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Working Paper 17-WP 572
January 2017

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Intellectual Property Rights and the Ascent of Proprietary Innovation in Agriculture

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Keywords

Appropriability, biotechnology, innovation, intellectual property, knowledge, market power, patents, plant breeders' rights, plant patents, R&D, trade secrets

Abstract

Biological innovations in agriculture did not enjoy protection by formal intellectual property rights (IPRs) for a long time, but the recent trend has been one of considerable broadening and strengthening of these rights. We document the nature of these IPRs and their evolution, and provide an assessment of their impacts on innovation. We integrate elements of the institutional history of plant IPRs with a discussion of the relevant economic theory and a review of applicable empirical evidence. Throughout, we highlight how the experience of biological innovation mirrors, or differs from, the broader literature on IPRs and innovation. We conclude with some considerations on the relation between IPRs and market structure and the pricing of proprietary inputs in agriculture.

When citing this paper, please use the following:

Clancy MS, Moschini G. 2017. Intellectual Property Rights and the Ascent of Proprietary Innovation in Agriculture. *Annual Review of Resource Economics*, volume 9. DOI: 10.1146/annurev-resource-100516-053524.

1. INTRODUCTION

Reflecting on a century of astonishing development, Gardner (2002, p. 8) notes that "American agriculture has been transformed in the past hundred years by changes in the technology of farming." At the beginning of the 20th century, 41% of the US workforce was employed in agriculture. A century later, this was down to 1.9%. Meanwhile, yields and multifactor productivity improved tremendously. Innovations that brought about such momentous changes include massive mechanization, improved breeds of animal and plants, the extensive use of chemical fertilizers and pesticides, and advancements in farm management practices. At the dawn of the 21st century, genetically engineered (GE) crops heralded the arrival of modern biotechnology to agriculture and the promise of genomics-based radical advancements. Precision agriculture is now poised to leverage big data to optimize inputs use at an extremely refined level, and to expand the use of robotics in revolutionary applications.

Questions about the nature of knowledge at the root of this technological change, its origin, and the role of private and public entities in this process remain critical. In this article, consistent with the seminal perspective articulated by Rausser (1999), we focus on the vital role that the creation of knowledge assets plays in bringing about new technology in agriculture, a process that is bound to continue to shape this sector for years to come. In particular, we emphasize the evolving role of intellectual property rights (IPRs) in providing incentives for biological innovations in agriculture, specifically improved plants, in a world where private research and development (R&D) investments are rapidly outpacing public resources. Beyond incentives, IPRs ultimately affect the ownership of knowledge assets and exert significant influence on the appropriation of the wealth creation that may flow from the adoption of innovations by a competitive agricultural sector (Moschini and Lapan 1997).

To an economist, the chief purpose of IPRs is to promote innovation. Since Arrow (1962), the case for IPRs rests on understanding that production of knowledge is subject to a unique combination of market failures: externalities, indivisibilities and uncertainty. Together with the recognition of the informational challenge and moral hazard problem that beset the public provision of innovations, there is a need to provide incentives to enable individuals and firms to exploit inventive opportunities. This requires the solution of the inherent appropriability problem that besets the production of knowledge, a quintessential public good (Langinier and Moschini, 2002). By granting the inventor temporary rights of exclusivity, legally based IPRs, such as patents, provide an *ex ante* profit motive to innovators. The *ex post* realization of this profit by (successful) innovators inevitably requires restricting use of the innovation below socially optimal level. IPRs, therefore, engineer a compromise between dynamic efficiency and static (in)efficiency (Nordhaus 1969).

Biological innovation in agriculture have unique features that make IPRs both especially desirable and potentially problematic. Formal protection for intellectual property arrived relatively late for such innovations. We document the nature of these IPRs and attempt to assess their impacts on innovation. We integrate elements of the institutional history of plant IPRs with a discussion of the relevant economic theory and a review of applicable empirical evidence. Throughout, we highlight how the experience of biological innovation mirrors, or differs from, the broader literature on IPRs and innovation. We conclude with some considerations on the relation between IPRs and market structure and the pricing of proprietary inputs in agriculture.

2. INTELLECTUAL PROPERTY FOR PLANT INNOVATIONS

The US Congress created the world's first modern patent system in 1836 (Moser 2016), but excluded biological organisms: new plant cultivars and breeds of livestock were ineligible for patent protection. US biological innovations in agriculture would not have a form of IPRs for nearly a century, until the 1930 Plant Patent Act for asexually reproduced plants, and later still for sexually reproduced plants, with the 1970 Plant Variety Protection Act. The latter followed the lead of a group of European countries, who had defined comparable plant breeders' rights (PBRs) in 1961. Stronger protections followed a 1980 landmark US Supreme Court decision that extended the admissible subject matter for utility patents to encompass biological products and processes.

2.1. Utility Patents

Patents are the oldest and arguably the strongest form of IPRs. In the United States, patents are issued by the US Patent and Trademark Office (USPTO) upon successful prosecution of an application. As with other rights defined by law, patents apply only in the jurisdictions granting them. International cooperation and harmonization of patent law is the prerogative of the World Intellectual Property Organization (WIPO). The conditions for patentability are fairly similar across jurisdictions. The criteria to be met "…include, most significantly, that the invention must consist of patentable subject matter, the invention must be industrially applicable (useful), it must be new (novel), it must exhibit a sufficient inventive step (be non-obvious), and the disclosure of the invention in the patent application must meet certain standards." (WIPO 2004). What defines the patented invention is laid out in one or more claims stated in the application, each of which stakes out specific property rights. As for the latter, a patent confers to the inventor the sole right to exclude others from economically exploiting the innovation (by making it, using it, selling it, etc.) for a limited time (20 years from the date of filing).

Although the conditions for patentability are quite similar across jurisdictions, differences have emerged as to patentable subject matter, especially for biological innovations relevant for agriculture. The traditional statutory scope of patents typically excludes important kinds of scientific discoveries, such as laws of nature, natural phenomena and abstract ideas. For a long time it was believed this precluded the patenting of biological innovations, which led to the development of *sui generis* protection systems such as plant patents and PBRs. In the United States this changed with the 1980 US Supreme Court decision in *Diamond v. Chakrabarty*, which held that modified microorganisms were in fact patentable. This landmark case opened the door for patent rights for virtually any biologically based invention, if obtained through human intervention. The USPTO recognized plants and plant parts as patent-eligible subject matter in its 1985 *Ex parte Hibberd* ruling. And, in its 2001 decision in *J.E.M. Ag Supply, Inc. v. Pioneer Hi-Bred*, the US Supreme Court held that plant seeds and plants themselves (both traditionally bred or produced by genetic engineering) are patentable under US law (Janis and Kesan, 2002a).

2.2. Plant Patents

As early as 1885, private cereal and fruit breeders were calling for IPRs for plants and the American Breeders Association pushed for similar legislation in 1905 (Kloppenburg 2004). Following food shortages in World War I and demand from farm bloc states, the legislature became receptive to the idea (Moser and Rhode 2011). Demand for protection was particularly acute from commercial growers of high-value luxury crops, such as horticulture and fruit trees, and less so from seed companies, who saw themselves predominantly as brokers rather developers of new varieties. Seeds, in addition to tubers, were also staple crops. In the climate of the Great Depression, extending market power over staple foods was unpalatable (Janis and Kesan 2002b). Moreover, it was still considered impractical to enforce property rights over sexually reproducing varieties. As these expressed natural variability from generation to generation, it was unclear exactly what aspects of an improved plant would be protected and how protected varieties would be identified after several generations.

