Flowers of Invention: The Economic Impacts of Patent Rights*

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Abstract

How do patent rights affect innovation and downstream production? Patent protection was introduced for plant biotechnology in the United States in 1985, and it affected crops differentially depending on their reproductive structures. Exploiting this unique feature of plant flower structure and a new dataset of crop-specific technology development, I find that the introduction of patent rights increased the development of novel plant varieties in affected crops. Technology development was driven by a rapid increase in private sector research investment, was accompanied by positive spillover effects on innovation in certain non-biological agricultural technologies, and led to an increase in crop yields. Patent rights, however, may come with potentially significant costs to the consumers of technology and distortions to downstream production. Nevertheless, despite higher spending on seeds, in US counties that were more exposed to the change in patent law because of their crop composition, land values and profits increased. Taken together, the results suggest that the prospect of patent protection spurred innovation and increased downstream productivity and profits.

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1 Introduction

Patent rights are often listed among a set of institutions that drive technological progress, and the ability to profit from new ideas via patent protection is at the heart of models of economic growth (e.g. Romer, 1990; Acemoglu and Robinson, 2012). Nevertheless, our understanding of the impact of patent rights on innovation and productivity growth remains relatively limited and the subject of intense debate (e.g. Lerner, 2009; Moser, 2016; Williams, 2017).[1] Moreover, even if patent rights spur innovation, they come with potentially higher costs for the consumers of technology. This trade-off between *ex ante* incentives for innovators and *ex post* distortions to downstream production is the key determinant of the economic impact of patent rights (Nordhaus, 1969). Thus, evaluating the impact of patent protection requires understanding its effect on both the developers and the consumers of technology.

This paper investigates how the introduction of patent rights for plant biotechnology in the US affected technology development and downstream agricultural production. While patent protection for most US inventions has existed since the 18th century, protection for new plants and crop varieties was excluded because living organisms were not considered patentable subject matter. Certain crops, however—those for which it was feasible to produce hybrid varieties—had *de facto* patent protection even without formal patent rights. Hybrid varieties are generated by combining the genetic material of parent plants and can only be produced by the developer with access to both parents. As a result, hybrids cannot be reproduced by farmers or competing inventors, affording innovators of hybrid varieties "the same commercial right that an inventor receives from a patented article" (Kloppenburg, 2005, p. 102). All other varieties, however, are reproducible and there was no way to prevent them from being copied, saved, and re-used by farmers.

Then, in its landmark 1985 *Ex Parte Hibberd* decision, the US Patent and Trademark Office ruled for the first time that seeds, plants, and plant tissue were patentable subject matter.[2] In the words of Lesser (1987), "[V]irtually overnight, and to the great surprise of many, seeds became patentable." *Nature* magazine reported, "At long last, 'everything under the sun made by man' [is] patentable [since the PTO] ruled that plants can be patented under the general patent statute" (Van Brunt, 1985). Biotechnology patenting surged almost immediately (Hodgins, 1987). This turning point provides a unique opportunity to study how the prospect of patent protection affects innovation and production. Did patent rights truly increase technology development and R&D investment? And if so, did the benefits of patent-induced innovation outweigh potentially higher downstream costs and distortions?

[1] Boldrin and Levine (2013, p. 3) even argue that there is "no empirical evidence that [patents] serve to increase innovation and productivity, unless productivity is identified with the number of patents awarded."

[2] Weaker forms of protection existed for some crops prior to 1985, but these, anecdotally, had little impact (see Section 2.1) and, empirically, had limited value to innovating firms (see Section 4.2.2).

I study the effect of patent protection for agricultural technology by exploiting the introduction of patent rights in 1985 alongside differences across crops in their exposure to the patent law. Innovation for crops with access to "built-in" protection through hybridization was substantially less reliant on formal intellectual property rights (Gupta, 1998). This motivates a difference-in-differences framework that compares innovation in crops that received true patent protection in 1985 for the first time with a control group that already had long-standing *de facto* protection and was therefore much less affected by the introduction of patent rights. The key determinant of whether hybrid varieties could be generated for a given crop is its flower structure (e.g., Wright, 1980; Butler and Marion, 1985). If a crop has "perfect flowers"—flowers that contain both the male and female reproductive parts—generating a hybrid is often technologically infeasible or prohibitively costly. When the male and female flowers are on separate parts of the plant, generating hybrid varieties is more straightforward (e.g., Whitford et al., 2013; Gupta et al., 2019).[3] Crops with perfect flowers—including wheat, barley, beans, and carrots—become the treatment group and crops with imperfect flowers—including corn, spinach, squashes, and cucumbers—had long-standing access to "built in" protection and therefore become the control group. The existence of this control group makes it possible to isolate the impact of the introduction of patent rights.

Before turning to the main analysis, I empirically validate each component of this empirical design. First, I document that agricultural biotechnology patenting was absent prior to *Ex Parte Hibberd* but surged almost immediately thereafter. There was no similar change in patenting activity for other agricultural technologies. Second, I document that crops with perfect flowers (i.e., treatment crops) are much less likely to have hybrid varieties. While actual hybrid development is in part an outcome of research effort and the development of hybridizaiton techniques, this result confirms that a fixed, crop-level feature of flower structure strongly predicts hybrid development. Third, using a stock market event study design, I show that receiving a treatment-crop patent leads to far higher abnormal returns than receiving a control-crop patent, especially when the control-crop patent references a hybrid variety. This finding confirms that formal patent protection is substantially more valuable for the treatment crops. Finally, I show that treatment and control crops are balanced across a range of covariates that determine the location, structure, and demands of innovation.

In order to compare technological progress in treatment and control crops over time, I compile a novel data set of crop-specific technology development. A common proxy for innovation is patenting activity; however, since this paper investigates the introduction of patent rights, patents themselves are not a useful measure. I overcome this challenge using

[3] While flower structure strongly predicts the ease of hybridization, it is not the only determinant of hybrid development. Section 2.3 describes hybrid development in greater depth while Section 4.2.1 documents empirically that flower structure is a strong predictor of hybrid development.

the United States Department of Agriculture's (USDA) *Variety Name List*. The *List*, maintained in order to prevent fraud in the seed market, is designed to be a comprehensive account of all crop varieties released in each year, compiled from a range of sources including variety release notices, official journals, seed catalogs, trade publications, and seed companies. This data set makes it possible to track crop-level innovation in new plant varieties—precisely the technology that became patentable in 1985—before and after the introduction of patent rights. I supplement the *List* with three additional measures. First, I compile data on R&D investment by crop from the USDA Current Research Information System (CRIS).[4] Second, I compile data on crop-specific patent grants in non-biological technologies, in order to study the spillover effects of biotechnology patent rights on innovation in other areas (e.g., mechanical technology). Third, I compile measures of crop yields (i.e., physical output per area) in order to estimate the impact of patent rights on one component of productivity.

The first main result is that the introduction of patent protection led to a dramatic increase in the development of new crop varieties. While variety development in treatment and control crops was on similar trends prior to 1985, treatment crops experienced a 119% relative increase in variety development during the ten years following the introduction of patent rights. The effect is driven by non-perennial crops—crops that must be re-planted every one or two years—for which profit opportunities from recurrent variety sale were plausibly largest and hence patent protection most valuable. Consistent with the historical narrative, the positive effect of patent rights on treatment compared to control crops was driven by the fact that control crops' advantage in variety development prior to 1985 was brought to zero during the ten years after *Ex Parte Hibberd* as variety development for treatment crops increased substantially. Patent rights thus spurred substantial technology development.

Next, I turn to additional crop-level outcomes. First, I show that the introduction of patent rights substantially increased private R&D investment and had no significant effect on public R&D investment. Thus, the rise in technology development seems to have been driven by private investment, consistent with the responsiveness of private sector firms to new profit opportunities. Second, using crop-specific patent data for non-biological inventions, I find that introduction of patent protection for biotechnology led to an increase in patent grants for some non-biological technologies; I find no evidence that it crowded out any technology area. Third, I find that the introduction of patent rights had a positive effect on crop-level physical productivity. Treatment crops experienced an 11% relative increase in crop yields during the ten years following the introduction of patent rights, a first indication that patent-induced technology development increased downstream productivity.

[4]To calculate research investment by crop-year, I aggregate the CRIS project-level data to the crop-by-year level. The CRIS data contain both public research investment and all private research investment in research projects that received any public funding. This limits coverage of private investment (see Section 5.3).

This first set of findings demonstrates that patent protection for plant varieties had a positive impact on innovation. While this finding cannot be taken for granted (see Boldrin and Levine, 2013; Williams, 2017), it does not necessarily imply that patent rights benefited the consumers of agricultural technology. Patent protection allows for monopoly pricing, which may have distorted input choices and increased the cost of technologies that would have been developed in the absence of patent rights (Nordhaus, 1969; Budish et al., 2016). Higher prices for biological inputs could limit or even reverse the effect of higher productivity on farm profits. Indeed, critics of patenting often focus less on their effectiveness at spurring innovation and more on their potential negative impacts on farmers due to higher input costs (Straub, 2005; Keteyian, 2008). Moreover, the use of improved technologies can have equilibrium price effects that further dampen the impact of patent protection on profits.

To study the impact of patent rights on downstream production, I focus on fixed geographic units—U.S. counties—and estimate the impact of county-level *exposure* to the change in patent law. Using models of maximum potential crop yield from the Food and Agriculture Organization's (FAO) Global Agro-Ecological Zones (GAEZ) database, I construct a county-level measure of exposure based on relative suitability for treatment crops compared to control.[5] If the ecological and geographic features of a county make it more suitable for treatment crops, then the county was relatively more exposed to the change in patent law, including both the patent-induced technology and potentially higher technology prices that come with it. I combine the county-level exposure measure with the 1969–2002 rounds of the US Census of Agriculture in order to estimate the impact of the introduction of patent rights on agricultural land values, capturing the net present value of agricultural profits.

The second main result of the paper is that exposure to the introduction of patent rights had a large, positive effect on the value of agricultural land. This result is robust to the inclusion of state specific trends as well as to controlling flexibly for trends in pre-period land values, land devoted to agriculture, agricultural revenues, farm size, and geographic location. Moreover, the exposure measure is uncorrelated with changes in agricultural land values *prior* to the introduction of patent rights in 1985, suggesting that this result is not driven by pre-existing trends. According to the most conservative estimates, the introduction of patent protection increased the total value of US agricultural land in 2002 by 7.5%. Thus, patent-induced technology was capitalized into a substantially higher value of agricultural land, indicating that the downstream expected benefits of new technology more than outweighed its costs. These estimates are consistent with existing accounts of biological innovation contributing to late-20th Century growth in the US agricultural sector (Kloppenburg, 2005).

What mechanisms drove the positive effect on land values? Consistent with higher costs

[5] I validate the GAEZ-derived exposure estimates and also re-produce the main county-level results using data on the distribution of production across crops from the 1982 Census of Agriculture.

of patented inputs, I find that more-exposed counties increased input spending on crop varieties but not on other inputs that did not experience a change in patent law.[6] Nevertheless, exposure to patent rights increased total agricultural profits, reduced profit volatility, and increased the share of county land area devoted to crop production. These findings indicate that patent-induced technology development, on average, increased crop productivity and resilience. The impact of patent rights on profits was driven by counties with the largest average farm size, and the introduction of patent rights also led the number of large farms and their share of total agricultural revenue to increase. These results indicate that new technology disproportionately benefited large farms and may have contributed to consolidation in the agricultural sector.[7] That said, most consolidation of the agricultural sector took place prior to 1985, so any impact of patent rights is small compared to the long-run trend.

Related Literature My main contribution is to study the impact of patent rights on both innovation and downstream production, exploiting the introduction of patent protection for crop biotechnology. In doing so, this paper contributes to three main strands of literature.

First, this study contributes to existing work on the consequences of patent protection. Patent rights are the main policy tool used to encourage innovation; yet, because patent rights and enforcement are endogenously determined, estimates of the impact of patent protection on technological progress are limited (Boldrin and Levine, 2013; Budish et al., 2016; Williams, 2017). Branstetter and Sakakibara (2002) argue that Japan's 1998 expansion of patent scope had a limited impact on firms' R&D, while Budish et al. (2015) document that cancer research is directed away from projects with shorter expected patent length. Other studies have investigated differences in patent law across countries (Lerner, 2002; Qian, 2007); studied how patent rights affect new technologies sent to 19th century World Fairs (Moser, 2005, 2012); and analyzed how anticipated changes in term length affect patenting (Bertolotti, 2026).[8,9] Further complicating the relationship between patent rights and innovation, other work has shown that patent protection for individual inventions hinders follow-on innovation (Murray and Stern, 2007a,b; Williams, 2013; Galasso and Schankerman, 2015).[10] Yet estimates of the impact of patent protection for an existing technology are very different from estimates of the impact of the availability of patent rights, which could affect the set of technologies that exist in the first place. Moreover, the value of patent protection is determined by *both* the amount of induced innovation and *ex post* losses in the

[6]The Census of Agriculture does not collect data on input quantities or prices.

[7]This is consistent with the idea that new varieties had complementarities with scale (Willingham and Green, 2019). Small farms may have benefited less while facing lower output prices as national output rose.

[8]Other work has studied the effects of copyright (Biasi and Moser, 2021; Giorcelli and Moser, 2020)

[9]A handful of case studies focusing on individual crops have investigated the impact of historical changes in weaker forms of IP in agriculture (Alston and Venner, 2002; Naseem et al., 2005; Moser and Rhode, 2011).

[10]Sampat and Williams (2019) find no evidence of this effect in an analysis of patents on human genes.

form of higher technology costs (see Nordhaus, 1969; Budish et al., 2016). I develop a novel identification approach to estimate the causal effect of the availability of patent rights on both innovation and downstream production. I focus on agricultural biotechnology in the US, a context in which the impacts of patent rights have been the subject of intense debate.

Second, this paper builds on broader literature investigating determinants of the direction of innovation. There is a long history of studying how US agricultural innovation has responded to changing conditions and policy incentives (e.g. Griliches, 1957; Hayami and Ruttan, 1971; Ruttan and Hayami, 1984; Olmstead and Rhode, 1993; San, 2023; Moscona, 2025; Andrews and Smith, 2025). Outside of agriculture, there are several empirical studies investigating how profit incentives affect the direction of technological change (e.g. Finkelstein, 2004; Acemoglu and Linn, 2004; Hanlon, 2015; Dugoua and Gerarden, 2025). Beyond profit opportunities, recent work has documented that the focus of innovation in the biological sciences responds forces ranging from to the desire to establish scientific priority (Hill and Stein, 2025a,b) to changes in public funding (Azoulay et al., 2019; Myers, 2020; Gross and Sampat, 2025), to personal experience and local knowledge (Fry, 2023; Dossi, 2024; Akerman et al., 2025). This paper shows that the strength of patent protection has strongly affected the direction of agricultural biotechnology, thereby reshaping US agricultural productivity.

