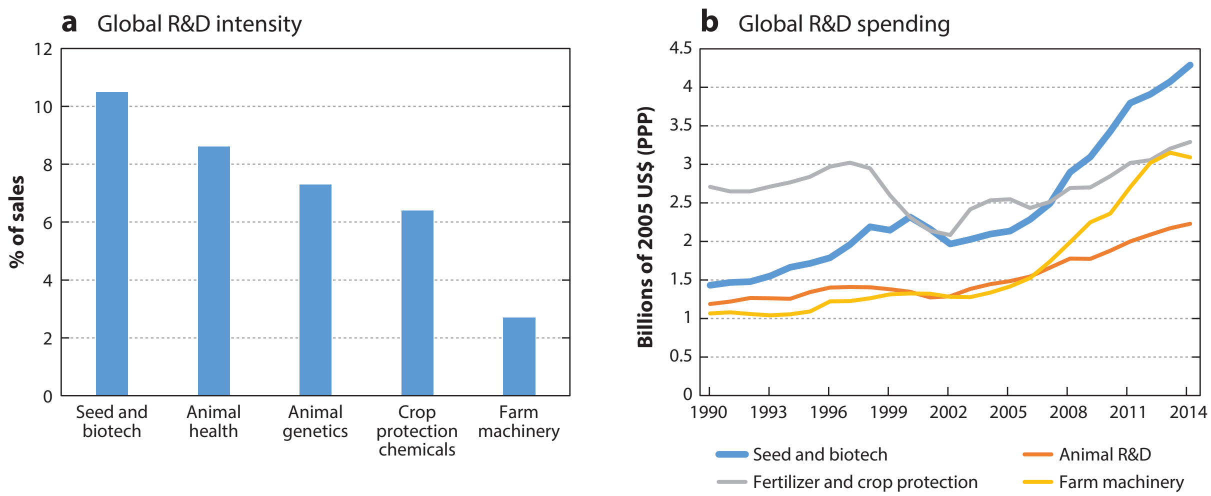

Figure 2

Global R&D spending in seed and biotech. (*a*) Global private R&D spending expressed as a share of revenues; data refer to 2009. (*b*) Global private R&D spending in real terms (2005 PPP) over time. Panel *a* based on data from Fuglie et al. (2011, table 7); panel *b* based on data from Fuglie (2016, tables 3 and 4).

for $20 billion and soybean seed for $7 billion. The North American market was estimated at $17 billion, dominated by corn (51%) and soybean (26%) (Syngenta 2016). The preeminence of corn and soybean, and of North and South America, is partly explained by the use of higher-priced GM seed.

The industry is characterized by high spending on research and development (R&D); the share of revenues devoted to R&D is higher than for any other agricultural input sector. Spending has nearly tripled in real terms over the past 25 years, with much of the increase occurring after 2004 (**Figure 2**). This partly reflects the development of GM traits, but spending is also high in non-GM markets. For instance, R&D spending in Dutch vegetable plant breeding has been estimated at 15–30% of sales (Schenkelaars et al. 2011).

EXTENT: WHAT DO WE KNOW ABOUT MARKET CONCENTRATION IN SEED AND BIOTECH?

As for other sectors, data on market shares in seed and biotech are typically not publicly available. Instead, researchers have used three main strategies to measure concentration in seed and biotech markets. A first approach estimates concentration ratios by combining information on leading companies' sales with an estimate of overall market size. A second approach uses privately held data. A third approach uses measures such as ownership of intellectual property rights (IPR) or regulatory approvals as proxies for market concentration.

Data on Global Sales and Market Size

Using the first approach, Fuglie et al. (2011) found that the global four-firm concentration ratio in seed and biotech had increased from 21% in 1994 to 54% in 2009; ETC Group (2013) put this figure at 58% in 2011. The same method underpinned statements that "three companies would sell 59% of the world's seeds" after the three seed mergers (Philpott 2016). Yet, there are several shortcomings in this approach. First, as pointed out by Bonny (2014, 2017), estimates of the overall size of the global seed market tend to vary, and some authors use implausibly low estimates. Bayer, Monsanto, Dow, DuPont, Syngenta, and BASF had combined seed and biotech sales of some $22 billion in 2016, but available estimates of the global market in 2016 vary from $54 billion to $69 billion; the resulting concentration ratio would thus range between 32% and 41%.[8] Beyond such problems of data quality, this method also gives misleading results because it aggregates markets using sales (value). Higher prices for GM seed imply that a higher weight is assigned to firms active in corn and soybean in North and South America (**Figure 1**). Before the mergers, for instance, Monsanto was the world's leading seed and biotech firm by sales, yet more than 80% of Monsanto's sales were concentrated in the Americas. In addition, this approach also says nothing about conditions in individual markets.

Privately Held Data

Some market research firms have detailed information on market size and market shares of various seed and biotechnology markets. Three well-known data providers are Kynetec, Phillips McDougall, and Kleffmann. Access to such privately held information can give a much richer view of concentration in seed and biotech markets. Two drawbacks of this method are its cost and potential restrictions on how researchers can communicate final results. A recent report by the OECD (2018) used data from Kleffmann to calculate concentration measures of seed markets. These are the most detailed and complete estimates available to date. The data focus on markets for germplasm, i.e., excluding GM traits.[9] **Table 1** shows estimates for 32 corn seed markets; the OECD study also contains estimates for soybean, wheat and barley, rapeseed, sunflower, cotton, sugar beet, and potato, albeit with varying degrees of country coverage.[10]

Deconinck (2019) summarizes the main insights. A first finding is important heterogeneity across crops and countries in the data set. For corn, for instance, the value-based Hirschman-Herfindahl Index (HHI) ranges from 933 in Belarus to almost 4,700 in Denmark.[11] A regression analysis suggests there are systematic differences between crops, even after correcting for market size, the use of GM, country fixed effects, and volume shares of public breeders and farm-saved seed. Based on the coefficients on dummy variables for different crops, all else equal, the HHI for cotton seed is 1,900 points higher than that for wheat and barley seed; effects are similarly large

[8] Sales of seeds and biotech in 2016 were $9,988 million for Monsanto, $1,505 million for Bayer, $2,657 million for Syngenta, $6,661 million for DuPont, $1,544 million for Dow, and negligible for BASF. Different market estimates for 2016 reviewed by Bonny (2017) range from $53.5 billion (Infinium) to $64.1 billion (Market Data Forecast); Kleffmann data used by OECD (2018) suggest a higher value of $69 billion. The higher estimates are consistent with the $45 billion estimate for 2012 by the International Seed Federation (ISF) and the trend growth evident in ISF's estimates between 2005 and 2012 (Ragonnaud 2013). Some other estimates are considerably lower. Phillips McDougall estimated the market at $35 billion in 2015, which would imply a concentration ratio of 63%. However, this market estimate does not capture all relevant crops (Bonny 2017).

[9] GM traits can be licensed by plant breeders; the Kleffmann data focus on germplasm (i.e., excluding the GM traits). Indirect data on market concentration in GM traits are provided below.

[10] The Kleffmann data set does not cover the large seed markets of China, India, and sub-Saharan Africa. On India, see Murugkar et al. (2007), Pray & Nagarajan (2014), and Spielman et al. (2014a,b); on sub-Saharan Africa, see Afr. Cent. Biodiversity (2015).