In 1930, the legislature compromised by extending a new form of patent protection over asexually reproducing plants (where each generation is genetically identical to the preceding), excluding food tubers (a staple). New varieties were eligible for protection if they were new and distinct (there was no requirement that plants be useful, e.g., more high yielding than existing varieties). The exclusivity granted by plant patents is currently 20 years (Aguirre 2006).

2.3. Plant Breeders' Rights

The UPOV (*Union pour la Protection des Obtentions Végétales*) convention agreed to in 1961 by a group of European countries represented the culmination of a long-standing quest to secure intellectual property protection to breeders at a time when it was believed that their innovations were outside the statutory subject matter of utility patents (Le Buanec 2006). The rights that it defined contemplate a commercial exclusivity, for a limited period, for plant varieties that met certain standards: distinctiveness, uniformity and stability (DUS), and novelty. The latter, it must be emphasized, is with respect to commercialization only (unlike utility patents, no inventive step is presumed). Hence, the eligibility standard for protection under UPOV is lower than for utility patents, but the rights granted are weaker as well. Two major differences are the so-called farmer's privilege and breeders' exemption. The former concerns the rights of farmers to save seeds from their harvest for the purpose of replanting, while the latter concerns the right of breeders to use (protected) varieties developed by others in their own breeding program.

Subsequent revisions (the last in 1991) extended the domain of the UPOV convention in terms of species covered, the length of protection (currently 20 years), and curtailed somewhat the extent of the farmer's privilege, which is now an option for member states, subject to the requirement that steps be taken to safeguard the legitimate interest of breeders.[1] Implementation of the breeders' exemption always faced the inherent difficulties of specifying a metric for distinctiveness, meant to prevent new varieties from unduly appropriating economic returns from genetic material developed by others. The onset of genetic engineering compounded this problem. If the insertion of one (patented) GE traits were sufficient to establish distinctiveness, marketing of a transgenic variety that relied exclusively on others' germplasm could, in principle, expropriate the value that such germplasm would otherwise have under PBR protection. These considerations led the 1991 UPOV

[1] In the European Union this is taken to mean that breeders must receive equitable remuneration (Dutfield 2011), which in some countries can take the form of an explicit royalty fee.

convention to drop the ban on double protection (by PBRs and utility patents), and to develop the concept of essentially derived variety (EDV) as a way to redress the balance of intellectual property between PBRs and patents.

The US Plant Variety Protection (PVP) Act of 1970 introduced a form of intellectual property protection for sexually reproducible plants (and for food tubers, which had been excluded from the 1930 Plant Patent Act). PVP certificates (PVPCs), issued by the US Department of Agriculture, afford exclusive rights to the varieties' owners for 20 years (25 years for trees and vines), consistent with the PBR notion encapsulated by UPOV. PVPCs therefore envision a well-defined breeders' exemption, subject to the implications of EDV provisions, as well as a farmer's privilege. With respect to the latter, the seed saving rights in the United States are actually broader than those codified in other jurisdictions, notably PBRs implemented in Europe. Subsequent amendments ensured that the provisions of the Act comply with the latest 1991 UPOV convention.

2.4. Trade Secrets and Contracts

A time-honored way of protecting intellectual property is to keep it secret (Friedman, Landes and Posner 1991). Trade secrets cover any confidential business information that may confer an advantage over competitors from the fact that it is not generally known. For trade secret to enjoy legal protection, it is generally required that reasonable efforts be spent to maintain secrecy. This protection is against another party's discovery by inappropriate means, but a trade secret does not protect against independent discovery or reverse engineering. Trade secrets can be quite important for plants, and its value for private entities' is enhanced by its complementarity with other strategies.[2] These include the use of hybrids (discussed in section 3.2), as well as contractual arrangements that prohibit seed replanting and/or the seed being used by others' breeding programs. Such restrictions, sometime referred to as bag tag licenses, are now routinely used to market seeds (Jondle, Hill and Sanny 2015).[3]

[2] Pioneer Hi-Bred International successfully used trade secrets to protect its germplasm in at least two high-profile cases (against Holden Foundation Seeds in 1991, and against Cargill in 2000).

[3] Valid contractual arrangements, however, can only be enforced between contracting parties, whereas the exclusionary rights conferred by patents are broader. This point is exemplified by the recent *Bowman vs. Monsanto* case, which concerned a farmer who had purchased soybeans to use as seeds from an elevator, rather than saving seeds produced on his farm (Kershen 2013).

2.5. International IPRs for Plants

A major development in the international landscape for IPRs was the 1994 Trade-Related Aspects of Intellectual Property Rights (TRIPS) agreement negotiated within the World Trade Organization (WTO) (Moschini 2004). International cooperation on IPRs had long been pursued in the context of WIPO, a United Nations agency (for PBRs, as noted, cooperation was the prerogative of UPOV, an intergovernmental organization). National treatment (the same rights are equally available to nationals and foreigners) was a cornerstone principle, but whether or not to provide IPR protection was not construed as an obligation. Furthermore, enforcement of IPRs in an international context was essentially non-existent. The main novelty of TRIPS was to mandate minimum standards of IPR protection to be provided by WTO members. Moreover, international enforcement of IPRs could now be pursued within the integrated WTO dispute-settlement procedures, including the threat of retaliatory sanctions—taking IPRs under the aegis of the WTO provided hitherto missing teeth to the agenda of strengthening international IPR protection.

Whereas TRIPS requires WTO members to offer patent protection to both products and processes in almost all field of technology, flexibility was envisioned for plant varieties: WTO members could opt for either patent protection or for an "effective *sui generis*" system. It was accepted early on that PBRs defined by UPOV meet TRIPS criteria. Although countries do not need to join UPOV to meet TRIPS requirements, it seems this has become the preferred path, leading to a surge in UPOV membership.[4] Use of utility patents on plant varieties specifically at present appears limited to the United States, although Japan, South Korea and Australia's legal landscapes are receptive to the use of patents for plant innovations (Janis 2014).[5] In European countries, plant innovations are included in the patentable subject matter, but plant varieties *per se* are explicitly not patentable by the statute of the European Patent Office, which also contains a statutory patentability exclusion for "essentially biological processes."[6]

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[4] As of April 15, 2016, UPOV claims 74 members. Of these, 44 joined after the coming into force of TRIPS in January 1, 1995.

[5] Japan's patent law requires an inventive step, and it remains an open question (hitherto untested in US courts) whether most breeding activities would meet this requirement (Janis 2014).

[6] Recent cases seem to suggest that this moot notion may be construed to encompass many modern breeding methods, which would therefore be excluded from patentability.

3. INNOVATION WITHOUT INTELLECTUAL PROPERTY

Just how indispensable is intellectual property protection for innovative activities? Some recent work has documented that the answer to this critical question may not be simple.

3.1. Innovation without IPRs: Some Evidence from Economic History

Until 1930, new plant varieties were not protected by intellectual property right. Petra Moser (2005, 2012) has used exhibition catalogs for great technology exhibitions held in 1851, 1876, 1893, and 1915 to track the impact of IPRs on innovation outside of agriculture over the same era. She finds widespread innovation by countries with no patent system, and surprisingly sparse use of patent systems when available (only 11% of British exhibits were patented, and only 15% of prize winning exhibits).