Finally, this paper adds to existing work on the determinants of agricultural productivity (e.g., Gollin et al., 2014; Adamopoulos and Restuccia, 2022). Recent work has emphasized important role of innovation, both in the US (e.g., Kantor and Whalley, 2019; Ortiz-Bobea et al., 2025) and globally (Gollin et al., 2021; Moscona and Sastry, 2025). The 20th century's Green Revolution—an episode of unprecedented global productivity growth—was precipitated by the development and diffusion of a relatively small number of new crop varieties (Evenson and Gollin, 2003a,b). Since 1960, 104 countries have adopted intellectual property protection for plant varieties and several more are debating its introduction. This paper documents that in the US, this protection had positive effects on technology development and patent-induced technologies generated productivity growth. That said, the consequences of plant variety patent rights could be very different across contexts (see Diwan and Rodrik, 1991; Berrutti and Ruzzante, 2025) and exploring the global consequences of the proliferation of intellecrual property protection is an important topic for future work.

The paper is organized as follows. Section 2 describes the history of patent rights for plant varieties and discusses the features of plant breeding and biology that underpin the empirical design. Section 3 discusses the data and Section 4 empirically validates each component of the empirical strategy. Section 5 presents the main results on innovation while Section 6 presents the results on downstream production. Section 7 concludes.

2 Background

2.1 Intellectual Property Protection for Plant Varieties

Most inventions have been patentable since 1790. However, for most of US history patent protection for new plant varieties—for example, seeds and runners—was not available since living organisms were not considered patentable subject matter. Farmers were permitted to save seeds from one season to the next, effectively "re-making" the invention and limiting the extent to which inventors could profit from technology development and sale (Kloppenburg, 2005, p. 265-6). The fact that farmers, breeders, or competing firms can re-generate and re-plant or sell plant varieties is the key feature of agricultural production that limits potential profits from biotechnology innovation.

During the early and mid-20th century, weak forms of intellectual property were introduced for some plant varieties. The Plant Patent Act of 1930 introduced some protections for vegetatively propagated plant varieties (i.e. plants that can reproduce asexually, thereby excluding most major US crops).[11] The Plant Variety Protection Act (PVPA) was passed by the US Congress in 1970 and introduced seed certificates that afforded breeders some limited protections. However, neither law prevented farmers from saving and re-using seeds or limited the extent to which other researchers could use and build on the protected variety in their breeding. For example, during the early 1980s over 90% of planted wheat was saved from the previous year, meaning seed developers had limited revenue opportunities, and the USDA retained the right to curtail even the PVPA's limited protections whenever this was deemed necessary (McMullen, 1987). Ultimately, this meant that these laws had little effect on effective intellectual property protection (Chen, 2005), and neither law was the subject of substantial infringement litigation (Kershen, 2003). In Section 4.2.2, I document more systematically that PVP certificates were of limited value to innovating firms.

The legal regime changed in 1985 with the *Ex Parte Hibberd* decision by the Patent and Trademark Office Board of Appeals. In 1980, the Supreme Court had ruled in *Diamond v. Chakrabarty* (5-4 decision) that a genetically modified bacterium that was useful for breaking down crude oil was patentable subject matter because "the patentee has produced a new bacterium with markedly different characteristics from any found in nature and one having the potential for significant utility." However, the USPTO was still not open to patent protection for plants or plant parts (Kloppenburg, 2005, p. 263). In 1985, the situation changed dramatically. A patent examiner rejected a variety patent application; however, the breeder argued that the variety was patentable subject matter following the *Chakrabarty* decision.

[11] See, for example, Moser and Rhode (2011), who discuss the introduction of plant patents and argue that they had a limited impact on innovation and technological progress.

The developer appealed the decision, and the USPTO Board of Appeals and Interferences reversed the rejection in *Ex Parte Hibberd*.

Following the decision, the USPTO released a notice stating that it is "now examining applications including claims to plant life–e.g., plants per se, seeds, plant parts" (Hodgins, 1987, p. 88). The change was a shock and major break from long-standing precedent (Van Brunt, 1985). It was immediately taken advantage of by breeders and seed companies (Lesser, 1987). There was a surge of patent applications, followed by a surge in patent grants in the years that followed (Hodgins, 1987, and Figure 2 below). Seed patents were actively enforced by seed companies themselves (Weiss, 1999), both through licensing agreements with third parties and through direct monitoring and investigation of farmers who purchased or leased patented technology (Blair, 1999, pp. 326-7).[12] Taken together, *Ex Parte Hibberd* "effectively ended the debate in the United States [...] on the complex questions raised by the extension of IP to self-replicating living organisms such as seeds and plants," and precipitated a surge in biotechnology patenting activity (Peschard and Randeria, 2020). Section A.1 discusses *Ex Parte Hibberd* and its impact in greater depth.

2.2 Hybridization and *De Facto* Protection

Even in the absence of formal patent rights, some varieties already had built-in intellectual property protection. In particular, hybrid varieties have *de facto* protection because they cannot be reproduced or saved without access to the "parent" varieties used to generate them (e.g. Butler and Marion, 1985; Fernandez-Cornejo et al., 1999; Fajardo-Vizcayno et al., 2014). As a result, hybrid seeds "provided the private sector a natural method of protecting plant breeding investments" since the offspring of hybrid seeds "produc[e] substantially lower yields, encouraging farmers to repurchase seeds every year" (Fernandez-Cornejo, 2004).

This feature of hybrid varieties is well known to both farmers and breeders, and it was understood that for the crops for which it was possible, hybridization allowed breeders to mimic formal patent protection. Indeed, Kloppenburg (2005, p. 102) writes that hybrid varieties have "the same commercial right that an inventor receives from a patented article." Fernandez-Cornejo et al. (1999) state specifically that the exemption of seeds and varieties from the Patent Act of 1790 did not apply to hybrid technology, which could circumvent the absence of formal patents. Gupta (1998, p. 1320) refers to this as "built-in" patent protection.

Why do hybrid varieties have "built-in" protection? Hybrids are produced by crossing two parent plants to produce the first generation hybrid (F1). Seeds produced as offspring

[12] Kloppenburg (2005, p. 266) discusses the enforcement strategies available to seed companies after *Ex Parte Hibberd*, including direct monitoring, collecting information from dealer networks, and selective prosecutions to demonstrate the cost of violation. He concludes, "Enforcement of property rights in patented seed is a practical proposition and even at modest level may provide substantial returns to seed firms."

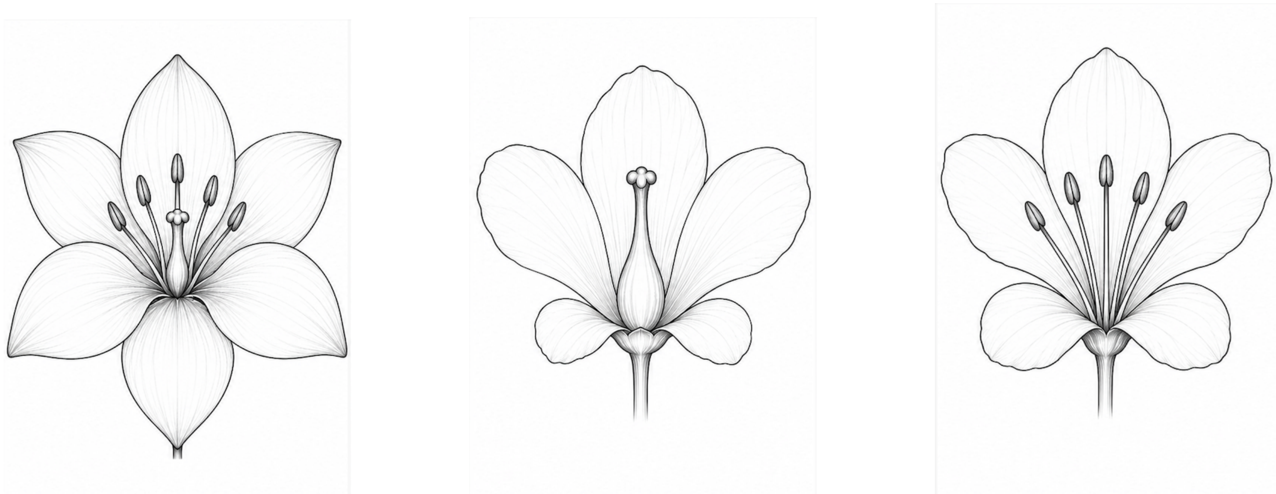
of the F1 hybrid—those that could be collected and re-planted by the farmer—do not retain the beneficial characteristics of the first generation, and thus are often of no use. Therefore, farmers are forced to return to the breeder every time they want a new seed and cannot save, sell, or replicate the improved variety. Moreover, without direct access to the inbred parent varieties used to generate the F1 hybrid, it is not possible for other breeders, marketing firms, or researchers to reproduce or sell the hybrid. Non-hybrid varieties, however, are often saved by farmers over several seasons without being repurchased, and also used directly in the process of breeding new varieties by other researchers. While seeds lose their efficacy over time, so farmers cannot plant with the same variety indefinitely, this feature of non-hybrid varieties eliminates the vast majority of potential profits from seed development.

The genetic reasoning behind this difference can be illustrated by a simple example. Suppose a breeder produces a hybrid variety by combining the male and female gametes of parent plants, Parent 1 and Parent 2. Further suppose that at a particular allele Parent 1 is *homozygous dominant* and Parent 2 is *homozygous recessive*. That is, Parent 1 has two copies of the dominant gene (AA) and Parent 2 has two copies of the recessive gene (*aa*). At that allele, the hybrid variety will be *heterozygous* (*Aa*) with probability 1. However, the offspring of the hybrid will be heterozygous at that allele with probability 0.5—with probability 0.25 it will be AA and with probability 0.25 it will be *aa*. Thus, the probability that offspring produced by the farmer matches the improved variety at this allele is 0.5.

In reality, the beneficial properties of a variety are not stored on a single allele since "hybrid vigor" results from the combination of many alleles and their interactions (e.g. McMullen, 1987; Fajardo-Vizcayno et al., 2014). Even if there were only alleles A through Z, the probability that the farmer reproduces the improved variety with any given offspring would be: $(0.5)^{26} = 0.0000000149$. While stylized, this example illustrates that the probability that a farmer reproduces the desired characteristics of the hybrid variety is vanishingly small. Moreover, even if by random chance the one second generation plant *were* productive, the farmer would have no way to re-produce or breed it, leading to non-uniform, unpredictable, or and often unproductive offspring (McMullen, 1987).[13] Non-hybrid varieties, however, can be reproduced exactly and do not need to be re-purchased from the developer.

Therefore, when formal patent protection was introduced, it was most relevant for non-hybrid varieties and hence crops for which hybrid varieties were scarce or difficult to generate. In the face of criticism for enforcing patent protection, biotechnology firms and industry

[13] As the stylized example illustrates, hybrids can only be uniformly produced because the parent strains are highly inbred (i.e., homozygous at all alleles); when two highly inbred strains are hybridized, the offspring will be uniform and identical. However, subsequent breeding of non-inbred strains which are heterozygous at many alleles will not generate uniform or predictable offspring. While early seed companies often marketed F2 (i.e, second generation) hybrids, the offspring of two specifically chosen F1 hybrid varieties, this was done mostly for ease of breeding at scale. Moreover, F2 hybrids are still the offspring of very specifically targeted and chosen F1 hybrid parents, and are often not as productive as the F1 generation (McMullen, 1987, p. 47).



(a) Perfect (b) Imperfect (Pistillate) (c) Imperfect (Staminate)

Figure 1: **Perfect vs. Imperfect Flowers.** This figure shows the distinction between perfect flowers, which contain both reproductive organs (Figure 1a), and imperfect flowers, which have either only the "female" (Figure 1b) or only the "male" (Figure 1c) reproductive organ.

organizations even point out that patent rights are nothing new since farmers had not been able to save hybrid seeds for decades—formal protection merely extended this feature of the seed market to all varieties.[14] Thus, hybrid varieties have built-in intellectual property protection even in the absence of formal patent protection and hence were less affected by the introduction of patent rights. As I describe in the next section, this implied that certain *crops* were more exposed than others to the patent law since hybrid development is substantially more costly for some crops than others.

2.3 Hybridization and Flower Structure

Some crops were much less exposed to hybridization—and hence much more affected by the change in patent law—than others. This was in large part due to a fixed, crop-level physiological characteristic that determines whether or not a hybrid variety can be developed: whether the crop has "perfect" or "imperfect" flowers (e.g. Wright, 1980; Butler and Marion, 1985; McMullen, 1987; Fajardo-Vizcayno et al., 2014). Perfect flowers have both the male and female parts of the plant in the center of the same flower; this is illustrated by Figure 1a, in which the pistil (i.e. female reproductive organ) and stamen (i.e. male reproductive organ) are on the same flower. Imperfect flowers have the male and female reproductive material on different parts of the plant; this is illustrated by Figures 1b and 1c, both of which would be on the same plant but which contain either only the pistil or only the stamen.

[14] See, for example: https://tinyurl.com/zww4ap9z.

When a crop has perfect flowers, it is often painstakingly difficult or impossible to generate new hybrids by combining genetic material from multiple plants (Whitford et al., 2013; Chakrabarty et al., 2023). Separating and re-combining the male and female reproductive material (e.g. preventing self-pollination and separately isolating the genetic material) is often technologically infeasible or extremely costly in crops with perfect flowers. Thus, throughout the 20th century, commercially viable hybrids for crops with perfect flowers remained "a painstaking technical feat" and very rare in practice, including for economically important crops like wheat (Curry, 2022). Even today, developing hybrids of perfect-flower crops often remains highly "impractical" (Muenchrath, 2023); for example, just 0.2% of global wheat acres are devoted to hybrid varieties (Gupta et al., 2019).

This meant that farmers of perfect-flower crops could often save seeds from season to season, limiting profit opportunities for breeders, while farmers of imperfect-flower crops could not. Existing survey data from just prior to *Ex Parte Hibberd* bears this out. In 1982 over 90% of land area devoted to wheat was planted with saved (as opposed to purchased) seeds, making it challenging for breeders to profit from wheat variety innovation.[15] Other examples of crops with perfect flowers are barley, beans, carrots, and turnips. This is strikingly different from the case of corn, a staple crop with imperfect flowers, for which just 5% of land area was planted with saved seeds (McMullen, 1987, pp. 86-7). Other examples of crops with imperfect flowers include squashes, cucumber, and spinach. Thus, imperfect-flower crops were much easier to hybridize, leading to *de facto* protection absent formal patent rights, while perfect-flower crops were far more affected by the change in patent law.