[11] The HHI is a standard measure of market concentration defined as the sum of squared market shares and reaching a maximum of 10,000 in the case of a monopoly. As a reference, if the market were split between n equal firms, the HHI would be 10,000 divided by n. The US Department of Justice (DOJ) and the Federal Trade Commission generally consider markets "highly concentrated" if the HHI is above 2,500, and "unconcentrated" if the HHI is below 1,500.

Table 1 Concentration in maize seed markets, 2016[a]

Country	Value		Volume	
	HHI[b]	C4 (%)[c]	HHI	C4 (%)
Argentina	2,510	73	2,274	71
Austria	2,071	77	2,041	76
Belarus	933	51	1,278	65
Belgium	1,761	72	1,703	71
Brazil	2,808	97	2,579	94
Bulgaria	3,563	91	3,600	89
Croatia	2,459	87	2,296	85
Czech Republic	1,342	63	1,342	63
Denmark	4,688	98	4,560	97
France	1,468	73	1,426	71
Germany	1,735	66	1,652	65
Greece	4,331	97	4,134	97
Hungary	2,355	81	2,160	79
Indonesia	2,850	95	2,539	87
Italy	3,242	93	3,109	92
Mexico	3,136	81	470	32
Netherlands	2,426	83	2,473	83
Philippines	1,700	72	864	52
Poland	1,105	57	1,167	59
Portugal	3,215	84	3,049	83
Romania	1,932	74	1,067	59
Russian Federation	1,358	67	1,378	6
Serbia	1,841	75	1,662	73
Slovakia	1,536	75	1,536	75
Slovenia	2,895	84	2,696	82
South Africa	4,448	99	4,448	99
Spain	3,235	89	2,879	86
Thailand	2,346	94	2,244	91
Turkey	3,261	89	3,069	87
Ukraine	2,473	80	1,741	68
United Kingdom	2,483	85	2,354	84
United States	2,614	82	2,463	80

[a]Data from OECD (2018) using the Kleffmann amis®AgriGlobe®database.
[b]HHI is the Hirschman-Herfindahl Index.
[c]C4 is the four-firm concentration ratio. Calculations refer to the shares in the overall seed market, including farm-saved seed.

for sugar beet (1,700 points) and sunflower (1,500 points), and to a lesser extent corn (990 points) and rapeseed (660 points).

A second finding is that companies often face the same competitors across different markets (multimarket contact), which could facilitate collusion (Bernheim & Whinston 1990). Out of 32 corn markets covered by the data set, Syngenta and DuPont were active in 31 markets and Monsanto in 29. However, the set of relevant firms differs by crop, and often includes firms with a focus on a specific region or crop. For instance, Asociados Don Mario is an important player in Latin American soybean markets but has little presence in other markets; NPZ is specialized in rapeseed. Other firms such as RAGT, Euralis, KWS, Limagrain, Nordsaat, or DSV are active across several countries and crops.

So far, no similar estimates exist for GM markets, although some detailed information is publicly available for US cotton and Canadian canola. For remaining markets, various indirect information sources need to be used. While these proxies have their shortcomings, all indicators point to a considerably higher level of concentration in markets for GM traits compared to markets for germplasm.

In the case of US cotton, Monsanto GM traits are found on about 90% of cotton acreage; most of this represents "Monsanto-only" traits, although about one-fifth of cotton acreage has traits by Monsanto and by other firms. This practice of stacked traits makes it difficult to compare the situation in cotton GM traits and cotton seed, but as discussed below, the market for cotton GM traits is clearly more concentrated and witnesses smaller changes in market share. In the case of Canadian canola, Bayer's LibertyLink herbicide-tolerance trait was present in 65% of the acreage in 2014, followed by 25% for Monsanto's Roundup Ready and 10% for BASF's Clearfield technology (a non-GM herbicide-tolerance trait). This would imply an HHI of 4,900, considerably higher than the (already high) HHI of 3,475 for canola seed (Brewin & Malla 2013, 2017; OECD 2018).

For some markets, the Kleffmann database used by OECD (2018) lists the ten best-selling varieties. Technical documentation on company websites makes it possible to infer which GM traits are included in these varieties. Based on this information, the number of firms active in GM markets is much smaller than the number of seed firms. Yet, the competitive situation differs by market. In US corn, stacked traits are the norm, and stacks typically combine traits of several firms, even for similar functions (e.g., both Roundup Ready and LibertyLink herbicide-tolerance traits). Such stacks were also important in Brazilian corn. For soybeans, by contrast, all of the top-ten varieties sold in Brazil, Paraguay, and Uruguay in 2016 had a Monsanto-only GM stack. In the Brazilian cotton market, several competing single-firm trait stacks were available, and Monsanto's market share appeared smaller than that of its competitors; in Mexican cotton, on the other hand, Monsanto appeared to be the only provider of GM traits, with even Bayer's cotton seed relying on Monsanto GM traits.

Alternative Proxies for Market Concentration

Regulatory data or patent ownership can be used as alternative proxies for concentration in GM markets (OECD 2018). Data from the International Service for the Acquisition of Agri-Biotech Applications' (ISAAA's) GM Approval Database shows that the total number of approved GM events is relatively small (as of July 2018, only 42 corn GM events had been approved for cultivation in the United States; only three soybean GM events in Paraguay; and only a single soybean GM event in South Africa). Markets with a smaller number of approvals are more likely to be dominated by Monsanto, perhaps reflecting the firm's first-mover advantage. For instance, all GM cotton traits approved for commercialization in India between 2002 and 2006 were Monsanto owned (Pray & Nagarajan 2012).

Data on biotechnology patents have been analyzed by Brennan et al. (2005), Graff et al. (2003a), Heisey & Fuglie (2011), Jefferson et al. (2015), and Louwaars et al. (2009). These studies all confirm that biotechnology is essentially the domain of the (former) "Big Six"; DuPont (now Corteva Agrisciences) and Monsanto have particularly important patent portfolios. But a comparison of approval and patent data also reveals the limitation of these proxies: The data on patents show DuPont as either the most important firm or a close second after Monsanto, while data on regulatory approvals suggest that Monsanto is firmly in the lead.

The dominance of Monsanto and DuPont in IPR does not appear to extend to CRISPR-Cas9. A detailed assessment by Egelie et al. (2016) showed that patents relevant to this emerging technology are relatively less concentrated, with the leading patent holder (MIT) responsible for about 5% of the total and with most patents held by universities or academic spinoffs (e.g., MIT, Harvard, the Broad Institute, University of California). Dow and DuPont jointly held some 4% of patents, while other firms such as Bayer-Monsanto or Syngenta did not appear to hold strong positions.

The data thus show that concentration in seed markets varies considerably by crop and by country, although there is evidence that the same set of firms competes across different markets. Biotech markets are more concentrated than seed markets, with a small group of firms (Bayer-Monsanto, Corteva/Dow-DuPont, Syngenta, BASF) accounting for nearly all activity in this market. However, judging by patents, these firms' positions appear much less formidable in the emerging area of gene editing.

CAUSES: STRUCTURAL CHANGES IN SEED MARKETS OVER TIME

The recent mergers and acquisitions are the culmination of a decades-long process of structural change triggered by the emergence of biotechnology in the 1980s (Schenkelaars et al. 2011). The new technology created complementarities between genetics, germplasm, and crop protection chemicals. The paradigmatic example is Monsanto's Roundup Ready GM trait, which makes crops tolerant to its Roundup (glyphosate) herbicide. To exploit these complementarities required combining the activities of firms working on agricultural chemicals, seed, and genetics. In addition, high fixed costs for R&D and regulatory science led to economies of scale (Fulton & Giannakas 2001).