Innovation without patenting is feasible because patents are not the only way for firms to appropriate value from their innovations (necessary to recoup sunk R&D costs). The results of a survey of manufacturers by Cohen, Nelson and Walsh (2000) suggest alternative methods of appropriation are also important such as lead time (rated effective by 52.8% of respondents), secrecy (51.0%), and complementary capabilities (sales and service 42.7%, manufacturing 45.6%). In contrast, only 34.8% of respondents rated patents as an effective means for appropriating the value of a new product innovation. Moreover, while there is considerable variability by industry, even in the medical products industry, where patents are most highly valued, only 54.7% of respondents rate them as effective.

Moser (2005) and Moser (2012) establishes secrecy was important outside agriculture during the 19th century. Industries amenable to protection by secrecy patented at a lower rate and countries with weaker patent protection tended to focus disproportionately in industries well protected by trade secrecy (Moser 2005, Moser 2016). As secrecy became less effective in the chemical industry (due to advances of the science), the US patenting rate for chemicals crept from 0% to 20% between 1851 and 1915, even as the patenting rate for manufacturing (where secrecy was never too effective) was stationary (Moser 2012).

In contexts where secrecy is not useful, the absence of IPRs may limit innovators' ability to appropriate value from their discoveries to the extent that they are not themselves users. Users may innovate themselves, however, if the individual benefits of an innovation outweigh R&D costs. A related setting is that of "open user innovation," wherein users of a product divide up the work of

R&D and then freely reveal the results (Von Hippel 2010). Open user innovation works best when the user values custom products that are specifically designed for the user's purposes (unlikely to be available from the market) and when R&D costs are modest, or if the R&D is itself pleasurable or a hobby. The free sharing of information can help open user innovation benefit from knowledge spillovers that might not be as prevalent when secrecy or even IPRs are used to appropriate value.

3.2. Innovation in Agriculture Before IPRs

The conventional view long asserted that biological innovation was minimal, and labor-saving innovations dominated technological advance in agriculture, up to the second third of the twentieth century. Evidence for this view included the stagnation of national yields, across all major crops, up to the 1930s. Olmstead and Rhode (2008), however, argue that biological innovation did occur in this period—the conventional view neglects the R&D necessary to maintain yields in the presence of biological pressures (pests, weeds, and disease), expand crops to new regions, and improve crops in ways not reflected in yield. For most crops, secrecy was not a viable strategy for a commercial breeder because biological products are self-replicating. Self-replication makes it very difficult to keep new cultivars secret because no reverse engineering is required to enter the market as a competitor: purchasing seed once is enough to reproduce the innovation. Yet even during this era, a small amount of private innovation did occur. Complementary sales, reputations, and brief lead times allowed some private actors to appropriate sufficient value from improved seeds to justify R&D (Moser and Rhode 2011).

In the 1920s, the discovery of hybrid corn strengthened the ability of private actors to appropriate the value of new corn varieties through secrecy. Corn hybrids rely on cross-pollinating two inbred lines to generate a hybrid, the first generation of which displays superior productivity. However, this "hybrid vigor" is lost in subsequent generations. In effect, hybrid corn does not truly self-replicate, and a private firm able to retain control of the pure lines can remain the exclusive source for the superior hybrid offspring. While the public sector also played an important role in developing location-specific hybrid varieties, a large number of private seed companies facilitated the rapid diffusion of hybrid varieties, which largely had replaced open pollinated corn by the 1960s (Griliches 1957, Dixon 1980).

Still, because secrecy was impossible for most crops, many of the innovators were users (farmers). Indeed, one reason plants were originally excluded from patents was because plant breeding was seen to be an activity involving the skills of an ordinary farmer (Huffman and Evenson 2006). The costs of farm-level selective breeding and experimentation were low enough for it to be worth doing, even if farmers only benefited individually from the improved seeds (incentives were stronger for large farms, and Olmstead and Rhode 2008 document more intensive breeding by large plantations). A form of open user innovation may also have taken place, with farmers freely sharing improved varieties. Indeed, biological innovation in the era had many of the features that made open user innovation attractive: users desired custom (location-specific) seeds, R&D costs were minimal (selective breeding was even a hobby for some), and research benefited significantly from free sharing of information. Huffman and Evenson (2006) also describe the important role of agricultural societies, which disseminated knowledge via meetings and fairs, facilitated the collection and dispersal of seeds, and offered prizes and awards for innovations.

In any event, it is essential to recognize that a vital role was played by the public sector (Alston et al. 2010), which took on R&D projects that were beyond the capabilities of individual users or user groups. The US government began facilitating biological innovation in the early 1800s by collecting and disseminating seeds from foreign locations. Initially, this work was opportunistically performed by foreign consuls and naval officers, but by 1862 the program had been handed off to the USDA, which funded expeditions and program officers whose specific goal was the discovery of useful seeds abroad. While most such seeds foundered in US conditions, a small number of successes could be very important. Foreign varieties were instrumental in creating modern wheat and cotton (Olmstead and Rhode 2008). Over time, the USDA also began to engage in large scale public breeding operations (Huffman and Evenson 2006).

To summarize, prior to IPRs for plants, biological innovation did occur. Some of this development was from the private sector, especially in crops were alternative means of appropriating the value of innovations was feasible (hybrid corn is the best such example). However, because of the difficulty in appropriating value from most crops, much of the innovation that occurred during this era was user generated or undertaken by the public sector.

4. IPRS AND THE PRIVATE INCENTIVE TO INNOVATE

Whereas some innovation without IPRs can occur, it does not follow that it will occur at socially desirable levels. Non-IPR strategies available to the private sector may provide insufficient protection to an innovation, or they may keep important knowledge secret for too long. IPRs can augment the set of strategies available to private innovators, thereby enabling R&D to proceed on projects that are not amenable to alternative strategies of appropriation (Clancy and Moschini 2013). But do stronger IPRs work as intended?

4.1. Stronger IPRs and Innovation

The broader empirical literature suggests the relationship between stronger IPRs and the rate of innovation is heterogeneous. Strengthening IPRs does not substantially increase the rate of innovation on average, but can have an impact on certain sectors if the institutional environment is strong and IPRs are not set too highly.

One of the challenges of estimating the impact of stronger IPRs on innovation is the need to measure innovation distinct from IPRs themselves. One approach is to look directly at R&D spending. Sakakibara and Branstetter (1999) examine the impact of a Japanese policy change in 1988 that had the *de-facto* effect of strengthening patents. Using a sample of 307 Japanese manufacturing firms, they conclude the policy shift did not impact R&D expenditure by these firms. Kanwar and Evenson (2003) use panel data on about thirty countries to determine if countries with stronger IPRs also have higher R&D intensity. While they finds stronger IPRs are correlated with greater R&D intensity, Falk (2006), using a longer time series on fewer countries, shows this relationship is not robust when endogeneity is controlled for.