Hybrid varieties have also been developed for some crops with perfect flowers, most prominently by employing cytoplasmic male sterility (CMS), which prevents self-pollination (Havey, 2004). However, even using CMS and related techniques, hybrids of perfect-flower crops have a mixed track record (Whitford et al., 2013), remain much more challenging and costly to develop (Curry, 2022), and were released largely after this study's sample period.[16] Nevertheless, throughout the empirical analysis I investigate the potential role of CMS hybridization and the fact that it facilitated the development of some hybrid varieties for perfect-flower crops. All results are robust to categorizing crops for which CMS systems have been developed as control-group crops or excluding them from the analysis entirely. Despite the existence of CMS, I use perfect flower structure as the main proxy for exposure

[15] The land planted with saved seed corresponded to the overwhelming majority of market value for cotton and soybeans as well, two other perfect-flower crops, at 97.6% and 82.8% respectively. To my knowledge, McMullen (1987) is the only source with data on the prevalence of seed saving in the US in any year; it is a fortunate coincidence that these data are from just prior to *Ex Parte Hibberd*.

[16] The first hybrid soybean, for example, was bred in 2003 by scientists who claimed that the key challenge was the "difficulty involved in changing the plant's trait of self-pollination" (See here: `https://tinyurl.com/bdzezzfm`). The first hybrid variety for barley was also not released until 2003, after this paper's main sample period (See here: `https://tinyurl.com/3w8hffav`).

to the change in patent law since it is fixed, pre-determined, and unaffected by endogenous investments in breeding technology, including techniques like CMS.

Summary Patent rights were introduced for crop biotechnology in 1985, but formal intellectual property protection affected some crops much more than others. Since hybrid varieties have *de facto* intellectual property protection, crops for which hybrids are easy to develop (i.e., crops with imperfect flowers) were *less exposed* to the change in patent law and, as a result, are the *control group* in the analysis. Crops for which hybrids are challenging or infeasible to develop (i.e., crops with perfect flowers) were *more exposed* to the change in patent law and, as a result, are the *treatment group* in the analysis. In Section 4, I empirically validate each component of this narrative, including the surge in patenting after *Ex Parte Hibberd* (Section 4.1), the tight link between imperfect flower structure and hybridization (Section 4.2.1), and the substantially greater potential value of patent protection for perfect-flower compared to imperfect-flower crops (Section 4.2.2).

3 Data and Measurement

3.1 Crop-Level Data

Crop Characteristics and Treatment Status In order to identify which crops were affected by the introduction of patent protection, I construct a data set of the flower structure and reproductive process of all crops produced in the US. This includes the main treatment variable used throughout the analysis, a crop-level indicator variable that equals one if a crop has perfect flowers. In total, this information was compiled from 339 separate sources.[17]

I also compile additional crop-level covariates from the EcoCrop Database, which contains information about plant-specific characteristics and growing conditions for over 2,500 species (see Moscona and Sastry, 2023). The database was compiled from a sweeping set of agronomist and expert surveys conducted during the early 1990s and contains a range of plant characteristics, in addition to upper and lower "cut-off" values for a range of environmental characteristics (e.g. temperature, rainfall) beyond which crop productivity declines. These data make it possible to check whether treatment and control crops are balanced on conditions that determine the location, structure, and demands of crop breeding.

Innovation I combine multiple sources to compile crop-specific measures of technology development and research investment. The key challenge is to identify measures of innovation that can be tracked both before and after the introduction of patent rights. A commonly

[17] Table A4 reports treatment status of all seed crops in the *Variety Name List*, discussed below.

used measure of innovative activity is patenting itself; however, patents are not useful for this study since, of course, they do not exist before the introduction of patent rights.

The main measure of crop-level technology development that I use is the USDA's *Variety Name List*. The *Variety Name List*, obtained through a Freedom of Information Act (FOIA) request, is a list of all released or commercialized crop varieties known to the USDA. This data set is essential because it makes it possible to consistently track variety development for each crop—the exact form of technology development that was newly-patentable—both before and after the introduction of patent rights. The USDA collects data on all released varieties in order to prevent fraud in the seed market; it is therefore designed to be as comprehensive as possible and uses a broad range of sources in order to identify new crop varieties including variety release notices, official journals, seed catalogs, seed trade publications, and names cleared for use by seed companies. Breeders have an incentive to report new varieties to the USDA because farmers can check the *List* to verify variety clearance. I digitized the full list and use it to compute the number of varieties released for each crop in each year.[18]

I supplement the *Variety Name List* with additional measures of research investment and technological progress in order to further investigate how patent rights affected crop-level innovation. First, to measure crop-specific research investment, I use project-level R&D spending from the USDA Current Research Information System (CRIS). CRIS began publishing research project-level investment data in 1970 and, crucially, reports the commodity or commodities that are the focus of each research project, making it possible to aggregate the project level data to compute a time-varying, crop-level measure of R&D investment.[19] CRIS compiles data for all research projects that received any public support; for this set of projects, the CRIS data also asks researchers to report private funding. Therefore, one caveat is that the data set does not contain *all* private R&D, only private R&D for projects that received any public funding; this makes directly comparing the level of public and private investment impossible.[20] Using this database, I construct crop-level measures of public R&D investment, private R&D investment, and the number of scientists involved in R&D.

Second, I use US patent data to measure crop-level innovation for all technologies other than crop varieties (e.g., harvesters, chemicals), as well as investigate trends in biotechnology patenting itself after 1985. This makes it possible to estimate spillover effects from biotechnology innovation to other areas of crop-level technology development. Using the patent database *PatSnap*, I compute the number of patents in Cooperative Patent Classification (CPC) classes that correspond to crop agriculture.[21] To match patents to crops, I search

[18]In later years, the *List* occasionally reports the company or breeder name for each variety. Unfortunately, this did not begin until after the period under investigation.

[19]When a single project covers multiple crops, I assign each crop its share of the project's total funding.

[20]I am not aware of any more systematic data on crop-level private research investment.

[21]This includes CPC classes A01B, A01C, A01D, A01F, A01G, A01H, and A01N.

for the name of each crop in the *Variety Name List* in all patent titles, abstracts, and keyword lists. Thus, unlike the *Variety Name List*, a downside to the patent data is that it is less straightforward to link individual technologies to crops. Nevertheless, these data make it possible to study trends in crop-level innovation across all technology areas.

Third, to study whether new varieties led to true technological progress, I measure the average yield of each crop (i.e., quantity of output per area) in the US using data from the Food and Agriculture Organization (FAO). For each year in the sample period, the FAO reports the area-weighted national yield for each crop and I use this as one proxy for downstream crop-level productivity.

3.2 County-Level Data

In order to study the downstream impact of biotechnology patent rights on the agricultural sector, I construct a county-level panel from the 1969-2002 rounds of the US Census of Agriculture (Haines, 2005). The Census is conducted roughly every five years, and the years included in the analysis are 1969, 1974, 1978, 1982, 1987, 1992, 1997, and 2002. The Census contains a range of information about the US agricultural sector, including county-level land value, agricultural revenue, expenditures on a series of inputs, farm size, and the area under cultivation for a broad set of crops. It also reports the number of farms in each county within a series of size and revenue bins.

To construct county-level exposure to the introduction of patent rights, I use data on crop-level predicted maximum potential yield from the Food and Agriculture Organization (FAO) Global Agro-Ecological Zones (GAEZ) database. These data are reported by the FAO as a raster grid, with each grid cell containing the maximum attainable yield for a given crop in that grid cell based on both ecological and topographical characteristics of the cell and characteristics of the crop. The potential yield model is constructed using parameters derived from controlled experiments, and not from data on actual agricultural inputs and output. Combined with the crop-level treatment variable, I use these data to construct a county-level measure of exposure to the introduction of patent rights as the relative suitability for treatment compared to control crops. I validate that this measure is strongly correlated with an analogous measure computed from actual planting patterns measured in the Census. This whole procedure is described in detail in Section 6.1.

4 Descriptive Evidence and the Empirical Strategy

This section empirically investigates the key facts that underpin the paper's empirical framework. The main empirical design exploits *time series* variation in patent protection—due to the introduction of patent rights for plant biotechnology in 1985—alongside *cross-sectional* variation across crops—due to differences in the potential bite of formal patent rights.

4.1 Time-Series Variation: Patenting After *Ex Parte Hibberd*

I document the key time-series variation by showing the dramatic surge in biotechnology patenting after the 1985 *Ex Parte Hibberd* decision. Figure 2a displays the time series trends in Cooperative Patent Classification (CPC) classes most closely linked to new plant varieties (see Section A.2 for a more detailed description).[22] There is no evidence of patents being issued prior to 1985. However, patent applications surged in the year following *Ex Parte Hibberd* and patent grants followed shortly thereafter.[23] Importantly, CPC classes are repeatedly back-filled and patents are re-classified over time, even as new classes are added or removed. Thus, the surge in patenting activity is not a mechanical consequence of the change in legal regime but rather a change in the characteristics of patented technology. Consistent with this, the sharp change in patent protection policy was mirrored by a marked trend break in crop-specific research investment (Figure A1a), especially in the private sector (Figure A1b). Figure 2b documents that there is no such trend break for patenting in all other crop technologies, suggesting the pattern in Figure 2a is not related to any aggregate trend in technological progress or innovation policy.[24] No marked change after 1985 is apparent and the trend is relatively flat throughout the sample period.

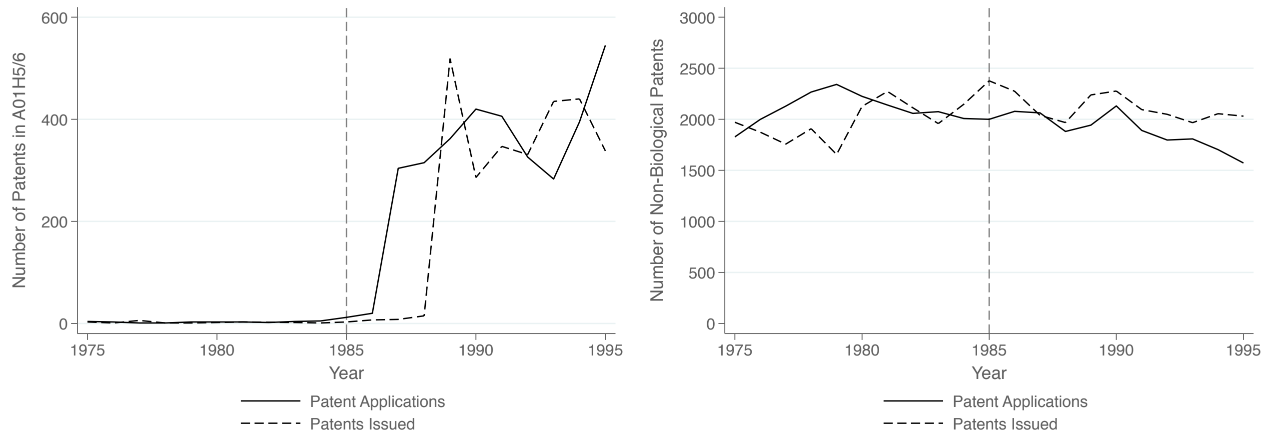
4.2 Cross-Crop Variation

Next, I verify the cross-crop variation in three steps. First, I show that crops with perfect flowers—the crop-level treatment variable—are much less likely to have hybrid varieties, meaning that they are much less likely to have "built in" intellectual property protection. Second, consistent with this feature of breeding, I show that formal patent protection for varieties of crops with perfect flowers is more valuable to innovating firms than it is for varieties of crops with imperfect flowers. Finally, I show that crops with perfect and imperfect flowers are similar across a broad range of other crop-level characteristics, suggesting that the latter is a reasonable control group for the former.

[22]Figure 2a focuses on a sample of all patents related to novel angiosperms (CPC classes A01H.5 and A01H.6). Figure A3a documents a similar pattern for the entire A01H CPC class, a broader definition of biotechnology patenting, and Figure A3b shows a similar pattern on a sample of patents categorized only as angiosperm seeds (CPC class A01H.5.10), a far narrower definition.

[23]This corroborates prior work that identifies variety-related patenting using data on applicants combined with patent text (Graff et al., 2003) or individually reading of a large number of patents (Kloppenburg, 2005).

[24]Figure A2 shows the same lack of trend break each non-variety patent class one-by-one.



(a) All Angiosperm Patents (CPC A01H.5 & A01H.6) (b) Non-Biological Patents (A01B & C & D & F & N)

Figure 2: **Agricultural Patenting: Time Trend.** Figure 2a displays the count of patent applications and patents issued in CPC classes A01H.5 and A01H.6 (plant varieties) while Figure 2b displays the count of patent applications and patents issued in non-biological CPC classes related to crop agriculture (CPC A01B, A01C, A01D, A01F, and A01N) over the same sample period. The solid lines represent patent applications while the dotted lines represent patent grants.

4.2.1 Flower Structure and Hybrid Development

The empirical strategy relies on the fact that a crop's flower structure is a key determinant of the ease of hybrid development, and hence the availability of *de facto* protection absent formal patent rights (see Wright, 1980; Butler and Marion, 1985; McMullen, 1987; Gupta, 1998; Fajardo-Vizcayno et al., 2014, discussed in Section 2.3). Here, I document empirically that flower structure strongly predicts hybrid variety development in the hypothesized way.

Using the crop-specific patent data (see Section 3.1), I identify all patents in which the word "hybrid" is used in the patent title or abstract in order to determine which patents explicitly relate to hybrid technology. There is a strong, positive relationship between an indicator that equals one if a patent mentions a crop with imperfect flowers (i.e., one of the control crops) and an indicator that equals one if it mentions the word "hybrid" (see Table A1). Among the sample of patents from CPC classes A01H.5 and A01H.6, the word hybrid appears in the title or abstract of 91% of patents associated with crops with imperfect flowers, highlighting the fact that hybrid development dominates variety development for these crops. Thus, while actual hybrid development is endogenous to research investment decisions, a fixed, crop-level feature of flower structure strongly predicts hybrid development—and hence the ease and prevalence of *de facto* protection. While technological advances, most notably cytoplasmic male sterility (CMS), have made it possible to develop hybrid varieties for certain treatment crops, the empirical design only relies on the fact that imperfect flower structure is a *strong predictor* of hybrid variety development, not that it is the *only predictor*.[25]

Taken at face value, the implied F-statistic of estimates in Table A1 over one thousand, suggesting that flower structure is a strong proxy for ease of hybrid development. Moreover, these estimates likely under-represent the relationship between flower structure and hybrid development for at least three reasons. First, they do not capture the extent to which hybrid varieties for crops with perfect flowers are more costly and challenging to develop in the first place. Second, even when they are developed, hybrid varieties for perfect flowers often do not confer the same productivity benefits (see Section 2.3). Third, in order to make empirical progress, these findings are based on a systematic analysis of patent data, which makes it possible to search for specific characteristics of technology. But precisely because they have built-in patent protection, many hybrid varieties may not have been patented in the first place, thereby understating the prevalence of hybrid varieties in the patent data.[26]

4.2.2 Flower Structure and the Value of Patent Rights

Next, I document that the introduction of patent protection led to a dramatic increase in the strength of effective intellectual property and that obtaining formal patent protection was particularly profitable to inventors of perfect-flower (i.e., treatment) crops.