Complementary Assets

To be useful to farmers, a valuable genetic trait needs to be inserted in a valuable variety. This creates a complementarity between traits and varieties (Heisey & Fuglie 2011). Combining these activities in a single company facilitates R&D and marketing. A further interaction is with crop protection chemicals. GM seeds and crop protection chemicals can be complements (as with herbicide-tolerance traits and herbicides) or substitutes (as with insect-resistance traits and insecticides), with different implications for firms' strategies (Just & Hueth 1993). Mergers are an effective way of internalizing positive spillovers from investing in complementary products, and also facilitate coordination of R&D.

Much of the consolidation in the 1990s and 2000s reflects such complementarities. Graff et al. (2003b) analyzed the seed and biotech industry in the 1990s and showed that firms sought to obtain diversified portfolios of patents in tools, traits, and varieties through both in-house R&D and acquisitions. Complementarity of such intellectual assets was clearly an important force driving structural change. Monsanto, originally specialized in chemicals and active in agriculture through its Roundup herbicide, recognized the potential of genetic engineering early on and acquired a range of seed companies and biotech firms that eventually became its core business. Other major companies active in the industry today have a similar history of combining crop protection chemicals, seed, and genetics. Syngenta counts among its predecessors companies such as Imperial Chemical Industries (chemicals), Vanderhave (seed), and Mogen (genetics). Corteva's ancestry includes DuPont (chemicals), Pioneer Hi-Bred (seed), Dow (chemicals), Agrigenetics (seed/genetics), Pannar (seed), and Verdia (genetics) (see **Supplemental Figure 1**).

A new complementarity potentially exists with digital agriculture. Big data can allow firms to learn more about the optimal combinations of seeds, traits, and agrochemicals, which in turn can lead to highly tailored recommendations to farmers (Kempenaar et al. 2016). Digital agriculture could create complementarities in R&D and marketing, and some observers expect that this technology may have a similar transformative effect as GM technology (Gullickson 2016). Monsanto's early lead in digital agriculture was cited by Bayer as one of the reasons for acquiring the firm, and the other major players have all developed digital or precision farming products.

Such complementarities interact in complex ways with IPR.[12] IPR are important for the seed and biotech industry, but their role in stimulating consolidation is not clear. On the one hand, strong IPR may make it harder for firms to build on each other's innovations, and mergers may be a way to resolve mutually blocking patent portfolios (Marco & Rausser 2008). On the other hand, strong IPR may stimulate firms to license their intellectual property, providing another way to combine complementary intellectual assets. In the United States, major firms often engage in extensive cross-licensing of intellectual property, for instance, to offer stacks with GM traits of several firms.[13]

Economies of Scale

In addition to complementary combinations, the evolution of the sector also shows mergers of firms with similar activities (e.g., Syngenta's acquisition of Adventa/Garst in 2004). Two types of fixed costs (regulatory costs and R&D) have been suggested as drivers of such horizontal consolidation.

Regulatory costs for introducing GM crops are considerable. Smart et al. (2017) show that the approval process takes 2,500 days in the United States and 1,800 days in the European Union. Estimates by Kalaitzandonakes et al. (2007) put the financial costs of compliance at between \$6 and \$15 million for a GM corn trait, with industry-funded studies suggesting costs as high as \$35 million or 26% of the total cost (Phillips McDougall 2011). Precise estimates are difficult, as firms would engage in safety testing even without explicit regulatory requirements, but there is no question that regulatory costs are sizeable. These high fixed costs likely explain why GM is less common for specialty crops that have smaller markets (Miller & Bradford 2010), and why GM markets in general have a high level of concentration (Qaim 2016). However, as regulatory costs represent a fixed sunk cost, the growing market for GM seed should be able to support a growing number of firms, unless regulatory costs are growing faster than the size of the market. Although regulatory burdens may contribute to a high level of concentration, it is thus not clear whether they explain increases in concentration over time.

Increasing R&D costs are probably a more important factor. In markets where competition depends on innovation, firms compete in part through their spending on R&D. A growing market increases the incentives to invest in R&D, thus endogenously raising fixed costs and creating barriers to entry for new firms (Sutton 2007). Anderson & Sheldon (2017) have documented this process in the US market for GM corn, and the facts reviewed earlier about the high R&D intensity of the industry and rising R&D spending are consistent with it. Mergers are then a rational response by firms to reduce the burden of R&D spending, an interpretation supported by interviews with industry executives conducted by Schenkelaars et al. (2011).

[12] On the importance of IPR in agriculture, see Clancy & Moschini (2017). For specific studies on IPR in biotech, see, e.g., Egelie et al. (2016) and Graff et al. (2003a); for a discussion of IPR in plant breeding and a comparison of patents and plant breeders' rights, see Lence et al. (2016).

[13] Some critics have referred to this practice as nontransparent oligopolies (Mammana 2014) or "nonmerger mergers" (ETC Group 2008, Howard 2009). This betrays a lack of understanding of the procompetitive role of licensing; as the discussion on US cotton below makes clear, a refusal to cross-license by a firm with a dominant patent portfolio would be considerably more harmful for competition.

In the recent mergers and acquisitions, both economies of scale and complementary assets played a role. ChemChina was not active in seed or biotechnology prior to its acquisition of Syngenta, although it was active in generic pesticides. In purchasing Syngenta, it expanded its portfolio in agricultural chemicals and acquired complementary seed and biotechnology assets. In the case of Dow and DuPont, prior to the merger the firms had different profiles, with Dow more focused on crop protection chemicals and DuPont more focused on seed and GM traits. Similarly, Bayer's Crop Science division derived most of its revenues from crop protection chemicals, whereas Monsanto's revenues consisted mostly of seed and biotech sales. The relative importance of asset complementarity and economies of scale matters for the evaluation of the effects of mergers, as discussed below.

IMPACT: WHAT DO WE KNOW ABOUT POSSIBLE EFFECTS ON PRICES AND INNOVATION?

This section reviews the available evidence on the impact of market concentration on prices and innovation; the next section discusses the potential effects of the recent mergers.[14]

In general, only a limited number studies have focused on the impact of market concentration on seed prices or innovation. Three studies have explored the link between market concentration and prices of conventional and GM seed for soybeans (Shi et al. 2009), corn (Shi et al. 2010), and cotton (Shi et al. 2011) in the United States and found evidence that higher market concentration leads to higher prices. For instance, estimates for corn indicate that moving from perfect competition to monopoly would raise the price of conventional seed by $15 per bag (relative to an average price of $94 per bag).[15] By contrast, analysis by OECD (2018) on a cross-country data set covering several crops did not find clear evidence of a relationship between measures of market concentration and seed prices.