As an alternative measure of innovation, Sakakibara and Branstetter (1999) look at patenting by Japanese firms in the United States (which experienced no shift in patent policy at the time of the Japanese reforms). If stronger Japanese patents induced more innovation by firms, it ought to lead to more US patenting by Japanese firms, but Sakakibara and Branstetter (1999) find no evidence this occured. More ambitiously, Lerner (2002) assembles a large historical dataset on patenting by 60 countries (with data as early as 1850) and records 177 instances where a patent policy was changed. To measure innovation, Lerner tracks patenting in Great Britain (where patent policy had been largely unchanged) by each country before and after their policy changes. Controlling for global patenting trends and instrumenting with international patent treaties, he finds policy changes that strengthen patents do not, on their own, increase the propensity of a country to patent in Great Britain, but there is a positive effect for high income countries that do not already have strong IPRs.

Lerner (2002) mixes together patents from across all industries, even though different industries rate the importance of patents very differently. It may be that a large impact of IPRs in some markets is masked by minimal responses in others. Arora, Ceccagnoli and Cohen (2008) suggests this is indeed the case. The authors use a survey of firms to estimate the patent premium for a typical innovation in each industry, as well as the R&D response induced by an increase in the patent premium. Consistent with other surveys, they find the patent premium is highest for the "medical instruments," "biotechnology," and "drugs and medicine" sectors. R&D spending in these industries is 40-55% more responsive to a strengthening of the patent premium than for the average.

Qian (2007) evades the problem of heterogeneous effects across industries by restricting attention to the pharmaceutical sector. During the 1980s and 1990s, a number of countries extended patent protection to pharmaceuticals. Qian matches each of these countries to control countries where no such change took place to evaluate the impact of the patent protection on pharmaceutical patents applied for in the United States. Echoing Lerner's results, Qian finds pharmaceutical innovation is only enhanced by stronger IPRs for countries with high GDP, education, or indices of economic freedom. Moreover, the relationship between IPRs and innovation is only positive up to a point (set too high, IPRs can reduce innovation).

4.2. IPRs and Cumulative Innovation

Another reason stronger IPRs may not uniformly raise the rate of innovation is because of their impact on the sharing of knowledge. One of the main attributes of knowledge—the basic output of R&D activities—is that it accumulates. At the purest level, the stock of knowledge cannot decrease, and its expansion by innovative activities can open up new possibilities for ideas, discoveries and inventions. To say that innovation is often cumulative, therefore, is somewhat of a platitude. Scotchmer (2004) provides a useful taxonomy with three types of cumulativeness (more than one of these may be relevant in any one innovation setting, of course). The first arises when a basic discovery has many subsequent applications (possibly in different fields). A good example is provided by the celebrated Cohen-Boyer gene-splicing discoveries, leading to the recombinant DNA technology that made possible the modern biotechnology industry. Another instance of cumulativeness arises when downstream innovations require multiple upstream discoveries (sometime taking the form of research tools) that play the role of essential complementary inputs. Most modern high-tech products, including crops embedding GE traits, clearly exhibit this feature. Finally, cumulative innovation can take the form of so-called quality ladders, where successive generations of better quality products supplant earlier ones (exemplified by the development of computer spreadsheet products, as noted by Bessen and Maskin 2009).

The cumulative innovation perspective is essential for plant-related innovations. The value of a seed to a farmer is encapsulated in its genetics, which codes the accumulation of desirable traits from innumerable generations of breeding and selection activities, some of which date back to the dawn of agriculture. Plant breeding, whether done by traditional methods or relying on modern molecular biology techniques, is somewhat unique in the context of cumulative innovation. Specifically, production of an improved variety is not possible without physical access to the relevant germplasm. Information per se, such as that disclosed by utility patents, is just not enough to provide the blueprint for an improved variety without access to the relevant biological material. All three types of cumulativeness discussed above play a role in plant-related innovations. The quality ladder model, in particular, appears to provide a useful abstract representation of breeding activities. It also highlights the central role of Schumpeter's (1942) notion of creative destruction: the current generation of product is the springboard of the next generation's improved version, which can render it unmarketable.

The standard normative case for IPRs as innovation incentives in the context of isolated innovations needs qualifications when innovation is cumulative (Scotchmer 1991). When an early discovery has little value per se, apart from enabling further discoveries, the incentive problem is to ensure that early innovators are compensated sufficiently for their contribution to later innovations, while also preserving an incentive for the latter to occur. Essentially this requires the transfer of profits from successful subsequent applications to the first innovator, and suggest a critical role for licensing (Green and Scotchmer 1995). *Ex ante* licensing is preferable to *ex post* licensing, as it avoids potential hold up problems, but is obviously difficult to implement in practice. Asymmetric information is pervasive in these licensing settings, and this can pose serious obstacles to efficient bargaining solutions (Bessen 2004). Licensing can also raise antitrust concerns. Mergers may partly substitute for licensing when the latter is problematic (Gilbert and Greene 2015), but mergers, as well as restrictive licensing, may negatively affect competition (in both R&D and the product market).

Uncertain patent rights can also slow the use of research tools. A contemporary example relevant to agriculture concerns the contested ownership of CRISPR-Cas gene editing, a technology with the potential to enable broad new research agendas in genetic engineering (Eglie et al. 2016). Even when patent rights are not in dispute, patents on early inventions may restrict access and discourage follow-on innovations, and indeed there is a long-standing concern that patents may actually slow innovation. Focusing on patent scope, Merges and Nelson (1990) conclude that narrow patents rights may best deal with this problem. By contrast, in its prospecting view of patents, Kitch (1977) advocates for broad patents.

The available empirical evidence, it turns out, only sheds limited light on the question of whether strong IPRs promote or limit innovation when the latter is cumulative. Williams (2013) studies the effects of (non-patent) IPRs on subsequent innovation using data from the sequencing of the human genome. Celera completed the task two years in advance of the publicly-sponsored Human Genome Project. In the intervening period, Celera licensed its data (with its intellectual property protected by contract law) for biomedical research ventures. The results suggest that Celera's (short-lived) exclusivity decreased subsequent research by about 20-30%. These results are similar in magnitude to those of Murray et al. (2009), who study the apparent natural experiment arising from the agreement, between DuPont and the National Institute of Health, to greatly facilitate access by academic researchers to patented genetically engineered mice.

Galasso & Schankerman (2015) study whether patents rights favor or impede subsequent innovation by contrasting patents for which at least one claim was invalidated (by the US Court of Appeal for the Federal Circuit) with patents that were upheld. Their identification strategy to establish causality relies on the assumption that judges have different propensities to invalidate patents, and the fact that their assignment to litigated cases is randomly determined. They find that patent invalidation increases citations by about 50%, suggesting a negative impacts of patents on follow-on innovation. They further show that these effects are mainly associated with patents in fields with complex technology and high fragmentation of patent ownership (computers, electronics, medical instruments and biotechnology).

Whereas the foregoing studies provide a modicum of empirical evidence that IPRs may hinder cumulative innovation efforts, Sampat and Williams (2015) conclude otherwise by studying patents related to the human genome. Using two quasi-experimental approaches to address the problem of selection bias, they find that gene patents have not had significant impacts on follow-on research or commercial investments.

It is important to understand that the foregoing empirical studies address a narrow question: given that the initial innovation has happened, do IPRs (e.g., patents) on this innovation favor or hinder subsequent innovation? But the question we would like to pose, from a policy perspective, is different: would a world without IPRs (or with weaker IPRs) results in more or less innovation? The latter question, crucially, recognizes that the initial innovation ought to be considered endogenous, and obviously affected by what IPR regime exists.