In order to compare the relative value of different forms of intellectual property, I estimate the impact of being granted each form on the stock price return of the innovating firm (see Kogan et al., 2017). If intellectual property protection for a particular invention is valuable, the firm's stock price should increase in response to the announcement that protection was issued. It is often the case that knowledge about *technology itself* exists prior to the date of patent issue since firms—and particularly the present sample of large, public firms—publicize new products extensively (Kogan et al., 2017). Thus, we can interpret changes in firm value around the patent issue date as the effect of the patent itself.

I measure the abnormal stock price return for each day in a two-day window surrounding the issuing of a utility patent or PVP certificate to any publicly traded firm during the sample period.[27] I then estimate the following regression specification:

$$AR_{fdpt} = \xi \cdot I_t^{post} + \alpha_p + \delta_{m,f} + \epsilon_{fd} \tag{1}$$

where the unit of observation is a firm-day and the sample consists of all days d within a

[25] Moreover, I document below that the main results are similar after re-classifying or fully excluding treatment crops for which hybrids have been developed through CMS (see Section 5.2).

[26] For this reason, it would be preferable to conduct this analysis on a measure of technology development other than patent data. However, this analysis is not possible using the *Variety Name List* since the *List* does not contain any additional descriptive information about each variety.

[27] Further data and estimation details are discussed in Appendix Section A.2.

two-day window of when each firm f is issued a patent. Let $t(f,d) \in [-2,2]$ index days within each event window and $p(f,d)$ index event windows. AR_{fdpt} is the abnormal return of firm f on day d and I_t^{post} is an indicator that equals one after the issue of intellectual property protection. The coefficient of interest is ξ, which captures the impact of being issued intellectual property on abnormal returns (see Kothari and Warner, 2007). All specifications include event window and firm-by-month fixed effects to ensure that ξ captures the impact of being issued intellectual property protection—directly comparing the days prior to the days post receipt—and not differences across issuing events or time periods.

First, I compare the value of utility patents, which were introduced in 1985, to the weaker pre-existing form of intellectual property, plant variety protection (PVP) certificates. I find no evidence that being issued a PVP certificate affects returns (Table 1, column 1). This is consistent with qualitative accounts suggesting that PVP certificates were relatively weak forms of intellectual property and of limited value to innovating firms since they did not restrict seed saving (Kershen, 2003; Kloppenburg, 2005). However, I find a large, positive effect of being issued a utility patent on returns (column 2). Event study estimates show no anticipation and a large increase in stock value following the patent grant (Figure A5). Thus, patent rights markedly increased the private value of available intellectual property.[28]

Second, I document that the private value of a patent grant related to a crop with perfect flowers (i.e, a treatment crop) is significantly higher than the private value of a patent grant related to a crop with imperfect flowers (i.e., a control crop). I estimate an augmented version of equation (1) that includes an interaction term between I_t^{post} and an indicator that equals one if a patent corresponds to a crop with imperfect flowers. Strikingly, the coefficient on the un-interacted term nearly doubles in magnitude while the interaction term is negative and statistically significant (column 3).[29] These estimates suggest that formal patent protection is substantially less valuable to innovating firms for crops in the control group. In order to show that this is driven by hybridization, I include an additional interaction with an indicator that equals one if the word "hybrid" appears in the patent title or abstract and find that the *entire* differential effect of patents related to control crops is driven by hybrids (column 4). Thus, the possibility of built-in protection makes formal patent protection significantly less valuable for control crops compared to treatment crops.

Together, these results highlight that the introduction of utility patents in 1985 represented a substantial increase in effective intellectual property protection and this protection

[28]While patent protection was introduced in 1985, it may have become more valuable when the US Supreme Court ruled explicitly on its constitutionality in the 2001 decision of *J. E. M. Ag Supply, Inc. v. Pioneer Hi-Bred International*. To make sure these post-2001 patents do not drive the results, the sample in Table 1 is restricted to years prior to 2001. The role of the Supreme Court ruling is discussed in more detail in Section A.2

[29]This does *not* imply that hybrid technologies are of lower value; Moser et al. (2018), for example, document substantial quality improvements embodied in hybrid varieties for maize. The estimates suggest, however, that patent protection itself was less privately beneficial to innovating firms.

Table 1: Stock Price Responses to Intellectual Property Grants

	(1)	(2)	(3)	(4)
	Dependent Variable is Abnormal Returns			
	PVP Certificates	Utility Patents		
𝟙(Post Issue Date)	-0.00154	0.00354**	0.00614***	0.00614***
	(0.00238)	(0.00140)	(0.00156)	(0.00156)
𝟙(Post Issue Date) x Control Crop			-0.00543**	
			(0.00221)	
𝟙(Post Issue Date) x Control Crop x "Hybrid" in Title/Abstract				-0.00607***
				(0.00200)
𝟙(Post Issue Date) x Control Crop x "Hybrid" NOT in Title/Abstract				0.00142
				(0.0100)
Firm x Month Fixed Effects	Yes	Yes	Yes	Yes
Issue Date Window Fixed Effects	Yes	Yes	Yes	Yes
Observations	1,069	869	869	869
R-squared	0.456	0.231	0.234	0.235

Notes: The unit of observation is a firm-day and the sample is restricted to a two-day window around the issue date of each patent or PVP certificate. Post Issue Date an indicator variable that equals one following the certificate or patent issue date within the two-day window. Hybrid Compatible is an indicator that equals one if the patent title or abstract contains the name of a hybrid-compatible (i.e. imperfect flower) crop. "Hybrid" in Title/Abstract is an indicator that equals one if the patent title or abstract contains the word "hybrid." Standard errors, clustered by firm-year, are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

was significantly more valuable for treatment compared to control crops. These findings corroborate the key underlying logic of this paper's empirical design.

4.2.3 Balance Between Treatment and Control Crops

Finally, the empirical analysis relies on the assumption that crops with imperfect flowers are an appropriate control group for crops with perfect flowers. While the main identification approach relies on parallel *trends* rather than balance in *levels*, I nevertheless investigate whether there are differences between treatment and control crops across a range of fixed crop-level characteristics that affect variety development. I rely primarily on the EcoCrop Database, which reports information about a broad set of crop physical and physiological characteristics. These characteristics determine plant growth and the structure of breeding; moreover, much of plant breeding is designed to adapt crop production to specific environmental conditions, so crop-specific environmental constraints are informative about the location and demands of variety development (e.g., Akerman et al., 2025). I also investigate differences in pre-period market size and prices, which could affect innovation trends.

I find no evidence of systematic differences between treatment and control crops along a broad set of dimensions (Table A3). Differences are all small compared to the sample mean, and only one of the 22 coefficients is significant at the 10% level or less, which is to be expected from random chance. Thus, treatment and control crops appear similar across a range of observable characteristics that affect the location and demands of variety development.

5 Patent Rights and Innovation

5.1 Empirical Strategy

This section investigates the impact of patent rights on technological progress. I estimate the effect of patent protection using a difference-in-differences design; that is, I compare treatment and control crops, before and after the introduction of patent rights in 1985. The main estimating equation is:

$$y_{ct} = \exp\{\alpha_c + \delta_t + \beta \cdot \text{Treat}_c \cdot \mathbb{I}_t^{\text{Post 1985}} + \mathbf{X}'_{ct}\Gamma + \epsilon_{ct}\} \quad (2)$$

For each outcome, the regression is estimated on a balanced panel of crops for the years 1975-1995. $\mathbb{I}_t^{\text{Post 1985}}$ is an indicator that equals one in all years after the extension of patent rights (i.e. after and including 1985) and Treat_c is a crop-specific indicator that equals one if a crop has perfect flowers (i.e., is a treatment crop). α_c and δ_t are crop and year fixed effects. In the baseline analysis, y_{ct} is the number of new crop varieties released for crop c in year t.[30] The coefficient of interest is β, the impact of the introduction of patent rights on crop-specific innovation in treatment relative to control crops. Since all crops are treated simultaneously by a single policy event, the concerns raised in recent literature about two-way fixed effects estimators and staggered treatment designs do not apply here (Roth et al., 2023). Under the parallel trends assumption, equation (2) identifies the average treatment effect on treated crops (Wooldridge, 2023). Standard errors are double clustered by crop and year.

In order to ensure that treatment and control crops were on parallel trends prior to the introduction of patent right, I present estimates from the following specification:

$$y_{ct} = \exp\left\{\alpha_c + \delta_t + \sum_{\tau \in \mathcal{T}^{pre}} \beta_\tau \cdot \text{Treat}_c \cdot \delta_\tau + \sum_{\tau \in \mathcal{T}^{post}} \beta_\tau \cdot \text{Treat}_c \cdot \delta_\tau + \mathbf{X}'_{ct}\Gamma + \epsilon_{ct}\right\} \quad (3)$$

Here, the coefficients of interest are the β_τ. The key identification assumption is that treatment and control crops were on similar innovation trends prior to the introduction of patent protection; that is, when $\tau \in \mathcal{T}^{pre}$, β_τ should not be statistically distinguishable from zero. When $\tau \in \mathcal{T}^{post}$, the β_τ identify the effect of patent protection on crop-specific innovation.

[30] For consistency with existing work in innovation economics (which follows Hausman et al., 1984), I use a Poisson pseudo maximum likelihood estimator (PPML) estimator. Throughout the analysis, I also show that I obtain similar results using ordinary least squares (OLS) and I rely on OLS for all non-count outcomes.

Table 2: Patent Protection and Novel Plant Varieties

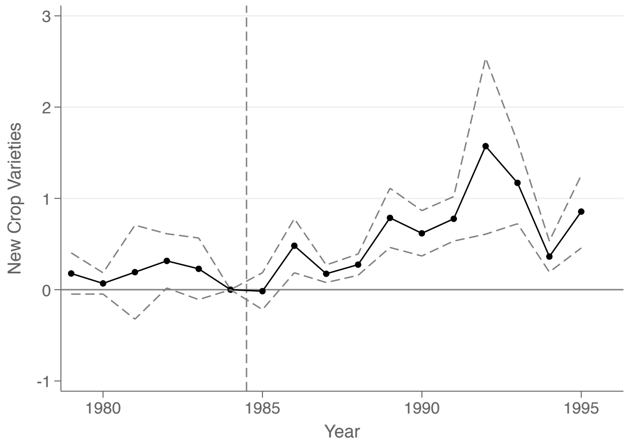
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Dependent Variable:	Number of New Varieties						
Treatment x $\mathbb{1}^{\text{Post 1985}}$	0.795***	0.920***	0.931***	0.919***	0.871***	0.563**	0.709**
	(0.240)	(0.322)	(0.327)	(0.329)	(0.279)	(0.266)	(0.298)
Crop Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
GMO Controls	No	Yes	Yes	Yes	Yes	Yes	Yes
Rain Sensitivity Controls	No	No	Yes	Yes	Yes	Yes	Yes
Reproduction Type Controls	No	No	No	Yes	Yes	Yes	Yes
Excluding asexually reproducing crops	No	No	No	No	Yes	No	No
Excluding 25% *most* innovation intensive crops	No	No	No	No	No	Yes	No
Excluding 25% *least* innovation intensive crops	No	No	No	No	No	No	Yes
Observations	2,260	2,260	2,060	2,060	1,200	1,522	1,400

Notes: The unit of observation is a crop-year. All specifications include crop and year fixed effects and the outcome variable is the number of new varieties. The controls are listed at the bottom of each column and are included as a fixed crop-level characteristic interacted with a full set of year fixed effects. Any sample restrictions are also noted at the bottom of each column. Standard errors, double clustered by crop and year, are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

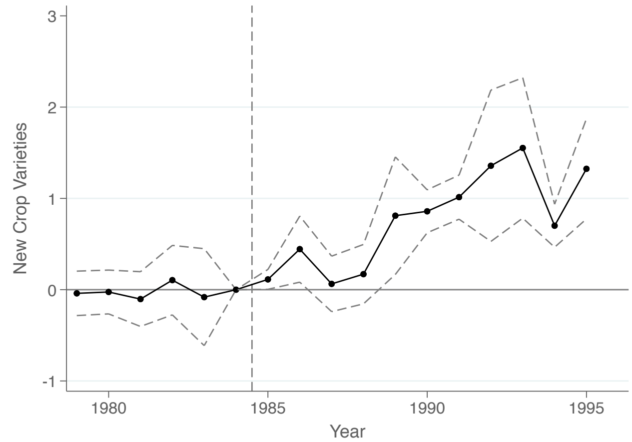
5.2 Main Results: New Crop Varieties

The first main result is that patent rights substantially increased the release of novel plant varieties. Table 2 reports estimate of equation (2) in which the dependent variable is the number of new crop varieties from the *Varieties Name List*. The baseline specification includes only crop and year fixed effects as controls (column 1) and implies that, compared to control crops, treatment crops experienced a dramatic increase in variety development following the introduction of patent rights. The results are very similar using the OLS analog of equation (2) (see Table A5). The baseline specification (Table 2, column 1), implies that treatment crops experienced a 119% increase in variety development compared to control crops, corresponding to 11.2 additional varieties for the mean crop in the sample. The remaining columns of Table 2 explore the robustness of the this finding to the inclusion of additional controls and to a series of sample restrictions; I return to these estimates below.