Two studies have looked at the potential effects of concentration on innovation in the US seed and biotech sector (Oehmke & Naseem 2016, Schimmelpfennig et al. 2004). One challenge is to find reliable data on both concentration and innovation. Both studies use US Department of Agriculture (USDA) data on field trials for GM crops as a proxy.[16] Schimmelpfennig et al. (2004) reported a negative impact of concentration on innovation, while Oehmke & Naseem (2016) reported a positive effect. This contradictory finding points to a broader problem with the underlying methodology, as the field trial data set was used in both studies to construct a proxy not only for innovation but also for concentration. In Schimmelpfennig et al. (2004), the proxy for concentration is essentially the inverse of the number of firms engaging in field trials, and it seems likely that the statistical findings are reflecting the growth in both the number of firms and the number of field trials during the period under study (1989–1998). Oehmke & Naseem (2016) use a four-firm concentration ratio of field trials over a longer period (1987–2012). If one firm ramps up its R&D faster than others, this would increase the measured concentration ratio as well as the

[14]A third economic outcome, product choice, is not discussed here; see Ciliberto et al. (2017), Ma & Shi (2013), Magnier et al. (2010), and Schenkelaars et al. (2011) on biotech. In the case of seed markets, some have voiced concern that a reduction of product choice will mean a reduction in genetic diversity (Mammana 2014), a topic on which little research is available. OECD (2018) reviews the available evidence.

[15]Firms selling GM seed must have some market power and hence charge a price above marginal cost, or else it would not be possible to recoup R&D investments. Recent research suggests that these firms have captured around three-fifths of the surplus generated by GM corn and soybean in the United States between 1996 and 2011, with the remainder benefiting farmers (Ciliberto et al. 2019).

[16]The data set used is available from the USDA's Animal and Plant Health Inspection Service (APHIS) Biotechnology Regulatory Services. A related paper by Brennan et al. (2005) uses the same data set to document growing concentration in field trials and patents.

measured innovation rate. This appears to have been the case, as Monsanto strongly increased its field trials between the early 1990s and the early 2000s, eventually accounting for more than half of all field trials before decreasing its annual number of field trials drastically in the course of the 2000s (OECD 2018). The use of proxies hence makes it difficult to draw strong conclusions from the data.

An alternative approach was used in OECD (2018), using data on actual market shares in seed markets and a measure of the introduction of useful new varieties in 50 European seed markets (defined as a combination of a country and a crop). In the European Union, a new variety can only be marketed if it is registered on the "national list" of an EU Member State, which in turn requires demonstrating the new variety's "value for cultivation and use" through field trials. The number of approved varieties can therefore be taken as a proxy for useful innovation. Using this indicator, there appears to be no link between concentration and innovation, although there is evidence that larger markets have a higher innovation rate. Data limitations made it difficult to perform more sophisticated analyses, but these results show no prima facie evidence of a negative impact of market concentration on innovation, nor of an inverted-U relationship (Aghion et al. 2005).

Mergers, Competition Policy, and Complementary Policy Options

In assessing the likely effects of mergers, competition authorities distinguish between horizontal mergers (between similar firms) and nonhorizontal mergers (between firms with complementary activities).[17] A horizontal merger removes a direct competitor and creates a firm with a larger market share. Moreover, the reduction in the number of players in the industry may make it easier for firms to collude. For these reasons, horizontal mergers are expected to pose a greater risk of anticompetitive effects, all else equal. A nonhorizontal merger by contrast does not remove a direct competitor and may create efficiency gains (e.g., a better coordination of R&D processes). But a nonhorizontal merger could still be anticompetitive, for instance, if the merger forecloses competitors' access to important inputs or customers. A seemingly innocuous merger may also reduce competitive pressures by removing a potential competitor or by making it easier to collude.[18]

Competition authorities took into account both horizontal and nonhorizontal effects in assessing the recent mergers (OECD 2018). Despite the importance of complementarities, without intervention by the competition authorities, the mergers would still have led to a strong increase in market concentration in some markets. In the Brazilian corn sector, where Dow and DuPont each had an important position, the merger would have increased the HHI by around 1,000 points to a level of 3,900.[19] The Brazilian competition authority imposed the divestiture of a large part of Dow's corn seed business in response. The Dow-DuPont merger also posed a risk in the corn market in South Africa, where DuPont was required to provide licenses to third parties for its intellectual property rights for corn seed. In the United States, the merger led to increased

[17] The US DOJ and the Federal Trade Commission have published separate merger guidelines for horizontal mergers (most recently in 2010) and for nonhorizontal mergers (1984). The European Commission similarly has separate guidelines on horizontal mergers (Official Journal C 31, 05.02.2004) and nonhorizontal mergers (Official Journal C 265, 18.10.2008).

[18] For instance, a merger between a company A and B active in different markets may make it easier for the combined firm to collude with a competitor C that is active in both markets (Bernheim & Whinston 1990).

[19] The Horizontal Merger Guidelines of the US DOJ consider that mergers "potentially raise significant competitive concerns" when they change the HHI by at least 100 points and lead to a postmerger HHI of more than 1,500 points, while mergers are "presumed to be likely to enhance market power" when they raise the HHI by more than 200 points and lead to a postmerger HHI of 2,500.

market concentration for corn and soybean, although these effects were not judged to pose a risk to competition.[20]

More concerns were raised about the Bayer-Monsanto merger. For instance, in Canada, this merger would have created a firm with a market share of about 68% in canola seed; in Mexico, the merger would have created a virtual monopoly in cotton seed. Large effects would also have occurred in the cotton seed markets of the United States, Brazil, and South Africa.[21] Brazilian competition authorities also expressed concern about the soybean seed market, where Bayer was playing only a small role but was ramping up its investments prior to the merger. In addition to effects in seed markets, there were other concerns such as in broad-spectrum herbicides; for example, Bayer's glufosinate-based Liberty herbicide was the main alternative to Monsanto's glyphosate-based Roundup.

Concerns about nonhorizontal effects were also most pronounced for the Bayer-Monsanto transaction. With complementary products, a firm can leverage its dominant position in one market to exclude rivals in the other market. For instance, Monsanto could hypothetically use a dominant position in herbicide-tolerance traits to obtain dominance in seed markets by refusing to license its traits to rival seed firms. In some jurisdictions, competition authorities therefore imposed additional conditions. The Russian competition authority, for example, required the firms to provide rivals with nonexclusive and nondiscriminatory access to Bayer and Monsanto's platforms for digital agriculture. Globally, Bayer divested a large number of businesses (including nearly its entire seed business, its digital farming business, and its glufosinate business) to obtain the necessary approvals.

It is too soon to assess whether these divestitures and other remedies were sufficient. However, some insights about the role of competition policy can be gained from the evolution of the US cotton seed market and, in particular, the aftermath of Monsanto's 2007 acquisition of Delta & Pine Land (OECD 2018). By the mid-1990s, the US cotton seed market was dominated by Delta & Pine Land (see **Supplemental Figure 2**). The firm achieved a market share of 66% in 1995 thanks to highly successful varieties as well as its acquisition of two rivals, Lankart and Paymaster, in the preceding year. None of the traditional Big Six firms had a significant position in the US cotton seed market at this point, although Delta & Pine Land collaborated with Monsanto to introduce Monsanto's insect-resistance trait (Bollgard) into Delta & Pine Land's cotton varieties.[22] GM cotton spread quickly, growing from 17% of the market in 1996 to 72% in 2000 and practically 100% in recent years.[23]

As companies sought to exploit the complementarities between GM traits and high-quality cotton varieties, mergers and acquisitions took place. Monsanto acquired Stoneville (the second largest firm) in 1997, but sold it in 1999 while seeking a merger with Delta & Pine Land. The DOJ blocked the merger, however, and Monsanto reacquired Stoneville in 2005. Bayer became

[20]In the case of ChemChina-Syngenta, there was no overlap in seed markets, although US and EU competition authorities required the divestiture of part of the pesticides business. In the Dow-DuPont merger, the firms also had to divest several assets related to agricultural chemicals, including DuPont's global R&D organization on crop protection chemicals.