This question is addressed, in the context of plant-related IPRs, by Moschini and Yerokhin (2008). They compare equilibrium outcomes that emerge under two alternative IPR systems: a standard utility patent, and a weaker form with the so-called research exemption. Such a feature, of course, is a central feature of PBRs, as discussed earlier. In a quality ladder model with stochastic innovation, they find that the welfare ranking of the two IPR regimes depends on the relative magnitudes of the costs of initial innovation and subsequent improvements, and either regime may dominate. The research exemption is most likely to provide inadequate incentives when the cost of establishing the initial research program is large. These conclusions are supported by the computational results of Lence et al. (2016), who compare patents and PVPCs in an explicit model of plant genetic improvement. Their framework rests on somewhat more special assumptions (including deterministic innovation) but it is parameterized to be broadly consistent with some stylized facts of the seed industry. They find that patents are best at promoting long-range research programs (such as the introduction of exotic germplasm). PVPCs promote faster diffusion of genetic improvements across firms, and can be superior to patents when diffusion effects dominate.

In both of the foregoing studies, stronger IPRs (i.e., without the research exemption) are always preferred by R&D firms, even when society would prefer weaker IPRs. Bessen and Maskin (2009), by contrast, find that even firms themselves may prefer the institutional setting without patents when innovation is both sequential and complementary (by the latter they mean the natural property that two innovators working towards a common goal increase the overall probability of success, relative to a single innovator). The required conditions are somewhat subtle, and include that competition resulting from imitation does not dissipate too much of the innovation gains that firms share in, and that the upper tail of the distribution of innovation values be sufficiently thick. They make a case that such conditions have empirical relevance, and suggest that their model is particularly suited to represent software innovation.

4.3. Effectiveness of PBRs

The exclusionary prerogative offered by PBRs are weakened by two key provisions: the farmer's privilege and the breeders' exemption. The latter is a cornerstone of PBRs—access to germplasm to provide the initial source of variation in breeding programs was deemed essential from the outset. The incentive implications that arise from the breeders' exemption were discussed in the preceding section. The farmer's privilege further weakens the appropriability power of PBRs because it erodes the ability of new variety developers to appropriate rent by selling seeds (Perrin and Fulginiti 2008). A new seed is an innovation that self-reproduces, in most cases (hybrid varieties being the most obvious exception) true to type. Hence, it has the characteristics of a durable good. A breeder with exclusive marketing rights on a newly developed variety is then faced with the well-known durable good monopoly problem and the predicaments of the Coase conjecture (Coase 1972, Bulow 1982). Given a seed-saving strategy, the farmer's benefit from the new seed is the present value of returns from many subsequent planting of the variety. But her willingness to pay is curtailed by the expectation that the seller will lower prices in the future. The inability of sellers to credibly commit to never doing that, however, leads to an equilibrium pricing that can drastically erode the ability of the monopolist to appropriate rent by pricing above marginal cost.

Given the farmer's privilege and breeders' exemptions, the general perception is that PBRs have comparatively low value to their holders. Lesser (1994), with a hedonic analysis of 1992 soybean seed prices, finds that PVPCs are associated with a 2.3% increase in value. In wheat, PVPCs do not appear to allow firms to exercise significant market power (Alston and Venner 2002). Finally, it does not appear PVPCs are frequently litigated, which might be expected if they conferred substantial market power (Janis and Kesan 2002b).

Despite the weakening effects of the farmer privilege and breeders' exemption, PBRs do prevent certain forms of expropriation valuable to private firms. Several studies have shown the enactment of the PVP Act led to an increase in R&D spending for crops eligible for the new protection. Perrin, Kunnings, and Ihnen (1983) and Butler and Marion (1985) each surveyed a large set of seed breeding companies on their R&D activities around the time of the Act's passage. There was a rapid increase in R&D spending for soybeans, as well as the number of active breeding programs, right around passage of the Act in 1970 (some surveyed firms explicitly stated they started breeding programs in response the PVP Act passage). In contrast, ineligible crops such as hybrid corn showed no such discontinuity. Malla, Gray and Phillips (2004), and Malla and Gray (2000) provide similar evidence for a Canadian context, where PBRs appear to have stimulated private R&D in the canola industry.

Whereas their availability stimulated the development of private breeding for some crops, the evidence is more mixed that PVPCs increased the rate of innovation. Perrin, Kuhnen, and Ihnens (1983) and Babcock and Foster (1991) were unable to detect a statistically significant shift in soybean and tobacco yields, respectively, when the Act passed, despite apparent increases in private soybean R&D spending and the dominance of the private sector in tobacco breeding. Carew and Devadoss (2003) detect a positive impact of Plant Breeders Rights on Canadian canola yields in some specifications, but this effect disappears when time fixed effects are included. Naseem, Oehmke, and Schimmlpfennig (2005) do find a net positive effect of PVPCs on US cotton yields, when they allow for a trend-break in yield growth in 1982. Alston and Venner (2002) find no evidence of higher wheat yields for varieties with PVPCs, but Kolady and Lesser (2009), who are able to control for several omitted factors by comparing wheat yields in each year with the yield of a reference plant, finds PVPCs are indicative of higher yields for one of the two wheat varieties they consider. Moreover, Kolady and Lesser (2009) find private wheat yields for both varieties considered outperform those developed by the public sector. They argue the private wheat industry would not exist if not for PBRs and attribute the greater yields of private wheat to the availability of PVPCs. Thomson (2015), however, finds the opposite in an Australian context. Assessing the impact of a shift from publicly supported breeding to a private system reliant on PBRs, he finds the rate of yield improvement worsened after switching to a private system.

4.4. Effectiveness of Plant Patents

In contrast to PBRs, plant patents do not have a farmer's privilege or a breeders' exemption. Perhaps for this reason, they appear to confer more value than a PBR. Plant patents are used by the groups that lobbied for their legislation: between 1930 and 2008, there were 20,982 plant patents granted (Pardey et al. 2013 supplemental materials) and of these the vast majority were ornamentals (80.8%), fruit (14.2%), and trees (2.3%). Moreover, plant patents do seem to confer a price premium. Drew et al. (2015), conducting a hedonic price analysis, find ornamental plants with a plant patent have a 23.5% price premium on average (although the premium varies widely by species, with some not significantly different from zero). On average, plants with expired patents have a lower price than those without patents and the premium declines with the age of the patent, suggesting the patent premium is not merely due to higher quality plants being patented.

Moser and Rhode (2011) examine the impact of the Plant Patent Act on the American Rose (which accounted for nearly half of plant patents between 1931 and 1970). Their results are broadly similar to those for PVPCs. First, a large commercial breeding sector emerged in the wake of Act, and major commercial breeders were the main users of plant patents. Second, despite the growth of the private sector, the overall rate of new American roses registered with the American Rose Society fell after plant patents were introduced. One potential explanation for the absence of a stronger impact on rose development is the widespread breeding of roses by users (in this case, hobbyists). Only 16% of new roses were actually patented, and so any decline in rose breeding as a hobby may well have overwhelmed increased activity in the commercial sector. In what appears to be the only investigation of the impact of the Plant Patent Act on other eligible plants, Stallman (1986) finds little or no evidence that it increased commercial breeding activity for other fruits.