Dynamics Next, I investigate dynamics. The main identifying assumption is that, absent the change in patent law, innovation in treatment and control crops would have been on similar trends. Figure 3 displays coefficient estimates from the event study analysis (equation 3). Treatment and control crops are on similar trends prior to 1985, yet they diverge markedly thereafter. The treatment effect grows over time. Figure A6 reports estimates using an extended pre and post-period and again, no pre-trend is apparent while the positive



(a) No Controls



(b) All Controls

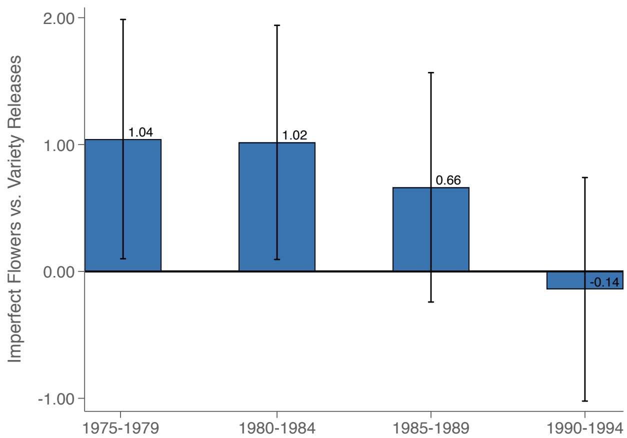
Figure 3: **Patent Protection and Novel Plant Varieties: Dynamic Estimates.** Coefficient estimates from PPML estimates of Equation (3). The dependent variable is the number of novel plant varieties in the crop-year. Crop and year fixed effects are included in both sub-figures. The additional controls included in Figure 3b are indicators for any released GMO and any GMO development, an indicator for asexual propagation, and optimal rainfall cut-off values, all interacted with a full set of year fixed effects. Standard errors are double clustered by crop and year. 95% confidence intervals are reported.

effect after 1985 is persistent.[31] The positive effect in the long run is important in light of existing evidence that patent protection can hinder follow-on innovation, which could limit the long-run effects of patent rights after an initial wave of technology development (see Murray and Stern, 2007a; Williams, 2013). These estimates are consistent with a positive, causal effect of patent rights on variety release.

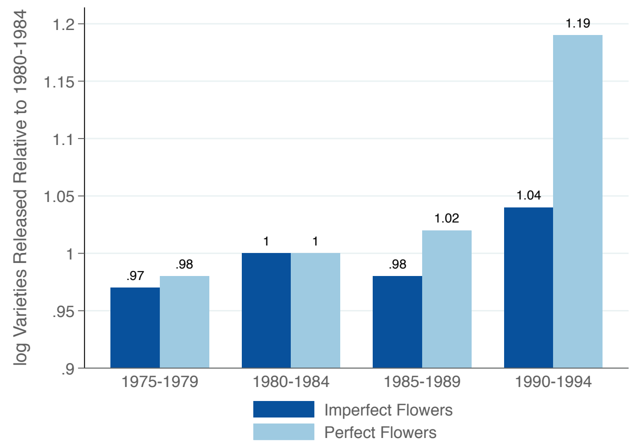
The logic underlying the identification approach is that control crops had *de facto* protection prior to 1985, and hence received greater investment in innovation; the introduction of formal patent rights, however, extended protection to treatment crops, which could now be protected for the first time. Consistent with this narrative, I find that during the pre-period, variety development in control crops—those with *de facto* intellectual property protection—was significantly higher (Figure 4a, bars 1-2). However, the gap declined by over one third during the period 1985-1989 and was eliminated entirely by 1990-1994 (bars 3-4). This pattern was driven by an absolute increase in variety development for treatment crops, rather than a decline for control crops, during the decade after 1985 (Figure 4b).

Together, these findings convey that variety development for treatment and control crops were on similar trends prior to 1985. However, it accelerated for treatment crops following the introduction of patent rights.

[31]Moreover, the estimated linear pre-trend -0.017 (0.021) and -0.020 (0.029) in the specifications without and with controls respectively; thus, the pre-existing trend is close to zero and statistically insignificant.



(a) Control vs. Treatment Crops Over Time



(b) Variety Release Trends

Figure 4: **Variety Development: Raw Differences and Time Trend.** Figure 4a reports the relationship between variety releases and an imperfect flower (i.e., control crop) indicator in each five year time period from a PPML regression model. 95% confidence intervals are reported. Figure 4b shows the raw number of varieties released for crops with perfect flowers (i.e. crops in the treatment group) and crops with imperfect flowers (i.e. crops in the control group) during each five year window, relative to varieties released during the 1980-1984 period.

Falsification: The Profit Motive A key difference brought about by the change in patent law was that farmers could no longer save, re-use, or re-sell non-hybrid varieties and as a result, they were forced to purchase seeds from the developer. This increased potential profits from variety development, potentially incentivizing innovation. However, other features of patent protection—for example, the disclosure requirement and the fact that patent holders had to publicize the details of their invention—might have also led to growth in variety development. To what extent does the change in potential profits underlie the main result?

To investigate this, I exploit differences across both treatment and control crops that determine the potential profit opportunities developing varieties. Certain crops are *perennial*, meaning they live for more than two years. If the ability to prevent the re-use of invented varieties drove the increase in variety development, the effect should be muted for perennial crops since the opportunities to re-sell a variety are more limited. Consistent with an important role for profit opportunities from seed sales, I find that the baseline results are driven by non-perennial crops (Table A6). Patent rights increased variety development by 129% in non-perennial crops while the effect for perennial crops is indistinguishable from zero.

Sensitivity Analysis: Controls and Sample Restrictions I investigate the sensitivity of the main result by including a series of additional controls or excluding outlier observations.

First, I account for the role of other ongoing trends in crop-level innovation, especially the development of genetically modified (GM) varieties during the late-20th century.[32] GM variety development and commercialization could itself be an *outcome* of patent rights and is only an empirical concern to the extent that crop-level GM development trends are spuriously correlated with the main treatment variable. It is also worth noting that actual release and adoption of GM varieties did not occur until *after* the time window displayed in Figure 3; therefore, they cannot be driving the baseline finding. Nevertheless, to ensure that the main results do not capture any independent effect of the rise of GMOs, I control directly for year fixed effects interacted with crop-level indicators for whether a GM variety has ever been released or developed (Table 2, column 2).[33] The estimates are very similar.

Second, to rule out any effect of spurious crop-level innovation trends or mean reversion, I show that the results are similar after controlling separately for year indicators interacted with variety release in 1975, 1980, and 1984; the inclusion of these additional 57 controls flexibly captures pre-period variety development trends (Table A7, columns 1 and 3). The results are also similar after including (log of) total varieties released during the entire pre-period, interacted with a full set of year fixed effects (columns 2 and 4). These estimates are consistent with the absence of pre-existing trends in the main event study analysis.

Third, I investigate whether the results are affected by crop-level physiological differences, which may correlate with technology development trends. This could also be important given the fact that the main treatment variable is constructed using one specific feature of crop-level physiology: flower structure. I have already documented that there is no systematic evidence of physiological differences between treatment and control crops across a broad set of crop-level covariates (Table A3). Nevertheless, I show that the main results are similar after controlling for a full set of year fixed effects interacted with an indicator that equals one if a crop can re-produce vegetatively—since these crops may experience different variety development dynamics—and with crop-level rain sensitivity measured in EcoCrop—the one variable with a (weakly) significant relationship with crop-level treatment status (Table 2, columns 3-4). The findings are also similar after fully excluding vegetatively-reproducing crops from the sample (Table 2, column 5).

Finally, I investigate whether the findings are driven by extreme observations. This could be important, in light of the limited set of crops in the baseline analysis (113) and the fact that some crops are much more economically important than others. I find no evidence that the results are driven the most or least innovation-intensive crops (Table 2, columns 6-7). The results are similar after dropping the innovation-intensive and least innovation-intensive 25% of the sample. While unsurprisingly, the results are somewhat attenuated after

[32] The rise of genetic modification is discussed in detail in Appendix Section B.2.

[33] There are just ten crops for which genetically modified versions have been introduced in the US: alfalfa, apples, canola, corn, cotton, papaya, potatoes, soybeans, summer squash, and sugar beets.

dropping the most innovation-intensive crops (column 6), the effect remains positive and significant. The findings are also similar controlling flexibly for trends specific to the major US field crops (Figure A7a) and C4 crops (Figure A7b), which have different photosynthetic potential and perhaps also innovation trends.

Sensitivity Analysis: Treatment Variable In the main analysis, I use a pre-determined feature of crop-level flower structure—in particular, an indicator that equals one if a crop has perfect flowers—as the main proxy for crop-level treatment status. The logic behind this design, which I verify empirically in Section 4.2.1, is that perfect flower structure prevents hybrid variety development, substantially increasing the potential benefits of formal patent protection. While this makes perfect flower structure a clear shifter of exposure to the change in patent law, there are some examples of hybrid varieties developed for some perfect-flower crops using a breeding technique known as cytoplasmic male sterility (CMS). CMS is a condition in which a plant cannot produce the male reproductive material (pollen) and therefore will not self-pollinate, making hybridization more straightforward.

Unlike flower structure, CMS breeding is an endogenous outcome of breeding choices, so I do not use hybridization via CMS in order to construct the main treatment variable. Nevertheless, to investigate the potential role of hybridization via CMS, I reproduce the main results after reassigning crops for which CMS systems have been developed to the control group (Table A8, columns 1-4) or after excluding them from the sample entirely (columns 5-8).[34] The estimates remain similar and, if anything, are attenuated when CMS crops are assigned to the control group. This is consistent with the fact that they are not true controls and with the observation that the penetration of hybrids developed through CMS was limited during the sample period (Havey, 2004).

Sensitivity Analysis: Inference One potential concern is that errors are correlated across related crops. The main results report regression estimates double-clustered by crop and year; here, I investigate the robustness of the findings to expanding the standard error cluster level and unit of observation definition. In particular, I rely on the taxonomic classification of each crop in the EcoCrop database and I reproduce the baseline estimates, double-clustering standard errors by *genus* and year (Table A9). For example, broccoli, cauliflower, and turnips are in the data as separate crops; however, all three crops are genetically similar and part of the *Brassica* genus, so they would be assigned to the same cluster. The precision of the estimates is very similar using this approach, or after fully collapsing the data to the genus-by-year level and reproducing the main results on that sample (Table A10).

[34] This set of crops was determined following Havey (2004); it includes several field crops, most notably sorghum, rye, and sunflower, along with a range of vegetable and oil crops.

Discussion of Magnitudes The baseline estimates suggest that patent rights roughly doubled variety development in treatment crops compared to control crops. While this effect is large, in many models of technology development, including standard endogenous growth models, there would be *zero* incentives to innovate were it not for the possibility of patent protection (e.g. Romer, 1990). Thus, patent rights could have a substantial effect on *ex ante* R&D investment decisions by increasing the potential returns to developing new technology.

To make progress on identification, this study relies on difference-in-differences comparisons across crops. Thus, as with all difference-in-differences estimates, the treatment effect is the differential change in variety development between the treatment and control groups. In this context, the results clearly show that patent rights led to a strong re-direction of innovation toward more exposed technologies. One interpretational challenge, however, is assessing whether or not patent rights had a positive effect on overall innovation.

A range of evidence lends support to the interpretation that the results are driven by an absolute increase in technology development rather than reallocation between control and treatment crops. First, private sector investment in crop breeding R&D increased dramatically throughout the sample period (see Figures A1 and A8), and during the longer period from 1960 to 2000, it increased by nearly 1500%. Thus, the industry does not seem to have been facing a binding aggregate resource constraint. Second, I find no evidence of an absolute decline in trend in variety development in the control group (see Figure 4). In the raw data, the results seem to result from a disproportionate rise in technology development for treatment crops. Third, discussed in greater detail below (see Section 5.4), I find no evidence that patent-induced innovation in biotechnology had negative spillovers on innovation in other technology areas, suggesting the results are not driven by shifting research investment across topics. Finally, the assumption that patent-induced technology had *zero* benefits for control crops seems, if anything, quite conservative since some new ideas or methods could be applicable across all crops. In all cases, however, it is not possible to know with certainty the counterfactual trends in the absence of the change in patent law.

5.3 R&D Investment

The previous section documented that patent protection increased the commercialization of plant varieties for treatment crops. I next investigate whether this was driven by changes in upstream R&D investment. One possibility is that the introduction of patent rights incentivized the release and commercialization of varieties, rather than a major change in investment. While causing or accelerating the diffusion of existing varieties could be part of the mechanism, with large potential benefits, it would have different implications (especially in the long run) from a world in which patent rights also spurred upstream investment.

Table 3: Patent Protection and Patterns of R&D Investment

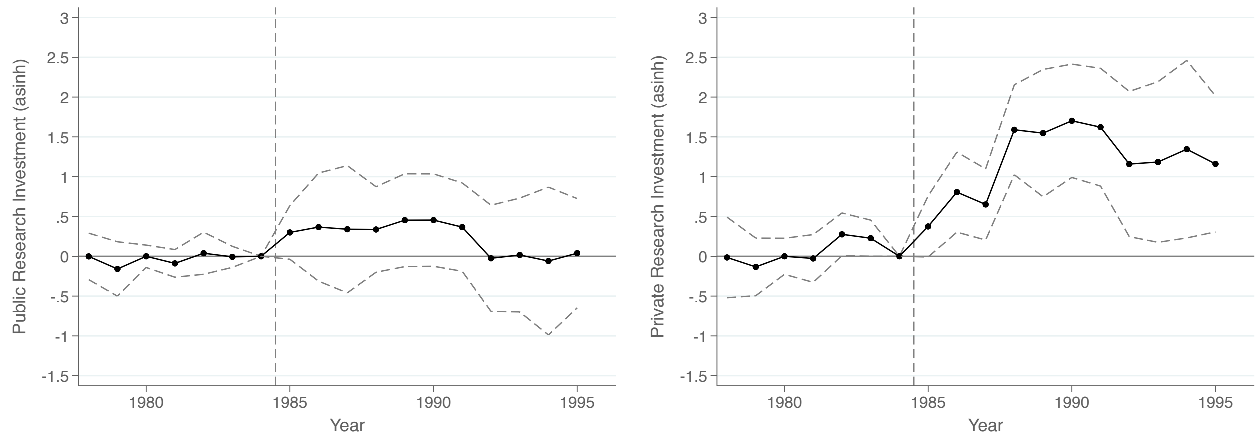
	(1)	(2)	(3)	(4)	(5)	(6)
Dependent Variable:	Public Research Investment			Private Research Investment		
Treatment x $\mathbb{1}^{\text{Post 1985}}$	-0.294	-0.0561	0.236	0.479**	0.672**	1.055***
	(0.771)	(0.256)	(0.268)	(0.207)	(0.319)	(0.363)
Crop Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
1975, 1980, and 1984 Investment x Year FE	No	Yes	Yes	No	Yes	Yes
All Baseline Controls	No	No	Yes	No	No	Yes
Observations	1,220	1,220	760	1,220	1,220	760
R-squared	0.842	0.983	0.991	0.927	0.952	0.969

Notes: The unit of observation is a crop-year. All specifications include crop and year fixed effects. The outcome variable the inverse hyperbolic sine of public R&D investment in columns 1-3 and the same for private R&D investment in columns 4-6. Baseline controls include indicators for any released GMO variety and GMO variety development, an indicator for asexual propagation, and optimal rainfall cut-off values, all interacted with a full set of year fixed effects. All columns report OLS estimates. Standard errors, double-clustered by crop and year, are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels

To study this question, I turn to crop-level data on R&D investment from CRIS and estimate the OLS analog of equation (2) with various measures of R&D investment as the outcome variable. First, I investigate the impact of patent protection on public research investment. I find a statistically insignificant relationship between the availability of patent protection and pubic investment (Table 3, column 1), which remains insignificant and close to zero after controlling for pre-period public investment in 1975, 1980, and 1984 interacted with year fixed effects (column 2) or after adding the full set of baseline controls from Section 5.2 (column 3). Event study estimates show no significant effects of crop-level treatment status on trends in public investment, before or after the change in patent law (Figure 5a).