[21]An ex ante assessment of the effect of the mergers in the United States by Bryant et al. (2016) suggested that cotton seed prices might have risen by 18% on average if the merger of Bayer and Monsanto's cotton seed activities had been allowed.

[22]Delta & Pine Land itself had also been involved in R&D on genetic modification, notably by collaborating with the USDA in the development of genetically sterile varieties. The technology was never commercialized because of public opposition to these "terminator" genes.

[23]All statistics referring to market shares and share of GM varieties are based on the USDA Agricultural Marketing Service, "Cotton Varieties Planted," various years (**https://www.ams.usda.gov/market-news/cotton**). Data up to 2017 can be found in OECD (2018).

active in the market in 2002 after its merger with Aventis CropScience and subsequently acquired AFD Seeds in 2005 and CPCSD in 2007. Dow had been increasingly active in the cotton seed market since the early 2000s through Phytogen, a joint venture with the J.G. Boswell Company.

In 2006–2007, Monsanto again attempted to acquire Delta & Pine Land. This time the DOJ allowed the acquisition but imposed several conditions (Lovells 2007). The DOJ had both a horizontal and a nonhorizontal concern. First, since Monsanto owned Stoneville at the time, a combined entity would have had a market share of around 60%. Second, nearly all GM traits used in the US cotton seed market at the time were developed by Monsanto. Post-merger, Monsanto could have refused competitors of Delta & Pine Land to use its traits, and vice versa, Delta & Pine Land could have refused to seek out non-Monsanto GM traits. Strong initial positions in cotton seed and GM traits could thus be used to stifle competition. To prevent this, the DOJ imposed several requirements. First, Monsanto had to divest Stoneville and several cotton varieties of Delta & Pine Land and of Monsanto, as well as Monsanto molecular technology. Bayer acquired most of the divested assets, with the exception of NexGen cotton varieties acquired by Americot. Second, Monsanto was required to license its GM traits to Stoneville, whereas Syngenta, which had been working with Delta & Pine Land to incorporate Syngenta's VipCot insect-resistance trait into a number of Delta & Pine Land varieties, obtained the right to acquire these varieties to complete the work. Finally, Monsanto was required to revise its licensing agreements to allow the stacking of Monsanto and non-Monsanto traits.

How did these measures affect the evolution of competition in the sector? The acquisition of Stoneville by Bayer strengthened its position as challenger, and the firm continued growing its market share, reaching 50% of the seed market in 2010. In later years, Bayer's market share declined considerably, but mostly because of the growing success of another challenger, Americot.[24] When Americot purchased the divested Monsanto assets in 2007, its market share was around 1%; by 2018, this share had grown to 30%. Phytogen similarly grew strongly, with its market share rising from 3% in 2007 to 15% in 2018. Delta & Pine Land's market share fell from 44% in 2007 to 37% in 2018 (**Supplemental Figure 2**). The remedies imposed hence appear to have been successful in maintaining competition and dynamism in the seed sector. The rise of Americot in particular suggests a direct link between some of the measures put in place and the subsequent evolution of the industry.

A somewhat different picture emerges when looking at the market for GM traits. At the time of the merger, 92% of US cotton acres were planted with GM seed: 88% contained only Monsanto GM traits, and an additional 2% contained a stack of Monsanto and non-Monsanto traits. Post-2007, the share of such mixed stacks increased strongly, reaching 35% of acreage in 2014 but falling to around 18% in recent years. Pure non-Monsanto GM trait stacks were practically nonexistent in 2007 but reached 17% of acreage in 2016. The growth of non-Monsanto and mixed stacks suggests that the measures imposed by the DOJ in 2007 prevented Monsanto from obtaining an unassailable dominant position in GM traits. On the other hand, Monsanto-only GM stacks occupied at least 50% of cotton acreage in any given year since 2007, and when mixed stacks are included, Monsanto's GM traits always covered at least 82% of cotton acreage (see **Supplemental Figure 3**).[25] The market for GM traits for cotton thus remains considerably more concentrated than the market for cotton seed.

The experience of US cotton suggests that remedies imposed by competition authorities can help bring about a dynamic and competitive market, but that such an outcome is by no means guaranteed. However, other policy options exist that can help stimulate competition and innovation in

[24] Bayer's cotton business was divested to BASF during the Bayer-Monsanto merger.

[25] In recent years, Monsanto-only GM stacks have again gained market share in part due to the success of Americot, which incorporates such stacks in its varieties.

seed and biotechnology (OECD 2018). First, even if regulatory costs may not be the main driver behind recent increases in concentration in the sector, it is clear that unnecessarily high regulatory burdens can act as a barrier to entry (or an incentive to exit the market). An appropriate regulatory framework must strike the right balance between providing safeguards to protect human health and the environment and ensure consumer acceptance, while avoiding excessive regulatory costs which would restrict competition or innovation. This question is particularly relevant for the new plant breeding techniques (Schaart et al. 2015).[26] Second, as the experience of the US cotton sector suggests, competition is stimulated when relevant intellectual property and genetic resources are easily accessible. For instance, access to patented genetic traits can be facilitated by patent clearinghouses, such as the International Licensing Platform for Vegetables (Bruins 2015, Kock & ten Have 2016), or by compulsory licensing when a dominant firm refuses to license its intellectual property to other market participants. Third, policy makers can take various steps to stimulate both public and private R&D in the sector. Public R&D in plant breeding historically played an important role in many countries, including the United States, and continues to do so around the world. But as private R&D in plant breeding grows, it makes sense for public R&D investments to shift toward areas underserved by the private sector (Heisey & Fuglie 2018). These include research on orphan crops, varieties with positive environmental benefits, or biofortification, or more fundamental research, such as developing new breeding methods. Policy makers can also provide institutional frameworks to stimulate private R&D, for instance, through public-private partnerships such as levy-funded plant breeding (Gray 2012).

CONCLUDING REMARKS

The seed and biotechnology sector is important for sustainable productivity growth in agriculture and presents an exciting area of research given ongoing innovations and structural changes. It is also a sector that has caught the broader public's attention because of concerns around corporate power and genetic modification. When evaluating the Bayer-Monsanto merger, for instance, the European Commission's Directorate-General for Competition received over one million petitions, emails, and tweets from concerned citizens, an unprecedented level of public interest for a merger assessment (Eur. Comm. 2018). Academics, policy makers, and the broader public are looking to understand the extent, causes, and effects of the dramatic structural transformation happening in global seed and biotechnology markets.

This review has summarized the available evidence. Recent consolidation has been driven by complementarities between seed, biotechnology, and crop protection chemicals—and potentially by a new emerging complementarity with digital agriculture—as well as by economies of scale related to R&D. So far, there is not much evidence to suggest harmful effects of concentration on prices or innovation.