4.5. Effectiveness of Utility Patents for Plants

Patenting of microorganisms, and a host of other biotechnology innovations rooted in the DNA manipulation of living organisms, now constitute patentable subject matter for most jurisdiction. Patenting of whole plants and specifically plant varieties, however, remains far less widespread, as discussed earlier. There are really no empirical studies of the impact of (recent) availability of utility patent protection on the rate of plant innovation. But there is plenty of suggestive evidence that the patenting of biological innovations has been essential for the development of modern biotechnology, including GE transgenic plants used in agriculture. Fixed costs are high in this setting, which make strong IPR protection particularly valuable for the private sector: a recent study estimated the cost for discovery, development and bringing to market of a plant biotechnology trait at $136 million (25.8% of which associated with regulatory requirements) (Phillips McDougall 2011).

Moreover, GE trait development requires use of a range of technologies from disciplines outside the traditional plant-breeding sector, which may be more responsive to stronger IPRs. Arora, Ceccagnoli and Cohen (2008) found biotechnology patents to have one of the largest patent premiums of any industry. Cohen's (2010) extensive review did not single out agricultural innovations, but finds utility patents are most valuable to medical, health, and chemical industries. Agricultural biotechnology shares many similarities with these sectors (it draws on a similar scientific basis, and is subject to regulatory oversight in similar ways). Also suggestive of the high value of agricultural biotechnology patents is the rate at which they are challenged. In the European Union, patents may be opposed (within nine months) if the challenger believes they do not meet patenting criteria. Because it is costly to challenge a patent, challenges imply the patent helps a firm exert market power. Schneider (2011) documents that European plant biotechnology patents are challenged twice as frequently as the typical patent.

In addition to their use in GE traits, in the United States the use of patents has rapidly overtaken the use of PVPCs for varieties of major crops. Moschini (2010) supplied evidence on the use of PVPCs and utility patents for varieties of the two most important commercial crops: corn and soybeans. Utility patents for varieties of corn and soybeans assumed a nontrivial role starting in the mid-1990s. For the last five years of the period considered (2005-09) the number of utility patents on varieties vastly exceeded that of PVPCs. Pardey et al. (2013) provide a more complete characterization of these trends by including plant patents as well, by covering all varieties, and by considering the longer time frame 1930-2008 (for the first half of this period, of course, only plant patents were possible).

Figure 1 returns the focus on corn and soybeans, and illustrates the number of PVPCs and utility patents issued over the last 40 years, from 1976 to 2015. Such counts are reported as the total for five-year periods, to smooth out year-to-year variations. This figure shows that the trend in growth uncovered by earlier studies has persisted. Indeed, nearly half of the utility patents on varieties ever issued were granted in the last five years (2011-15). Interest in PVP certificates appears to have shot up as well in recent years: the number of PVP certificates issued in the period 2011-15 were three time and four times as large as in the period 2006-2010, for soybeans and corn, respectively.

This all suggests patents are valued highly by the seed industry. Moreover, as in the case of PBRs and plant patents, the privatization of seed development continued to deepen after plants were granted utility patent protection. While private corn varieties already accounted for 100% of planted US acres by 1980 (facilitated in part by hybrid technology), the percent area of US land planted with private (as opposed to public) sector varieties of wheat rose from 5% to 24% between 1980 and the late 1990s, while the percent planted with private varieties of cotton rose from 72% to 93% over the same period. Most dramatic was the increase in private soybeans from 8% to 70-90% over the period (Heisey, Srinivasan, and Thirtle 2001).

Over this same period, the seed industry also rapidly expanded R&D in breeding and biotechnology, both relative to private agricultural R&D in other sectors and relative to public funding of agricultural R&D. Between 1975 and 2010, private sector agricultural R&D in the seed and biotechnology sectors grew spectacularly, from $80mn (in constant 2010 dollars) to $2.2bn. Over the same period, all other private sector R&D for agricultural inputs rose from $1.4bn to $2.5bn (Pray and Fuglie 2015), and public sector spending on all agricultural R&D rose from $4.0bn in 1975 to $5.9bn in 2006, declining thereafter to $5.3bn by 2009 (USDA 2012).

Stronger IPRs surely contributed to the rapid emergence of a large GE seed industry. While there are no studies to examine the impact of utility patents on the rate of agricultural innovation, there has been some work on the impact of GE technology on the rate of biological innovation in agriculture. To the extent that the development of GE crops depended on strong patent protection, these gains may be partially attributed to stronger IPRs. Both Nolan and Santos (2012) and Leibman et al. (2014) take as a benchmark Duvick's (2005) finding that over the 1930s-2001, traditional crop breeding (including hybridization) contributed to maize yield gains of 1.8 bu per acre per year. They then compare this gain to the observed rate of yield gain since GE technology emerged. Nolan and Santos (2012) suggest GE technology may have boosted corn yield gains by about 40% over what they would have been otherwise. Leibman et al. (2014), using historical data on average US yields, suggest an increase on the order of 30%. Xu et al. (2013) find empirical evidence that GE traits boosted realized yields in US corn but not in US soybeans. Yield enhancements due to GE varieties may be even more significant in developing countries (Qaim and Zilberman 2003).

5. STRENGTHENING OF IPRS, INDUSTRY CONSOLIDATION AND INNOVATION

As discussed in the foregoing, legal protection of intellectual property for plant innovations is marked by a late start relative to other products and processes, but shows a distinct trend towards strengthening and broadening the reach of IPRs. This trend impacts the nature and structure of R&D, with implications that bear on innovative activities, the structure of agricultural production, and the distribution of profit along the food supply chain as well as internationally.

The implementation of the TRIPS agreement has led to some harmonization, but mostly strengthening, of IPR protection for plant-related innovations around the world. In particular, protection has increased relatively more in low-income and middle-income countries than in high-income countries (Campi and Nuvolari 2015). The wisdom of including IPRs in the WTO has been questioned (e.g., Panagariya, 1999; Srinivasan, 2002). TRIPS mandates mostly affected developing countries, as developed countries already offered IPR protections in most areas. Whereas multilateral reduction in trade barriers can be beneficial to all countries, strengthening IPR protection in developing countries has the potential to simply transfer rent towards R&D-intensive developed countries and increase the cost of new technologies for developing countries.

There is, however, a real economic problem that international coordination of IPRs is trying to address. Knowledge is a global public good, and its production can be sustained by promoting private R&D investments. The standard tradeoffs that emerge in a closed economy have some nuanced implications for a trading world economy (Grossman and Lai 2004). Insofar as IPRs promote R&D, stronger protection in one country creates positive spillovers for consumers in other countries. Harmonization of IPR protection turns out to be neither necessary nor sufficient for efficiency in a world with heterogeneous countries (vis-à-vis market size and their capacity for innovation). But the inherent free rider problem means that the uncoordinated Nash equilibrium of countries acting independently results in inefficiently low protection. Whether stronger IPR protection improves plant innovations in developing countries remains an open question. For many developing countries, agricultural research has been done predominantly by public institutions, and the major constraint on agricultural innovations has been a lack of sustained research funding rather than the lack of suitable IPRs (Wright and Pardey 2006). Technology transfer by large firms based in developed countries, however, could considerably benefit from improved IPR institutions in the developing world.

5.1. IPRs and Industry Consolidation

The strengthening of IPRs for plants has been concomitant with an increasing role of the private sector in performing agricultural R&D, and an increasing consolidation of the seed and agro-chemical industry that carries out most plant-related innovative activities. Needless to say, these developments have been controversial (Kloppenburg 2004, Matson, Tang and Wynn, 2012).