Second, I investigate the impact of patent protection on private research investment. I estimate a positive and significant relationship between the availability of patent protection and private research investment (column 4), which, if anything, increases in magnitude after conditioning on trends in pre-period private investment (column 5) and the full set of baseline controls (column 6). Turning to event study estimates, I find no evidence of differential trends between treatment and control crops prior to the introduction of patent rights; however, trends in private R&D sharply diverge after 1985 and are already significantly different by 1986 (Figure 5b). These results are consistent with the important role of potential profit opportunities in directing private R&D (e.g., Acemoglu and Linn, 2004; Finkelstein, 2004).

One shortcoming to this analysis is that the CRIS data only reports private investment for projects that received some public funding. This means that these results could understate



(a) Public Research Investment

(b) Private Research Investment

Figure 5: **R&D Investment: Dynamics.** This figure reports coefficient estimates from the OLS analog of equation (3). The dependent variables are the inverse hyperbolic sine of public research investment (a) or private research investment (b) in the crop-year pair. Crop and year fixed effects, along with all baseline controls are included in both sub-figures. Standard errors are double-clustered by crop and year. 95% confidence intervals are reported.

the true effect of patent rights on private investment, especially in the long run, if a growing share of research was *fully* privately funded. While I am unaware of more systematic crop-level data on private R&D investment, aggregate data on all private sector R&D investment related to crop breeding tell a similar story. Private R&D in breeding increased substantially after 1985; while breeding and chemical R&D investment were on similar trends before 1985, they diverged sharply after 1985 as private breeding R&D took off (Figure A8).[35] While this aggregate trend is only suggestive, it is consistent with a long-run increase in private sector breeding research resulting from the introduction of patent rights.

Finally, I investigate how the introduction of patent rights affected the distribution of investment across researchers. While patent protection had no significant effect on the total number of crop-specific scientist years, it had a positive and significant impact on investment per scientist-year (Table A11).[36] Thus, the extension of patent protection led to a dramatic increase in private investment and greater investment per scientist.

5.4 Spillover Effects on Non-Biological Technologies

The impact of patent protection for plant varieties might extend beyond biotechnology if it had spillover effects on other technology classes. For example, new seed technologies might

[35]Data on *total* private sector research investment in both (i) breeding activity and (ii) agricultural chemicals were compiled from Klotz et al. (1995) and Fernandez-Cornejo (2004).

[36]In CRIS, it is not possible to distinguish between scientist-years funded by public versus private sources.

give rise to the development of complementary non-variety inputs, like harvesters that are only productive with specific (e.g., hardier) crop varieties.[37] Spillover effects, however, need not be positive. For example, in some contexts modern crop breeding has reduced chemical dependence and perhaps also innovation in chemical technology (see e.g. Robinson and Cowling, 1996). More generally, agricultural firms may increase investment in variety development by reducing investment elsewhere, generating negative spillover effects. Understanding the sign and magnitude of these spillovers is important for determining the overall impact of patent protection on innovation.

To investigate these possibilities, I report estimates of equation (2) in which the outcome is the number of crop-specific patent grants in a series of different technology classes (Table A12).[38] First, I document a positive effect on harvester technology development (column 1), consistent with the observation that biological and mechanical technologies can often be complementary in production. Second, I document weaker but still positive spillover effects on other mechanical inputs, including planting, sowing, and fertilizing technologies (column 2) and soil working technologies (column 3). Third, I find no evidence of any effect, positive or negative, on chemical technology development (column 4) or post-harvest and processing technology development (column 5). This null result suggests that the positive effects in columns 1-3 were not driven by, for example, an overall increase in crop-level demand or innovative effort, which would have likely been accompanied by a corresponding increase in post-harvest innovation. Finally, I report the impact on crop-specific patent totals, both with (column 6) and without (column 7) chemical patents, which are substantially more numerous than non-chemical patents, thus driving a large part of the result.

Together, these findings suggest that the introduction of patent protection for biotechnology may have spurred new technology development in some non-biological crop technologies, and particularly those related to harvesting and soil working, potentially amplifying its overall effect. I find no evidence of declining technology development in any patent class, suggesting that the introduction of patent protection for seeds did not substantially pull innovative activity away from other technology areas.

5.5 Physical Productivity

I next investigate the relationship between patent rights and average crop yields. There are several reasons that the positive effect on new varieties may not have translated into

[37] A famous example is the development of the tomato harvester by engineer Coby Lorenzen and crop breeder Gordie Hanna at the University of California in 1959. The development and use of mechanical harvesting technology required the development and use of a novel tomato variety that was sufficiently hardy and would not be destroyed in the harvester.

[38] To identify crop-specific patents, I search for the name of each crop in the *Variety Name List* in all patent titles and abstracts. Thus, the sample size can differ across technology classes since some crops may not appear.

Table 4: Patent Protection and Crop Yields

	(1)	(2)	(3)	(4)	(5)
Dependent Variable:	log Crop Yield			Δ log yield 1970-5 through 1980-5	Δ log yield 1980-5 through 1990-5
Treatment x $\mathbb{1}^{\text{Post 1985}}$	0.106*	0.108**	0.119*		
	(0.0505)	(0.0513)	(0.0652)		
Treatment				0.0369	0.132**
				(0.0534)	(0.0653)
Crop Fixed Effects	Yes	Yes	Yes	-	-
Year Fixed Effects	Yes	Yes	Yes	-	-
1980 and 1984 log Yield x Year FE	No	Yes	Yes	-	-
All Baseline Controls	No	No	Yes	Yes	Yes
Observations	1,494	1,478	1,447	74	74
R-squared	0.981	0.983	0.983	0.044	0.082

Notes: The unit of observation is a crop-year in columns 1-3 and a crop in columns 4-5. In columns 1-3, all specifications include crop and year fixed effects; the outcome variable is (log of) crop specific yield and the controls included in each specification are noted at the bottom of each column. In column 4, the dependent variable is the change in log crop yields between the 1970-1975 average and 1980-1985 average; in column 5, it is the change in log yields between the 1980-1985 average and the 1990-1995 average. Baseline controls include the GMO release and GMO development indicators, the rainfall sensitivity cut-off measures, and the vegetative reproduction indicator, all interacted with a full set of year fixed effects in columns 1-3 and included as crop-level variables in columns 4-5. Standard errors, double-clustered by crop and year, are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

meaningful changes in productivity. For example, and technology development induced by patent rights may have been of low quality or concentrated in business stealing and "copy-cat" invention that had limited downstream benefits. Technology might have also targeted features of crop production unrelated to physical productivity—like taste, costs, or resilience—that would not affect average yields. These additional margins through which technology may have improved production value are captured by the analysis in Section 6.

To study the impact of the introduction of patent rights on crop yields, I estimate the OLS analog of equation (2) in which the outcome variable is (log of) national crop yield. I find a positive relationship between the availability exposure to patent rights and crop yields (Table 4, column 1). The effect is similar after controlling flexibly for crop-specific pre-period yield trends (column 2) and after including the full set of baseline time-varying controls (column 3). The estimates suggest that patent rights for innovation increased downstream crop yields by 10-11%. This is a first indication that the introduction of patent rights had meaningful, positive downstream impacts on the agricultural sector.

To ensure the results are not driven by any pre-existing relationship between crop-level treatment status and crop yield trends, I estimate the relationship between the crop-level treatment variable and the change in (log of) crop yields *prior* to the change in patent law (i.e., from 1970-1985).[39] The coefficient estimate is small in magnitude and statistically indistinguishable from zero (column 4). This stands in sharp contrast to the relationship between the treatment variable and the change in crop yields *after* the introduction of patent rights (i.e., from 1980-1995) estimated in the same way (column 5). Together, these results indicate that the introduction of patent rights had a discernible, positive impact on crop yields.

6 Downstream Effects: County-Level Analysis

The previous sections documented that patent rights for agricultural biotechnology spurred new technology development. However, this does not necessarily imply that they increased downstream productivity and profits. First, the development of new technologies does not mean that these technologies translated into meaningful gains in downstream profits. Second, monopoly pricing of patented technologies—including technologies that would have been developed without patent rights—may have increased input costs faced by farmers. This could dampen or even reverse the effect of patent rights on profits. General equilibrium price effects may have further limit the benefits from new technology.

To study the downstream effects of patent protection on production, I estimate the effect of county-level exposure to patent rights on agricultural land values. This makes it possible to capture the both the benefits of new technology alongside its potentially higher cost. I find that exposure to patent rights substantially increased agricultural land values, suggesting that the benefits from new technology more than compensated for the higher costs of biotechnology inputs. I then investigate the mechanisms that underpin this relationship.

6.1 Empirical Strategy

I exploit the fact that counties were differentially exposed to the change in patent law depending on their crop composition; counties that are more suitable for treatment crops were more exposed to the surge in technology development induced by the introduction of patent rights, while counties that are more suitable for control crops were less exposed.

I determine each county's exposure to the introduction of patent rights based on the share of county land on which it was optimal to cultivate treatment crops. To estimate this share, I use FAO GAEZ models of crop-specific maximum potential yield, along with producer prices from the USDA for the year prior to treatment. For each grid cell g, I determine the optimal crop $c(g)$ as

$$c(g) = \text{argmax}_c \{A_{cg} \cdot \text{Price}_c\}$$

[39] Yield at each endpoint is calculated as an average over the five year period in order to make sure the result is not driven by any outlier year.

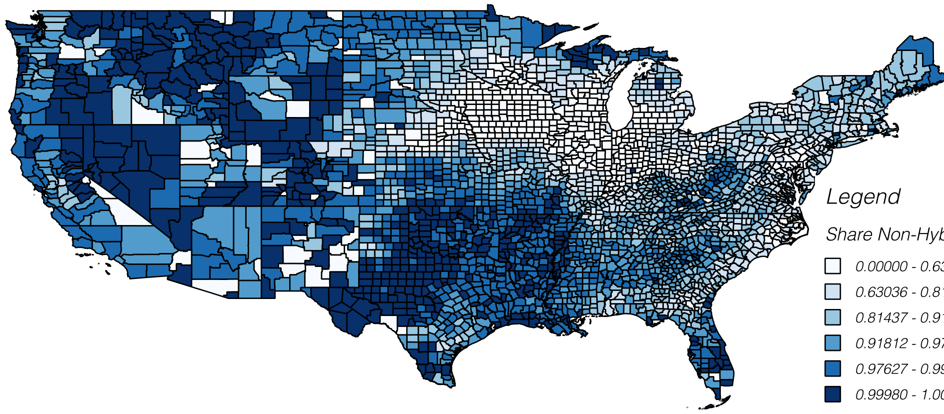


Figure 6: **County-Level Exposure to the Change in Patent Law** Counties are color-coded (in sextiles) based on the share of cropland devoted to treatment crops in the 1982 Census of Agriculture. Darker-colored counties are more exposed to the change in patent law while lighter colored counties are less exposed to the change in patent law.

where A_{cg} is the maximum potential yield of crop c in cell g and Price$_c$ is the national producer price of crop c in 1984.[40] For each county i, I compute exposure to the introduction of patent rights as the share of county land on which treatment crops are predicted to grow:

$$\text{Exposure}_i = \text{Share Treatment}_i = \frac{\sum_{g \in i} \mathbb{I}_g\{c(g) \in \text{Treat}\}}{\sum_{g \in i} \mathbb{I}_g\{c(g) \in \text{Treat}\} + \sum_{g \in i} \mathbb{I}_g\{c(g) \in \text{Control}\}}$$

where $\mathbb{I}_g\{c(g) \in \text{Treat}\}$ is a grid-cell-level indicator that equals one if $c(g)$ is a treatment crop. Thus, Exposure$_i$ captures the extent to which counties were more or less suitable for treatment crops, as determined by features of ecology and geography that drive crop-specific productivity incorporated into the FAO-GAEZ model.

The GAEZ-derived predicted share is strongly correlated with the actual share of treatment crops planted in each county measured directly in the Census of Agriculture from 1982, the closest Census year (Figure A9, t-statistic = 10.2). However, the GAEZ-derived measure is unaffected by endogenous production choices that could be correlated with trends in county-level characteristics. County-level exposure to the patent law change—the share of each county's farmland devoted to treatment crops—is displayed in Figure 6. Several patterns are intuitive; for example, the white-shaded region in the upper Midwest and Plains region is the "corn belt" and corn is a large, control crop in the data.

I estimate the county-level impact of exposure to the introduction of intellectual property

[40]This methodology closely follows Costinot and Donaldson (2012).

protection using the following estimating equation:

$$y_{it} = \alpha_i + \delta_{st} + \phi \cdot \text{Exposure}_i \cdot \mathbb{I}_t^{\text{Post 1985}} + \mathbf{X}'_{it}\Gamma + \epsilon_{it} \tag{4}$$

where i indexes counties, s indexes states, and t indexes census rounds. In the baseline specification, y_{it} is the value of agricultural land per acre.[41] The value of agricultural land captures the net present value of profits from agricultural production and has the benefit of capturing both the benefits of new technology alongside its potentially higher cost. α_i and δ_{st} denote county and state-by-round fixed effects respectively.[42] The inclusion of state-by-round fixed effects means that the main estimates only compare counties within the same state that nevertheless have different levels of exposure; thus, these estimates do not exploit the broad regional differences (e.g., between the upper Midwest and the Northeast) that are apparent in Figure 6. Standard errors are double-clustered by county and state-census-round pair, and the baseline sample period is 1969-2002.

The coefficient of interest is ϕ, which captures the impact of exposure to patent rights on local land values. The magnitude and even the sign of ϕ are unclear *ex ante*. The availability of new technology may raise expected profits. At the same time, higher input costs—including for technologies that would have been developed in the absence of patent rights—may do the opposite (Nordhaus, 1969; Budish et al., 2016).