Yet, as this review also shows, a gap remains between the demand and supply of evidence on these questions. This gap is sometimes filled with approximations that may be misleading, as when estimates of global market concentration are used for want of more detailed data. In assessing mergers, competition authorities suffer less from this limitation, as they have direct access to confidential information held by firms, but the resulting findings are often confidential as well and hence do little to reassure the broader public or to stimulate academic research. Researchers are increasingly using private market research data (Ciliberto et al. 2019; OECD 2018; Shi et al. 2009, 2010, 2011). Where such detailed data are available, they typically show a more nuanced picture, with considerable heterogeneity across crops and countries and with (so far) mixed evidence on

[26]On the regulatory implications of genome editing, see Friedrichs et al. (2019) and Kearns (2019).

effects of market concentration on prices or innovation. But large knowledge gaps remain. Available data sets have incomplete geographical coverage (with notable gaps in the developing world, particularly China, India, and sub-Saharan Africa) and incomplete crop coverage (with data on vegetable seeds particularly lacking). In terms of mechanisms behind potential anticompetitive behavior there is considerable scope to explore the role of multimarket contact and of common ownership.[27]

Promising areas for future work also include the potential complementarities between digital and precision agriculture on the one hand, and seeds, biotechnology, and agricultural chemicals on the other. Another focus is the role of new plant breeding techniques that typically reduce the time and cost of developing new varieties (and pose challenges for existing regulatory approaches). These developments could influence the further development of the sector.

Finally, an interesting question is how structural change in seed and biotechnology compares with trends in animal genetics. Although more attention has been devoted to plant breeding, animal breeding plays a similarly essential role in raising productivity in the livestock sectors (Derry 2015, Olmstead & Rhode 2008). The field is experiencing similar technological trends (Van Eenennaam 2017), and the animal genetics industry seems similarly concentrated (Heisey & Fuglie 2011). More research into the evolution of the animal genetics sector would be valuable in its own right and would provide an interesting comparative perspective on the seed and biotechnology industry.

DISCLOSURE STATEMENT

The author is not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

ACKNOWLEDGMENTS

The author wishes to thank Matin Qaim from the editorial committee of this journal as well as Justus Wesseler and Sophia Gnych for helpful comments. This review builds on a study coordinated by the author at the OECD; the author gratefully acknowledges the support and contributions of OECD colleagues and a wide range of experts from competition authorities, government agencies, and universities. A detailed list of acknowledgments can be found in the OECD study. The opinions expressed and arguments employed herein are solely those of the authors and do not necessarily reflect the official views of the OECD or of its member countries.

LITERATURE CITED

Afr. Cent. Biodiversity. 2015. *The expansion of the commercial seed sector in sub-Saharan Africa: major players, key issues and trends*. Rep., Afr. Cent. Biodiversity, Johannesburg. **https://www.acbio.org.za/wp-content/uploads/2015/12/Seed-Sector-Sub-Sahara-report.pdf**

Aghion P, Bloom N, Blundell R, Griffith R, Howitt P. 2005. Competition and innovation: an inverted-U relationship. *Q. J. Econ.* 120(2):701–28

Alston J, Andersen MA, James JS, Pardey P, eds. 2010. *Persistence Pays: U.S. Agricultural Productivity Growth and the Benefits from Public R&D Spending*. New York: Springer

[27]Torshizi & Clapp (2019) are the first to explore common ownership in the US seed sector, but their data consist of nationwide annual time series for soy, corn, and cotton, which limits the extent to which strong conclusions can be drawn. However, given recent studies exploring common ownership in other sectors (OECD 2017, Schmalz 2018), this is a promising topic of research.

Anderson B, Sheldon I. 2017. R&D concentration under endogenous fixed costs: evidence from genetically modified corn seed. *Am. J. Agric. Econ.* 99(5):1265–86

Barrows G, Steven S, Zilberman D. 2014. Agricultural biotechnology: the promise and prospects of genetically modified crops. *J. Econ. Perspect.* 28:99–120

Beckmann V, Soregaroli C, Wesseler J. 2006. Coexistence rules and regulations in the European Union. *Am. J. Agric. Econ.* 88(5):1193–99

Bennett AB, Chi-Ham C, Barrows G, Sexton S, Zilberman D. 2013. Agricultural biotechnology: economics, environment, ethics, and the future. *Annu. Rev. Environ. Resour.* 38:249–79

Bernheim BD, Whinston MD. 1990. Multimarket contact and collusive behavior. *RAND J. Econ.* 21(1):1–26

Bonanno A, Materia VC, Venus T, Wesseler J. 2017. The plant protection products (PPP) sector in the european union: a special view on herbicides. *Eur. J. Dev. Res.* 29(3):575–95

Bonny S. 2014. Taking stock of the genetically modified seed sector worldwide: market, stakeholders, and prices. *Food Secur*. 6(4):525–40

Bonny S. 2017. Corporate concentration and technological change in the global seed industry. *Sustainability* 9(9):1632

Brennan M, Pray C, Naseem A, Oehmke J. 2005. An innovation market approach to analyzing impacts of mergers and acquisitions in the plant biotechnology industry. *AgBioForum* 8(2–3):89–99

Brewin DG, Malla S. 2013. The consequences of biotechnology: a broad view of the changes in the Canadian canola sector, 1969 to 2012. *AgBioForum* 15(3):257–75

Brewin DG, Malla S. 2017. The value of a novel biotechnology. *China Agric. Econ. Rev.* 9(3):355–68

Bruins M. 2015. A full count for vegetables. *Eur. Seed* 2(1), Apr. 27. **http://european-seed.com/a-full-count-for-vegetables/**

Bryant H, Maisashvili A, Outlaw J, Richardson J. 2016. *Effects of proposed mergers and acquisitions among biotechnology firms on seed prices*. Work. Pap. 16–2, Agric. Food Policy Cent., Texas A&M Univ., College Station, TX. **https://www.afpc.tamu.edu/research/publications/files/675/WP_16-2.pdf**

Campi M, Nuvolari A. 2015. Intellectual property protection in plant varieties: a worldwide index (1961–2011). *Res. Policy* 44(4):951–64

Ciliberto F, Moschini GC, Perry ED. 2019. Valuing product innovation: genetically engineered varieties in US corn and soybeans. *RAND J. Econ.* 50:615–44

Clancy MS, Moschini GC. 2017. Intellectual property rights and the ascent of proprietary innovation in agriculture. *Annu. Rev. Resour. Econ.* 9:53–74

Deconinck K. 2019. New evidence on concentration in seed markets. *Glob. Food Secur.* 23:135–38

Derry ME. 2015. *Masterminding Nature: The Breeding of Animals, 1750–2010*. Toronto: Univ. Toronto Press

Egelie K, Graff G, Strand S, Johansen B. 2016. The emerging patent landscape of CRISPR-Cas gene editing technology. *Nat. Biotechnol.* 34(10):1025–31

ETC Group. 2008. *Who owns nature? Corporate power and the final frontier in the commodification of life*. Commun. 100, ETC Group, Val David, Quebec. **http://www.etcgroup.org/content/who-owns-nature**

ETC Group. 2013. *Putting the Cartel before the Horse…and Farm, Seeds, Soil, Peasants, etc. Who will control agricultural inputs, 2013?* Commun. 111, ETC Group, Val David, Quebec. **http://www.etcgroup.org/sites/www.etcgroup.org/files/CartelBeforeHorse11Sep2013.pdf**

Eur. Comm. 2018. *Statement by Commissioner Vestager on Commission decision to give conditional approval to Bayer's plans to buy Monsanto and decision fining producers of capacitors fl254 million for participating in a cartel*. Press Release, March 21, Eur. Comm., Brussels. **https://ec.europa.eu/commission/presscorner/detail/en/IP_18_2322**

Evenson R, Gollin D. 2003. Assessing the impact of the Green Revolution, 1960 to 2000. *Science* 300(5620):758–62