To some extent, consolidation in these industries mirrors a general trend in the economy, but it also reflects unique elements that bear on the importance of IPRs. The wave of major consolidations in the seed and agro-chemical industry that took place in the 1990s was a consequence of the disruptive effects of biotechnology innovations in agriculture, specifically the development and marketing of GE crops. To capture value from this revolutionary technology, firms needed to combine highly complementary assets with diffuse ownership. Specifically, patented GE traits—themselves a bundle of numerous patented technologies—need to be introduced into elite germplasm (often also proprietary), using proprietary GE tools. The challenges for reaching an efficient solution to this problem can be formidable. Patented inputs that are essential for a new product give each patent holder blocking power, which makes realization of the innovation susceptible to a hold-up problem (Shapiro 2001). This problem is particularly acute when patent rights are highly fragmented, which led Heller and Eisenberg (1998) to postulate the so-called tragedy of the anticommons (the excessive allocation of property rights can result in underutilization of knowledge). Market-based solutions to this problem include patent pools and cross-licensing. But, with high transaction costs, aggregation of the required IPRs may more efficiently be pursued by mergers and acquisition. Graff, Rausser and Small (2003) articulate this perspective in detail, and provide empirical evidence to support the notion that the consolidation of the agricultural input industry was consistent with an endogenous restructuring in the pursuit of coordination of complementary intellectual assets. The critical role of patent rights in explaining observed mergers and acquisitions of firms engaged in plant biotechnology innovation was confirmed by Marco and Rausser (2008).

Industry consolidation naturally breeds concentration of innovative activities, and of critical innovation outputs. A glimpse of these effects is provided by examining the owners of PVPCs and patents on varieties. Table 1 focuses on the last five years of Figure 1, which have seen the most intense activity for both PVPCs and utility patents. This table reports the distribution of ownership for awarded PVPCs (applicants) and utility patents (assignees), for both corn and soybeans. It is immediately clear that two companies—DuPont and Monsanto—account for the vast majority of these IPR instruments.[7] The combined total of these companies account for 83% of corn PVPCs, 86% of soybean PVPCs, 88% of corn utility patents, and 77% of soybeans utility patents. Syngenta is a distant third player, while Dow has a significant presence only in patenting maize varieties.[8] A striking result in Table 1 is the almost complete absence of public institutions. Apart from a handful of soybean PVPCs obtained by some public universities, there appears to be nothing else in this

[7] We have made every effort to accurately reflect assignments to subsidiaries to the parent company (e.g., Asgrow and Dekalb are counted for Monsanto). Also, many of Monsanto's soybean variety patents are jointly assigned with Stine Seeds. Because the latter company seems to have no independent patenting of its own, the table counts these patents for Monsanto.

[8] Dow is the fourth largest assignee for maize utility patents (with its Agrigenetics/Mycogen unit), whereas the fourth largest assignee for soybeans is actually MS Technologies, an Iowa-based company that collaborates with Dow AgroSciences.

five-year period. Pardey et al. (2013) also comment on the lack of varietal rights assertion by public institutions, despite large investments in agricultural research performed at universities, research foundations and government agencies. They also provide some evidence on the evolution over time of this ownership concentration, which has increased somewhat.

Complementary evidence on the evolution of ownership in plant genetics is provided by Jefferson et al. (2015), who focus on plant-related gene patents rather than on utility patents on plant varieties. They also found that private sector ownership dominates, but the public sector presence in plant gene patenting is significant, amounting to about 25% over the period 1990-2014 (although they note a gradually widening gap between private and public ownership of plant gene patents). They also note that DuPont and its affiliates hold the largest collection (more than half) of all plant gene patents they identify.

5.2. Pricing of Proprietary Innovations

IPRs convey exclusive rights that, when effective, allow innovators to charge supra competitive prices. Having documented the steady rise of IPRs for plant-related innovations, one may ask whether an impact on seed prices can be detected. Figure 2 reports some suggestive evidence by plotting seed prices for corn, soybean and wheat for the period 1990-2015. Seed prices are from the National Agricultural Statistics Service (NASS): corn hybrid seed, price paid, $/80,000 kernels; soybean seeds, price paid, $/bu; and winter wheat, price paid, $/bu. As a control, we also plot expected product prices measured by Chicago Board of Trade (CBOT) futures prices (specifically, the average of daily closing prices, over the period January to March, for the December contract delivery for corn and wheat, and the November contract delivery for soybeans). To make them immediately comparable, the six series were converted to indices (1990=1). It is quite clear that, for the period considered, seed prices for corn and soybeans have increased considerably. Indeed, they have increased considerably more than the corresponding output price. Divergence between the rate of increase of seed and output prices appear to start in the late 1990s, with the rapid adoption of GE varieties. The comparison with wheat is instructive because IPRs have played a much smaller role for wheat. Interestingly, for winter wheat the trajectory of seed price is very much in line with the increased commodity prices. For corn and soybean seeds, on the other hand, the price increase over this period is at least twice as large as the observed commodity price increase.

6. CONCLUSION

Formal protection for intellectual property arrived relatively late for agricultural (biological) innovations and has resulted in a diverse set of IPR forms. But the trend has clearly been one of strengthening and broadening of the scope of IPRs, in the United States and internationally. Because biological organisms such as plants can be easily reproduced and multiplied, lack of IPRs severely hinders innovators' ability to appropriate returns from their efforts. Insofar as such incentives are necessary, the trend towards strengthening of IPRs should be conducive to increased private research efforts. The evolution of the seed industry, and the major expansion of agricultural R&D activities, is certainly consistent with this perspective. Indeed, stronger IPRs have been vigorously embraced by this industry and have contributed to a major transfer of breeding activities from public institutions to an increasingly concentrated private sector.

Beyond R&D investments, there remains a shortage of empirical evidence that stronger IPRs have resulted in larger innovation gains. The literature on the impact of plant patents and PBRs on innovation using traditional breeding techniques provides mixed conclusions. GE technology, on the other hand, appears to have many characteristics that make it likely to respond to stronger IPRs. Whereas there is no direct measure of the impact of utility patents on plant innovation, some empirical evidence suggests that the use of GE technology has accelerated the rate of plant innovation for some crops. In any case, the agricultural literature seems consistent with the broader empirical work on IPRs and the rate of innovation, which indicates the effects tend to be heterogeneous by industry, and which is rather ambivalent as to the link between strong IPRs and the rate of innovation. It bears noting at this juncture, however, that the challenges inherent in trying to uncover causality in these settings are formidable. It may be unreasonable to insist on weaving strong policy conclusions about IPRs on the available empirical evidence.

Much attention about the strengthening of IPRs has been devoted to the concern that it may adversely affect innovation. Economic theory provides some reasons for apprehension, especially in cumulative innovation contexts relevant to plant innovation. The empirical evidence, while inconclusive, suggest the possibility IPRs might in fact have detrimental effects on innovation if set too strictly. But the evidence also suggest certain industries, including biotechnology, do benefit from strong IPRs. Biological innovations in agriculture are increasingly tied to advancements in basic science and modern molecular biology techniques, and their supply has migrated almost completely to the private sector. Without strong intellectual property, it is difficult to see how industry could justify the large R&D investments seen in recent years.