6.2 Main Results

Estimates of equation (4) are reported in Table 5.[43] In column 1, only county and census round fixed effects are included on the right hand side, along with the patent protection exposure measure. The coefficient of interest is positive and significant, suggesting that county-level exposure to the introduction of patent rights for agricultural biotechnology had a positive average effect on the new present value of agricultural profits.

Next, I add state-by-census round fixed effects, fully absorbing all time trends at the state level, including all state-level changes in agricultural policy, investment, and climate (column 2). This also absorbs the effect of any average differences across states in the exposure measure and its impact on land values. Nevertheless, the effect remains positive and sig-

[41] This strategy follows a range of prior work that uses agricultural land values as the preferred measure of farm wealth when estimating the long run economic impact of shocks or policy (e.g. Hornbeck, 2012; Donaldson and Hornbeck, 2016). Other work focuses instead on farm profits (e.g. Deschênes and Greenstone, 2007). While there are issues with this approach (see Fisher et al., 2012), I explore the impact on profits in Section 6.3.

[42] The baseline estimates are weighted by (log of) pre-period farmland, in order to make sure that the results are not driven by small or non-agricultural counties. Un-weighted estimates are similar (Table 5, columns 3-4).

[43] While it might be preferable to measure only land value, state-by-year fixed effects absorb all state-level trends in building and building improvement prices (see Donaldson and Hornbeck, 2016). Moreover, below I report estimates with agricultural profits as the dependent variable, and the results are very similar.

Table 5: Patent Rights and Agricultural Land Value: Baseline Estimates

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent Variable:	log Value of Land and Buildings Per Acre				Δ log Land Value 1969-1982	Δ log Land Value 1982-1997
Exposure x $\mathbb{1}^{\text{Post 1985}}$	0.161***	0.0980***	0.0968***	0.0830**		
	(0.0317)	(0.0297)	(0.0306)	(0.0388)		
Exposure					-0.0335	0.147**
					(0.0309)	(0.0656)
County Fixed Effects	Yes	Yes	Yes	Yes	-	-
Census Round Fixed Effects	Yes	-	-	-	-	-
Census Round x State Fixed Effects	No	Yes	Yes	Yes	-	-
1974, 1982 log Land Value x Census Round FE	No	No	Yes	Yes	-	-
Weighting	log Area	log Area	log Area	None	log Area	log Area
Observations	24,350	24,350	24,183	24,249	3,046	3,026
R-squared	0.897	0.921	0.935	0.920	0.016	0.001

Notes: In columns 1-4, the unit of observation is a county-year and the sample includes all census rounds from 1969-2002. All specifications include county and year fixed effects. In columns 1-3, the specification is weighted by pre-period (log of) county-level farmland and in column 4 it is unweighted. Columns 3-4 include log of agricultural land value (the dependent variable) in 1974 and 1982, both interacted with a full set of census round indicators. In columns 5 and 6, the unit of observation is a county. Standard errors, double clustered by state-year and county in columns 1-4 and clustered by state in columns 5-6, are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

nificant. To further account for any potential location-specific trends, I control directly for pre-period trends in agricultural land values by including (log of) land value in 1974 and 1982 interacted with census round fixed effects (column 3). While the baseline specification is weighted by (log of) agricultural land area in order to make sure that the results are not driven by small or non-agricultural counties, the estimates are similar with no weighting (column 4). The estimates remain similar in both cases.

To test for pre-existing trends in the relationship between county-level exposure to patent protection and agricultural land values, I estimate the relationship between Exposure_i and the change in (log of) agricultural land values from 1969-1982 (i.e., the rounds prior to the passage of the patent law). The coefficient estimate is close to zero, negative, and statistically insignificant (column 5), suggesting that the main results are not driven by pre-existing trends in land values. Using the same specification, I find that Exposure_i is highly positively correlated with changes in agricultural land values between 1982-1997, the period during which the change in patent law took place (column 6). These estimates are consistent with a positive, causal effect of the introduction of patent rights in agricultural land values.

Turning to magnitudes, the estimate from column 2 (the specification that includes state-by-round fixed effects) implies that patent rights increased agricultural land values in the mean-exposed county by 7.4%. Aggregating this effect across all counties in the US, these estimates imply that patent rights for agricultural biotechnology increased the value of US farmland in 2002 by 7.5%, corresponding to roughly \$80 billion.[44] Thus, these estimates suggest that patent protection was a major driver of US agricultural productivity growth in recent decades. As one benchmark, this is roughly the amount by which global warming has reduced US agricultural land values since the mid-20th century (Moscona and Sastry, 2023), highlighting the varied forces that both spur and constrain productivity growth. Moreover, this paper ignores the potential impacts of US innovation on productivity growth elsewhere in the world. Existing evidence suggests that international spillovers from agricultural R&D can be large (e.g., Lachaud and Bravo-Ureta, 2022; Moscona and Sastry, 2025). That said, from 1982 to 2002 US agricultural land values increased by over 40%; thus, patent rights do not come close to explaining the growth of the US agricultural sector that took place during the studied period, suggesting that other forms of technology development (e.g., in the public sector) and efficiency gain were also paramount.

Sensitivity Analysis These baseline results are robust to a series of alternative specifications (see also Appendix C.1). First, the results are similar following the inclusion of a range of additional controls that might affect land value trends (Table A13), including local geography and pre-period features of the agricultural economy (e.g., farm area, farm size, agricultural output), all interacted with census round fixed effects. The results are also not affected by differential access to irrigation (Table A14). Second, the precision of the results is similar using alternative strategies for clustering the standard errors to account for spatial and temporal correlation, including Conley (1999) standard errors using several possible values of the spatial and temporal cut-off values (Table A15). Third, the results are similar using alternative approaches to measuring the main exposure variable, including measuring crop shares directly from the 1982 Census (Table A16), or doing the same after re-assigning crops with CMS systems to the control group (Table A17). The estimates are also similar when the sample period is restricted to a narrower window around the policy change (Table A18).

6.3 Mechanisms and Trade-Offs

The positive effect of patent rights on land values suggests that the benefits of patent-induced technology in more-exposed counties more than compensated for the potentially higher cost of patented inputs. What mechanisms underpin this positive average effect? I next investigate the relationship between exposure to patent rights and direct measures of input spending and profits during the sample period.

[44]The aggregation procedure is described in more detail in Appendix Section C.2. The estimate relies on the "intercept assumption" that there was zero effect of the extension of patent rights in counties whose land was 100% devoted to control crops. The validity of this (conservative) assumption is discussed in Section C.2.

Table 6: Spending, Land Use Adjustments, and Profits

	(1)	(2)	(3)	(4)	(5)	(6)
					Profits	
Dependent Variable:	log Spending on Seeds	log Total Spending	log Cropland	Share Cropland	Total (asinh)	Positive Profits (=1)
Exposure x $\mathbb{1}^{\text{Post 1985}}$	0.0979**	0.0270	0.0374**	0.00745*	0.290**	0.0232***
	(0.0393)	(0.0291)	(0.0190)	(0.00383)	(0.125)	(0.00820)
County Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Census Round x State Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
All Additional Controls	Yes	Yes	Yes	Yes	Yes	Yes
Observations	23,950	24,220	23,652	23,692	24,184	24,191
R-squared	0.911	0.972	0.976	0.970	0.743	0.611

Notes: The unit of observation is a county-year. All specifications include county and state-by-year fixed effects, as well as all additional controls. These include the dependent variable in 1974 and 1982, both interacted with census round fixed effects, and county-level latitude, longitude, and pre-period (log) farmland, farm revenue, and average farm size, all interacted with a full set of census round fixed effects. The outcome variable in each specification is listed at the top of the column. Standard errors, double clustered by state-year and county, are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

Input Spending and Land Use First, consistent with patent rights increasing the cost of seeds and crop varieties, I estimate a positive relationship between exposure to the patent law change and spending on crop varieties (Table 6, column 1). The extension of patent rights *did* have a discernible positive impact on farmers' expenditure on the newly-patentable technology. I find no evidence of increased spending on any other agricultural input category (Table A19), suggesting that the increase in seed spending was not driven by any across-the-board expansion of production or change in input prices.[45] Since seed spending represents only a fraction of overall input spending for crop production, the effect on total input spending is positive but statistically insignificant (Table 6, column 2).[46]

Second, I investigate how patent rights affected land use choices. I estimate a positive effect on land used for crop production, measured either as (log of) total cropland (column 3) or the share of county farmland devoted to crops (column 4). Thus, higher crop productivity also led to an expansion of land used for crop production, potentially contributing to the increase in agricultural land values documented in the previous section. Expanding the set of land that is suitable for crop production—including by increasing potential productivity on marginal land—is a well-documented consequence of agricultural technology development

[45]Data on seed prices themselves are scarce, particularly for years prior to 1985, making direct analysis of crop-level seed price changes impossible.

[46]In the Census, 18% of input spending for crop production is devoted to seeds on average (s.d. = 7%). This share increased throughout the sample period, and particularly after 1985, rising by 60% from 1982-2002.

Table 7: Farm Size Heterogeneity and Consolidation

	(1)	(2)	(3)	(4)
	Profits			
	Total (asinh)	Positive Profits (=1)	log(Farms >$100k)	Share Rev. to Farms >$100k
Exposure x $\mathbb{1}_t^{Post\ 1985}$			0.0523*	0.0109***
			(0.0300)	(0.00320)
Exposure x $\mathbb{1}^{Post\ 1985}$ x Bottom Quartiles	0.0773	0.00991		
	(0.147)	(0.00937)		
Exposure x $\mathbb{1}^{Post\ 1985}$ x Top Quartile	0.388**	0.0226**		
	(0.183)	(0.0109)		
Coefficient Difference p-value	*0.090*	*0.270*	-	-
County Fixed Effects	Yes	Yes	Yes	Yes
Census Round x State Fixed Effects	Yes	Yes	Yes	Yes
All Additional Controls	Yes	Yes	Yes	Yes
Observations	24,184	24,191	21,202	21,151
R-squared	0.743	0.612	0.960	0.829

Notes: The unit of observation is a county-year. All specifications include county and state-by-year fixed effects, as well as all additional controls from Table 9. These include the dependent variable in 1974 and 1982, both interacted with census round fixed effects, and county-level latitude, longitude, and pre-period (log) farmland, farm revenue, and average farm size, all interacted with a full set of census round fixed effects. The outcome variable in each specification is listed at the top of the column. Standard errors, double clustered by state-year and county, are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

(e.g., Akerman et al., 2025) and a potentially important impact of patent-induced innovation.

Profits and Volatility Third, I investigate the relationship between patent rights and in-sample agricultural profits, measured as total revenue net of non-labor input costs. The coefficient of interest is positive and significant, suggesting that even in the short run, exposure to patent-induced technologies increased total farm profits (column 5) and the probability that total county-level profits were positive (column 6). These estimates also validate the land value results from Table 5; moreover, measured profits are unaffected by any determinant of local economic activity other than agricultural revenues and input costs.

New technology can affect both the level of productivity and the resilience of production in the face of shocks (e.g., through improved pest or drought resistance), thereby reducing profit volatility. To investigate this possibility, I estimate the relationship between Exposure_i and the change in the standard deviation of agricultural profits between the pre-treatment and post-treatment period (Table A20). The coefficient estimates are negative and significant, suggesting that patent-induced technology development not only raised average profits but also reduced profit volatility, perhaps by reducing sensitivity to shocks. This may be an additional driver of the overall positive effect on agricultural land values.

Farm Size and Consolidation Fourth, I investigate the relationship between patent rights and farm scale. Several qualitative accounts have argued that large farms benefited disproportionately from the growth in improved seed varieties, while profits on small farms have been substantially eroded by higher seed prices and lower prices for agricultural commodities (e.g. Willingham and Green, 2019). This has been explained by production complementarities between new seed varieties and farm scale, and as well as fact that prior to 1985 many small farms remained profitable only by saving seeds for several growing seasons.[47]

Consistent with these accounts, I find that the positive impact of patent rights on downstream profits is driven by counties with the largest pre-period average farm size (Table 7, columns 1-2).[48] I report the estimate from an augmented version of equation (4), in which the independent variable is interacted with indicators for whether average county-level farm size is in the top quartile or the bottom three. The effect of exposure to patent rights is substantially larger for counties with larger farms.

Dovetailing with these heterogeneous effects, I find that introduction of patent rights had a positive effect on the number of farms in the highest revenue bin recorded by the Census (column 2) as well as the share of total revenue flowing to these largest farms (column 3). These results indicate that patent rights may have contributed to the consolidation of US agricultural land. However, taking the estimates at face value, they suggest that in the mean-exposed county, patent rights increased the share of revenue flowing to the largest farms by only one-tenth of a standard deviation. Moreover, much of the long-run consolidation of US farmland had already taken place by 1985 and therefore cannot be explained by patent rights or the recent wave of technology development.[49]

7 Conclusion

Institutions that protect intellectual property are of potentially central importance for economic growth and development. They remain the main policy lever to encourage innovation by allowing inventors to internalize some of the positive externalities created by their inventions. However, since patent regimes are endogenously determined, our understanding of the impact of patent rights on technological progress and downstream productivity is lim-

[47] Even absent any patent rights, farmers would have to re-purchase seeds every several years due to declining efficacy of saved seeds as conditions change. Indefinitely using the pre-existing seed stock was therefore not an option, and patent protection forced farmers to re-purchase seeds every year, even if there were limited potential benefits to using the new technology.

[48] Farm size is defined as total agricultural revenue per farm measured in the 1982 Census of Agriculture.

[49] Most US farmland consolidation took place *prior* to 1985. The number of farms in the US declined from 7 million during the 1930s to 2.5 million in 1985; the steepest decline occurred between 1940 and 1970. From 1985 to the present, the number of farms declined from 2.5 to 2 million. Any impact of patent rights should be considered within this long-run consolidation trends. See: `https://tinyurl.com/yfw59fh7`

ited. While patent rights provide potentially crucial *ex ante* incentives that encourage technology development, the quantitative importance of patent rights for spurring technology development remains unclear. Moreover, patents also increase *ex post* costs to consumers of technology, including for technologies that would have been developed in the absence of patent incentives. These distortions could undermine the social benefits of patent protection.

This paper investigates the impact of the introduction of patent rights for agricultural biotechnology in the US. To isolate causal effects, I exploit the sudden introduction of patent protection in 1985 combined with unique features of plant biology that determine crop-level exposure to changes in formal intellectual property protection. I find that the introduction of patent rights led to a substantial increase in novel variety development. This was driven predominantly by an increase in private research investment, had positive spillover effects on innovation in certain non-biological crop technologies, and increased crop yields. Furthermore, I show that counties that were more exposed to the change in patent law due to their crop composition experienced a large increase in agricultural land values and profits.