Fernandez-Cornejo J, Just R. 2007. Researchability of modern agricultural input markets and growing concentration. *Am. J. Agric. Econ.* 89(5):1269–75

Friedrichs S, Takasu Y, Kearns P, Dagallier B, Oshima R, et al. 2019. Policy considerations regarding genome editing. *Trends Biotechnol*. 37(10):1029–32

Fuglie K. 2016. The growing role of the private sector in agricultural research and development world-wide. *Glob. Food Secur.* 10:29–38

Fuglie K, Heisey P, King J, Pray CE, Day-Rubenstein K, et al. 2011. Research investments and market structure in the food processing, agricultural input, and biofuel industries worldwide: synthesis of results. In *Research Investments and Market Structure in the Food Processing, Agricultural Input, and Biofuel Industries Worldwide*, ed. KO Fuglie, PW Heisey, JL King, CE Pray, K Day-Rubenstein, et al., pp. 1–24. Econ. Res. Rep. 130, USDA, Econ. Res. Serv., Washington, DC. **https://www.ers.usda.gov/publications/pub-details/?pubid=44954**

Fulton M, Giannakas K. 2001. Agricultural biotechnology and industry structure. *AgBioForum* 4(2):137–51

Graff GD, Cullen SE, Bradford KJ, Zilberman D, Bennett AB. 2003a. The public-private structure of intellectual property ownership in agricultural biotechnology. *Nat. Biotechnol.* 21(9):989–95

Graff GD, Rausser GC, Small AA. 2003b. Agricultural biotechnology's complementary intellectual assets. *Rev. Econ. Stat.* 85(2):349–63

Gray R. 2012. Intellectual property rights and the role of public and levy-funded research. In *Improving Agricultural Knowledge and Innovation Systems: OECD Conference Proceedings*, pp. 183–203. Paris: OECD

Gullickson G. 2016. How digital ag is helping to drive the proposed Bayer-Monsanto deal. *Successful Farming*, Sept. 7. **http://www.agriculture.com/news/how-digital-ag-is-helping-to-drive-the-proposed-bayer-monsanto-deal**

Heisey PW, Fuglie KO. 2011. Private research and development for crop genetic improvement. In *Research Investments and Market Structure in the Food Processing, Agricultural Input, and Biofuel Industries Worldwide*, ed. KO Fuglie, PW Heisey, JL King, CE Pray, K Day-Rubenstein, et al., pp. 25–48. Econ. Res. Rep. 130, USDA, Econ. Res. Serv., Washington, DC. **https://www.ers.usda.gov/publications/pub-details/?pubid=44954**

Heisey PW, Fuglie KO. 2018. *Agricultural research investment and policy reform in high-income countries*. Econ. Res. Rep. 249, USDA, Econ. Res. Serv., Washington, DC. **https://www.ers.usda.gov/webdocs/publications/89114/err-249.pdf?v=43244**

Hernandez MA, Torero M. 2013. Market concentration and pricing behavior in the fertilizer industry: a global approach. *Agric. Econ.* 44(6):723–34

Herring R, Paarlberg R. 2016. The political economy of biotechnology. *Annu. Rev. Resour. Econ.* 8:397–416

Howard P. 2009. Visualizing consolidation in the global seed industry: 1996–2008. *Sustainability* 1(4):1266–87

ISAAA (Int. Serv. Acquis. Agri-Biotech Appl.). 2018. *Global status of commercialized biotech/GM crops: 2018*. Brief 54-2018, ISAAA, Ithaca, NY. **http://www.isaaa.org/resources/publications/briefs/54/default.asp**

Jefferson OA, Köllhofer D, Ehrich TH, Jefferson RA. 2015. The ownership question of plant gene and genome intellectual properties. *Nat. Biotechnol.* 33(11):1138–43

Just RE, Hueth DL. 1993. Multimarket exploitation: the case of biotechnology and chemicals. *Am. J. Agric. Econ.* 75(4):936–45

Kalaitzandonakes N, Alston JM, Bradford KJ. 2007. Compliance costs for regulatory approval of new biotech crops. *Nat. Biotechnol.* 25:509–11

Kearns P. 2019. Foreword. *Transgenic Res.* 28(Suppl. 2):39–40

Kempenaar C, Lokhorst C, Bleumer EJB, Veerkamp RF, Been T, et al. 2016. *Big data analysis for smart farming: results of TO2 project in theme food security*. Res. Rep., Wageningen Univ. Res., Wageningen, Neth. **https://library.wur.nl/WebQuery/wurpubs/507764**

Kingsbury N. 2009. *Hybrid: The History and Science of Plant Breeding*. Chicago: Univ. Chicago Press

Kloppenburg J. 1988. *First the Seed: The Political Economy of Plant Biotechnology, 1492–2000*. Madison: Univ. Wisc. Press

Kock MA, ten Have F. 2016. The 'International Licensing Platform—Vegetables': a prototype of a patent clearing house in the life science industry. *J. Intellect. Property Law Pract.* 11(7):496–515

Lence SH, Hayes DJ, Alston JM, Smith JSC. 2016. Intellectual property in plant breeding: comparing different levels and forms of protection. *Eur. Rev. Agric. Econ.* 43(1):1–29

Louwaars N, Dons H, Van Overwalle G, Raven H, Arundel A, et al. 2009. *Breeding business. The future of plant breeding in the light of developments in patent rights and plant breeder's rights.* Work. Pap., Wageningen Univ. Res. Cent., Wageningen, Neth. **https://papers.ssrn.com/sol3/papers.cfm?abstract_id=1720088**

Lovells H. 2007. DOJ uses novel divestiture provisions to clear Monsanto/Delta & Pine land deal. *Lexology*, Aug. 20. **https://www.lexology.com/library/detail.aspx?g=bd9632c4-5d6f-4803-8d0d-1d64bdf36715**

Ma X, Shi G. 2013. GM versus non-GM: a survival analysis of U.S. hybrid seed corn. *Agric. Resour. Econ. Rev.* 423:542–60

MacDonald JM. 2017. Consolidation, concentration, and competition in the food system. *Fed. Reserve Bank Kansas City Econ. Rev.* 2017:85–105. **https://www.kansascityfed.org/~/media/files/publicat/econrev/econrevarchive/2017/si17macdonald.pdf**

Magnier A, Kalaitzandonakes NG, Miller DJ, Goldsmith PD. 2010. Product life cycles and innovation in the US seed corn industry. *Int. Food Agribus. Manag. Rev.* 13(3):17–36

Mammana I. 2014. *Concentration of market power in the EU seed market*. Rep., Greens/EFA Group Eur. Parliam., Brussels. **http://www.agricolturabiodinamica.it/wp-content/uploads/2015/07/Rapporto-Green-EU-sul-monopolio-delle-sementi-n-Europa.pdf**

Marco AC, Rausser GC. 2008. The role of patent rights in mergers: consolidation in plant biotechnology. *Am. J. Agric. Econ.* 90(1):133–51

Miller JK, Bradford KJ. 2010. The regulatory bottleneck for biotech specialty crops. *Nat. Biotechnol.* 28(10):1012–14

Mumm RH. 2013. A look at product development with genetically modified crops: examples from maize. *J. Agric. Food Chem.* 61(35):8254–59

Murugkar M, Ramaswami B, Shelar M. 2007. Competition and monopoly in Indian cotton seed market. *Econ. Political Wkly.* 42(37):3781–89

OECD (Organ. Econ. Co-Op. Dev.). 2014. *OECD competition policy roundtables: competition issues in the food chain industry 2013*. DAF/COMP(2014)16, OECD, Paris. **https://www.oecd.org/daf/competition/CompetitionIssuesintheFoodChainIndustry.pdf**

OECD (Organ. Econ. Co-Op. Dev.). 2017. *Common ownership by institutional investors and its impact on competition*. DAF/COMP(2017)10, OECD, Paris. **https://one.oecd.org/document/DAF/COMP(2017)10/en/pdf**

OECD (Organ. Econ. Co-Op. Dev.). 2018. *Concentration in Seed Markets: Potential Effects and Policy Responses*. Paris: OECD Publ.