Beyond the incentive issue, the ownership structure of fundamental knowledge assets mediated by strong IPRs necessarily impacts the distribution of welfare gains attributable to innovations. Agriculture remain largely a competitive sector. The innovations that flow to the production sector create wealth, but their proprietary nature means that a (possibly large) share of the resulting welfare gains can be claimed by input suppliers. The path of technological change for the sector, once largely influenced by public research and the farmers' own ingenuity, appears increasingly shaped by the decisions of a highly R&D-intensive, and increasingly consolidated, input and technology-providing industry.

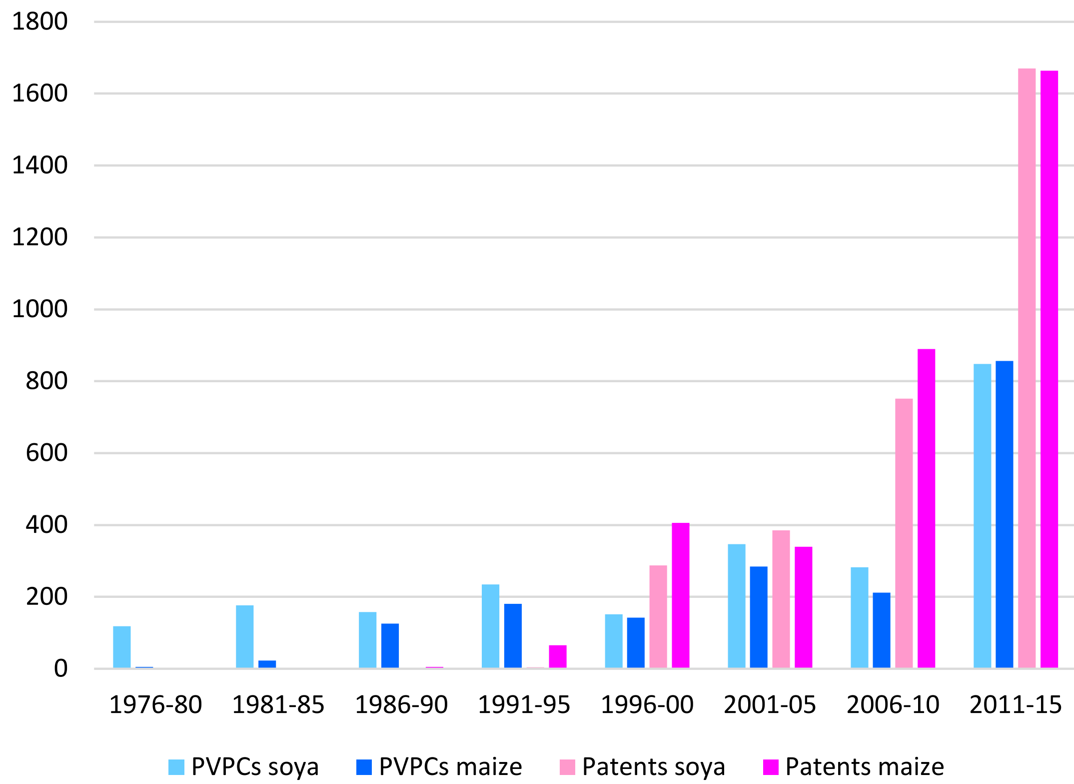
DISCLOSURE STATEMENT

The authors are not aware of any affiliation, memberships, funding, or financial holdings that might be perceived as affecting the objectives of this review.

ACKNOWLEDGEMENT

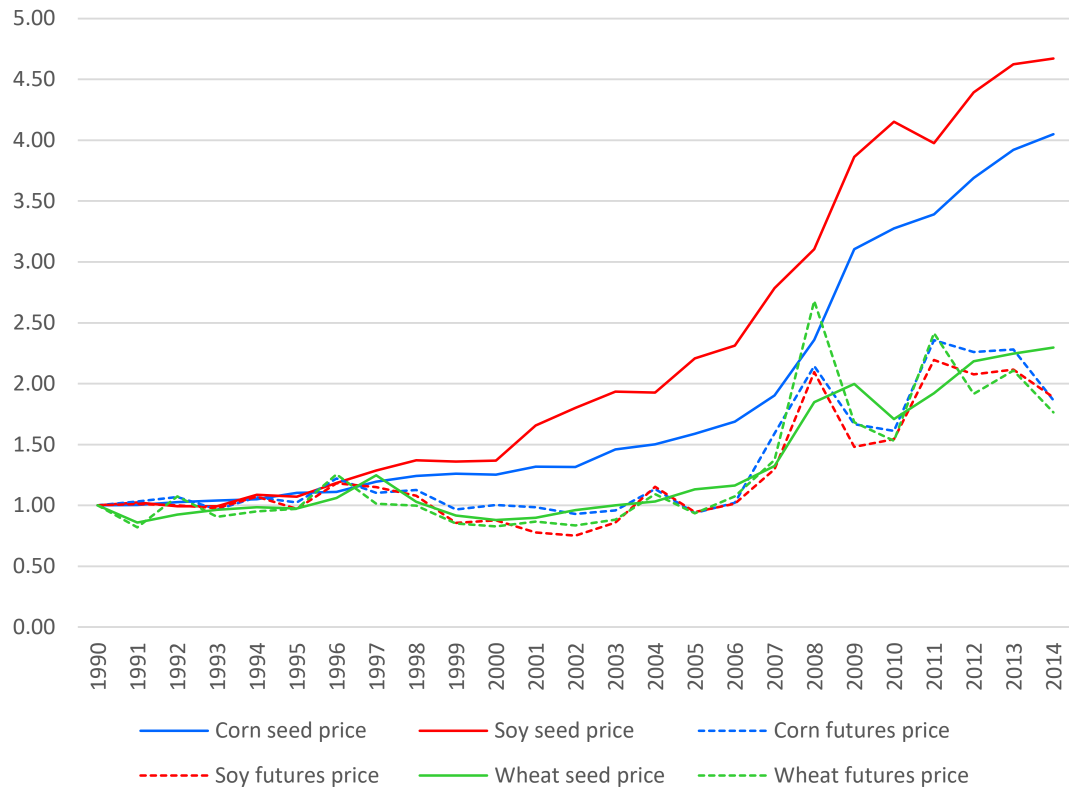
The views expressed are the authors' own and do not necessarily reflect those of the USDA or the Economic Research Service. Some of the research discussed in this review has been supported by the National Institute of Food and Agriculture, U.S. Department of Agriculture, grant No. 2015-67023-22954.

Figure 1. Number of U.S. PVPCs and Utility Patents on Varieties, 1976-2015



Source: Data assembled from USDA and USPTO.

Figure 2. US Seed Prices and Expected Output Prices, Corn, Soybeans and Wheat, 1990-2014 (indices, 1990 = 1)



Source: Computed from NASS data and CBOT data.

Table 1. Distribution of Ownership for PVPCs and Utility Patents on Varieties, 2011-2015

	PVPCs		Patents	
	Maize	Soybeans	Maize	Soybeans
DuPont	52.7%	56.6%	39.0%	29.4%
Monsanto	30.4%	29.6%	49.1%	47.3%
Syngenta	16.6%	11.8%	5.4%	8.0%
Dow	0%	0%	4.6%	1.4%
Other private	0.4%	0.2%	1.8%	13.2%
Public	0%	1.8%	0.1%	0.6%
Total (number)	856	848	1,663	1,671

Source: Data assembled for USDA and USPTO.

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