Oehmke JF, Naseem A. 2016. Mergers and acquisitions (M&As), market structure and inventive activity in the agricultural biotechnology industry. *J. Agric. Food Ind. Organ.* 14(1):19–32

Olmstead A, Rhode PW. 2008. *Creating Abundance: Biological Innovation and American Agricultural Development*. Cambridge, UK: Cambridge Univ. Press

Phillips McDougall. 2011. *The cost and time involved in the discovery, development and authorisation of a new plant biotechnology derived trait*. Rep., Sept., Phillips McDougall, Midlothian, UK. **https://croplife.org/wp-content/uploads/pdf_files/Getting-a-Biotech-Crop-to-Market-Phillips-McDougall-Study.pdf**

Philpott T. 2016. Monsanto now belongs to Bayer. *Mother Jones*, Sept. 13. **https://www.motherjones.com/environment/2016/09/whoa-monsanto-about-get-swallowed-german-giant-bayer/**

Pray CE, Nagarajan L. 2012. *Innovation and research by private agribusiness in India*. Discuss. Pap. 01181, IFPRI, Washington, DC. **http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.435.495&rep=rep1&type=pdf**

Pray CE, Nagarajan L. 2014. The transformation of the Indian agricultural input industry: Has it increased agricultural R&D? *Agric. Econ.* 45(S1):145–56

Qaim M. 2009. The economics of genetically modified crops. *Annu. Rev. Resour. Econ.* 1:665–94

Qaim M. 2016. *Genetically Modified Crops and Agricultural Development*. New York: Palgrave MacMillan

Ragonnaud G. 2013. *The EU Seed and Plant Reproductive Material Market in Perspective: A Focus on Companies and Market Shares*. Brussels: Eur. Parliam. **http://www.europarl.europa.eu/RegData/etudes/note/join/2013/513994/IPOL-AGRI_NT(2013)513994_EN.pdf**

Schaart J, Riemens MM, van de Wiel CCM, Lotz LAP, Smulders MJM. 2015. *Opportunities of new plant breeding techniques*. Res. Rep., Wageningen Univ. Res. Cent., Wageningen, Neth. **https://www.wur.nl/en/Publication-details.htm?publicationId=publication-way-343932313632**

Schenkelaars P, de Vriend H, Kalaitzandonakes N. 2011. *Drivers of consolidation in the seed industry and its consequences for innovation*. Rep., COGEM, Bilthoven, Neth. **https://www.lisconsult.nl/files/docs/consolidation_seed_industry.pdf**

Schimmelpfennig DE, Pray CE, Brennan MF. 2004. The impact of seed industry concentration on innovation: a study of US biotech market leaders. *Agric. Econ.* 30(2):157–67

Schmalz MC. 2018. Common-ownership concentration and corporate conduct. *Annu. Rev. Financ. Econ.* 10:413–48

Sexton RJ, Xia T. 2018. Increasing concentration in the agricultural supply chain: implications for market power and sector performance. *Annu. Rev. Resour. Econ.* 10:229–51

Sheldon I. 2017. The competitiveness of agricultural product and input markets: a review and synthesis of recent research. *J. Agric. Appl. Econ.* 49(1):1–44

Shi G, Chavas JP, Stiegert KW. 2009. Pricing of herbicide-tolerant soybean seeds: a market-structure approach. *AgBioForum* 12(4):326–33

Shi G, Chavas JP, Stiegert KW. 2010. An analysis of the pricing of traits in the U.S. corn seed market. *Am. J. Agric. Econ.* 92:1324–38

Shi G, Stiegert KW, Chavas JP. 2011. An analysis of bundle pricing in horizontal and vertical markets: the case of the U.S. cottonseed market. *Agric. Econ.* 42(S1):77–88

Smart RD, Blum M, Wesseler J. 2017. Trends in approval times for genetically engineered crops in the United States and the European Union. *J. Agric. Econ.* 68(1):182–98

Smith S, Cooper M, Gogerty J, Löffler C, Borcherding D, Wright K. 2014. Maize. In *Yield Gains in Major U.S. Field Crops*, ed. S Smith, B Diers, J Specht, B Carver, pp. 125–72. Madison, WI: Am. Soc. Agron./Crop Sci. Soc. Am./Soil Sci. Soc. Am. Inc.

South PF, Cavanagh AP, Liu HW, Ort DR. 2019. Synthetic glycolate metabolism pathways stimulate crop growth and productivity in the field. *Science* 363(6422):eaat9077

Spielman DJ, Kennedy A. 2016. Towards better metrics and policymaking for seed system development: insights from Asia's seed industry. *Agric. Syst.* 147:111–22

Spielman DJ, Kolady DE, Cavalieri AJ, Rao NC. 2014a. *Structure, competition and policy in India's seed and agricultural biotechnology industries*. Res. Note 3, CSISA, **http://csisa.org/wp-content/uploads/sites/2/2014/09/Research-Note-3.pdf**

Spielman DJ, Kolady DE, Cavalieri AJ, Rao NC. 2014b. The seed and agricultural biotechnology industries in India: an analysis of industry structure, competition, and policy options. *Food Policy* 45:88–100

Sutton J. 2007. Market structure: theory and evidence. In *Handbook of Industrial Organization*, ed. M Armstrong, RH Porter, pp. 2301–68. Amsterdam: North-Holland

Syngenta. 2016. *Our industry 2016*. Rep., Syngenta, Basel, Switz. **https://www.syngenta.com/sites/syngenta/files/GRI/our-industry-syngenta.pdf**

Torshizi M, Clapp J. 2019. *Price effects of common ownership in the seed sector*. Work. Pap., Univ. Alberta. **https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3338485**

Van Eenennaam A. 2017. Genetic modification of food animals. *Curr. Opin. Biotechnol.* 44:27–34

Van Etten J, Lopez Noriega I, Fadda C, Thomas E. 2017. The contribution of seed systems to crop and tree diversity in sustainable food systems. In *Mainstreaming Agrobiodiversity in Sustainable Food Systems*. Rep., Bioversity Int., Maccarese, It. **https://www.bioversityinternational.org/fileadmin/user_upload/online_library/Mainstreaming_Agrobiodiversity/4_Seed_Systems_for_Crop_Tree_Diversity.pdf**

Wesseler J, Bonanno A, Drabik D, Materia VC, Malaguti L, et al. 2015. *Overview of the Agricultural Inputs Sector in the EU*. Brussels: Eur. Parliam. **http://www.europarl.europa.eu/RegData/etudes/STUD/2015/563385/IPOL_STU(2015)563385_EN.pdf**

Wesseler J, Smart RD, Thomson J, Zilberman D. 2017. Foregone benefits of important food crop improvements in Sub-Saharan Africa. *PLOS ONE* 12(7):e0181353