This analysis leaves several important issues unexplored. First, the analysis is focused on the US, a country with a large agricultural sector and a long history of agricultural technology development. The impact of patent rights in other countries could be different if the effective domestic market size is smaller, opportunities to productively adopt foreign technologies are greater, or enforcement of intellectual property protection is less effective. Identifying the contexts in which the benefits of patent rights outweigh the costs, and vice versa, is an interesting area for future work (see Diwan and Rodrik, 1991). Second, while this paper is focused on agricultural biotechnology, it would be interesting to explore how the effect of patent rights compares across different industries. It is possible, for example, that agricultural biotechnology is a context in which patent rights are especially impactful since, absent formal protection, new non-hybrid seeds can be easily re-used, replicated, and re-sold; there is little a breeder can do to extract rents. In other areas, trade secrets may effectively substitute for patent protection, but also come with their own costs. Finally, especially in the long run, patent rights might also affect the market structure of innovation, as well as the characteristics and diversity of new technology. This process could have additional effects on downstream productivity, profits, and production resilience.

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Supplemental Material

"Flowers of Invention: The Economic Impacts of Patent Rights" by Jacob Moscona

A The Empirical Design: Background and Validation

A.1 *Ex Parte Hibberd* and patent protection in the US

The extension of patent rights to crop varieties through *Ex Parte Hibberd* represented a major and surprising turning point. Qualitative accounts suggest that the decision had a sudden and substantial impact on the effective strength of intellectual property protection for plant varieties. William Lesser (1987) wrote, "[V]irtually overnight, and to the great surprise of many, seeds became patentable." In his sweeping history of US plant biotechnology, Kloppenburg (2005, p. 263) writes that *Ex Parte Hibberd* "overturned a half century of federal patent policy" and was the key turning point extending patent protection to plant varieties.

The importance of the decision was noted in the press and by trade organizations. *Nature* magazine reported: "At long last, 'everything under the sun made by man' [...] is potentially patentable [since the PTO] reversed its 50-year stance, and ruled that plants *can* be patented under the general patent statute" (Van Brunt, 1985). After the decision, Bill Richards wrote in the *Wall Street Journal* that the ruling would "shake up the $3 billion dollar U.S. seed industry" (Richards, 1985). The International Seed Trade Federation noted the profound impact of being able to prevent farmers from saving seeds (Kloppenburg, 2005, p. 264).

Legal scholars have opined on the importance of the decision. Blair (1999, p. 317) writes that "plant patentability under 35 USC 101 was squarely addressed in Ex Parte Hibberd." Blair (1999) argues extensively that the change brought about by *Ex Parte Hibberd* afforded breeders with much stronger protection compared to what was possible previously. Ewens (1999) concurs that *Ex Parte Hibberd* marked the critical moment when plants became eligible for patent protection. The effect of *Ex Parte Hibberd* was also reflected in the US's approach to international patent law. In negotiating the TRIPS Agreement, the US "asked for mandatory recognition of plant patents in order to bring international standards into line with US policy stemming from *Ex Parte Hibberd*" (Ewens, 1999, p. 302). US negotiators treated *Ex Parte Hibberd* as settled US policy and used it as a basis for its stance in international negotiation.

A.2 Validating the Shock to Patent Rights

Time Series Trends First, I show there was a major increase in biotechnology patenting after *Ex Parte Hibberd*. To identify plant biotechnology patents, I use each patent's Cooperative

Patent Classification (CPC) class. The broadest CPC category I use is A01H, defined as *New plants or processes for obtaining them; plant reproduction by tissue culture techniques*. I also use two refinements of this definition, focusing on sub-classes of A01H. The first is focusing on both A01H.5 and A01H.6, which are defined respectively as *Angiosperms, i.e. flowering plants, characterized by their plant parts; Angiosperms characterized otherwise than by their botanic taxonomy* and *Angiosperms, i.e. flowering plants, characterized by their botanic taxonomy*. To further focus on seeds in particular, I present results using A01H.5/10, titled *Seeds*.[50]

There is a stark and marked trend break in patents in classes A01H.5 and A01H.6 after 1985 (Figure 2). The pattern is very similar focusing on the full A01H patent class (Figure A3a), ruling out the possibility that the rapid increase in the individual CPC sub-classes is driven by any classification error or idiosyncrasy. The pattern is also similar focusing on the much narrower category A01H.5/10 (Figure A3b), though for reasons described above, this likely misses many relevant patents. There is no corresponding change in any other agricultural patent class (Figure A2), including (i) *Soil working in agriculture or forestry; parts, details, or accessories of agricultural machines or implements, in general* (A01B), (ii) *Planting; sowing; fertilizing* (A01C), (iii) *Harvesting; mowing* (A01D), and (iv) *Processing of harvested produce; hay or straw presses; devices for storing agricultural or horticultural produce* (A01F).

Hybrid Varieties and Flower Structure A key ingredient for the empirical design is the fact that it is much harder (if not impossible) to develop hybrid varieties for plants with perfect flowers. To document the relationship between a flower structure and hybrid development, I report the relationship between an indicator that equals one if a patent relates to a plant with imperfect flowers and an indicator that equals one if a patent relates to a hybrid variety. These estimates are reported in Table A1 for all patents in A01H.6 and A01H.6 (column 1) or all patents in A01H (column 2). To identify patents related to imperfect flower plants, I searched each patent's title and abstract for the name of each imperfect flower crop in the baseline sample, using name synonyms (e.g. corn and maize) where appropriate. To identify patents related to hybrids, I searched for the word stem "hybrid" in all patent titles and abstracts. The estimated correlations are large and highly significant. The correlation coefficient is about 0.6; in both cases the F-statistic is greater than one thousand.

The Economic Value of Patent Rights Next, I investigate the private value of biotechnology patents by estimating the impact of being issued a patent on the stock price returns of the relevant firm. Daily stock price data are from the Wharton Research Data Services (WRDS)

[50] The CPC scheme handbook issues a warning that A01H.5/10 is impacted by re-classification into one of several categories within A01H.6, and thus should not be considered comprehensive; they note "All groups listed in this Warning should be considered in order to perform a complete search." This is why I report all results also using the definitively complete set of all patents from A01H.5 and A01H.6 .

Center for Research in Security Prices (CRSP). The choice of a two-day window follows Kogan et al. (2017) and the use of abnormal, instead of raw, returns follows Kothari and Warner (2007). Abnormal returns were computed by estimating the relationship between daily stock price and the S&P 500 return interacted with year fixed effects on the analysis sample, allowing the relationship between S&P 500 movement and stock prices to vary by year. The residual from this estimation is defined as the abnormal return. All reported estimates are very similar using raw returns as the dependent variable rather than abnormal returns.

I conducted a comprehensive search in the WRDS CRSP database of all firms that were issued either a plant biotechnology patent or a PVP certificate, and were publicly traded for at least part of the sample period. This led to the following sample of firms: Agribio, Archer, Bayer, Campbell, Cascade, De Kalb, Del Monte, Honda, Hybritech, Lubrizol, Monsanto, Novartis, Semini, Standard Oil, and Syngenta. The data were harmonized to account for mergers that took places during the sample period and changes in firm-level trading structure. Data on all issued PVP certificates were compiled from certificate-level data published by the USDA and publicly available at the following link: `https://apps.ams.usda.gov/CMS/`.

The impact of patent and PVP certificate issuance on abnormal returns is reported in Table 1. In each case, the sample includes all patents (or certificates) issued to a publicly traded firm during the noted sample period, as well as the two day window around the date of the patent grant announcement. There is a positive and significant effect of patent issuance on abnormal returns, but no such effect for PVP issuance. The difference between the two coefficients is statistically significant. Figure A5 reports event study estimates of the impact of being issued a utility patent on abnormal returns. Moreover, the main text documents extensively that patent rights were more valuable for treatment compared to control crops (Section 4.2.2). These results confirm the key cross-crop variation in the empirical design.

The Role of *Subsequent* Supreme Court Action While patent protection was introduced for plant biotechnology in 1985, the US Supreme Court did not rule officially on its constitutionality until the 2001 decision of *J. E. M. Ag Supply, Inc. v. Pioneer Hi-Bred International*. An interesting question is whether the value of patents for plant biotechnology became even more valuable after the Supreme Court ruling in 2001.[51] Table A2 reports estimates from an augmented version of (1) that includes an interaction between the post issue date indicator and an indicator that equals one for patents issued *after* 2001. If the decision significantly increased the value of patent protection to firms, we would expect the interaction to be positive. However, the estimated interaction is statistically indistinguishable from zero. The

[51]Several pieces of evidence suggest they were valuable to innovating firms *prior* to 2001. First, Figure 2 shows a surge of patenting activity after 1985 and before 2001. Second, the sample period used in Table 1 is entirely prior to 2001. Indeed, in his majority opinion, Justice Thomas noted the widespread use and acceptance of patents for plant biotechnology to justify his ruling.

value of being issued a plant biotechnology patent did not seem to change significantly after the Supreme Court decision. Consistent with this finding, Figure A4 shows no evidence of a major trend break in variety patent applications or grants after 2001.

Balance Between Treatment and Control Crops Table A3 reports a series of balance tests comparing treatment and control crops. Columns 1 and 4 report the variable name for each crop-specific characteristic; columns 2 and 5 report the sample mean for that characteristic; and columns 3 and 6 report the regression coefficient and standard error from a regression of the crop-level characteristic on crop-level treatment status. All characteristics in the first nine rows are from the EcoCrop database published by the UN FAO; the EcoCrop data are reported at the plant species level and I hand-linked each crop in the main sample to species names in the EcoCrop data. This data set is described in greater length in Moscona and Sastry (2023). The bottom two rows use crop-level area harvested and price, estimated separately in 1975 and 1984 and published by the USDA.

B Crop-Level Analysis: Additional Details

B.1 Additional Results and Sensitivity Analysis

This section reports the additional results and sensitivity checks that accompany the main crop-level analysis (Section 5). Table A4 lists all seed crops included in the *Variety Name List*, along with the number of varieties released during the pre-period for each crop, the land area devoted to each crop (whenever reported in the 1982 Census of Agriculture), crop-level treatment status, and a series of other crop-level characteristics.

Table A6 estimates heterogeneous effects in the baseline effect of patent rights on variety development based on whether or not a crop is perennial. Data on whether each plant species is perennial or not was obtained from the EcoCrop database, introduced in Section A.2. A crop is perennial if it need not be re-planted every year; the same plant is used from one year to the next. Thus, a farmer purchases the variety once and re-uses the same plant year after year, without having to re-purchase the variety. If preventing farmers from saving seeds is an important part of the mechanism, then we would expect the effect to be larger for non-perennial crops that have to be re-planted every year. Consistent with this hypothesis, I estimate a large, positive effect of the introduction of patent rights on varieties using the sample of non-perennial crops but a much smaller effect using the sample of perennial crops.

I also report a range of sensitivity checks of the baseline results on the relationship between patent protection and variety development. Figure A6 reports the event study estimates with an extended pre- and post-treatment period. Table A7 shows that the results are very similar controlling directly for pre-trends in variety development; that is, I include as controls the number of varieties released in three pre-period years — 1975, 1980, and 1984— interacted with year fixed effects. Table A8 reports estimates in which crops for which CMS systems have been developed are assigned to the control group (columns 1-4) or excluded from the sample (columns 5-8). Table A9 documents that the estimates are very similar clustering standard errors by *genus* and Table A10 shows that the results are also similar if the regressions are estimated at the genus-by-year level. Information on the genus of each plant species was obtained by matching each crop to the EcoCrop database.

The rest of the results in this section relate to the additional crop-level dependent variables. Table A11 investigates the impact of patent rights on research investment, measured in the form of scientist-years. This is an additional measure of investment reported in the CRIS data; unfortunately, scientist-years are not reported by source (i.e. public vs. private).

B.2 Genetic modification and the "biotechnology revolution"

An important question is the relationship between this paper's findings and the rise of genetic modification (GM) and its use in plant biotechnology. The ability to patent plants and plant parts may have been an important force driving technological progress in GM technology. Many GMOs in use today are non-hybrids and require patent protection to prevent farmers from saving and re-using seeds; moreover, substantial fixed cost and upfront development cost was required so it is conceivable that the ability to protect intellectual property was an important pre-requisite for this process.

The rise of GMOs is only a potential concern for the analysis to the extent that crop-level GM investment trends were spuriously correlated with crop-level treatment status *for reasons other than changes in patent protection*. While *ex ante* it is challenging to come up for a mechanism that would lead to this pattern, given the eventual importance of GM varieties for the agricultural sector I nevertheless investigate this topic in greater detail.

To what extent are the main results of the paper driven, in part, by this "biotechnology revolution"? First, it is worth pointing out that the first GMOs were not even released until the very end of this paper's sample period. The first GMO *in the world* was released by Calgene in 1994; the now-ubiquitous Roundup-Ready varieties produced by Monsanto were not released until 1996. Moreover, in 1996 *zero* percent of US seed sales were GM varieties; still in 2001, only 9% of seed sales were GM varieties (Bonny, 2017, p. 10). Thus, GM varieties alone could not be driving the paper's baseline finding (Figure 3).

Second, GMOs have only been released in the US for a small number of crops, and have been developed for only a slightly larger set of crops.[52] The results are very similar after

[52] See the US FDA authorization page: https://tinyurl.com/44j9mmw3

fully excluding these crops from the analysis. Moreover, I show that all crop level estimates reported in Section 5 are robust to controlling flexibly for whether or not a GMO has ever been released or developed for each crop. That is, I construct an indicator that equals one if a GMO variety for a crop has been released and another if it has been developed, and control for both indicators interacted with year fixed effects. All results remain very similar.

Finally, it is possible that the rise of GM varieties contributed to the longer-run effects of patent rights. While the main event study figures end in a decade after the change in patent law (Figure 3), when I extend the sample period further the estimated effects seem to increase over time (Figure A6). While this is only suggestive, this pattern could be due to the benefits of patent protection for GM variety development; that said, it is not possible to verify this directly by identifying GM varieties in the *Variety Name List*.

C County-Level Analysis: Additional Details

C.1 Sensitivity Analysis and Controls

This section reports additional details and sensitivity analysis corresponding to the county-level part of the main empirical analysis (Section 6).

Additional Controls Table A13 explores the robustness of the baseline estimates to the inclusion several additional controls; these controls take the form of interactions between fixed county-level characteristics and census round indicators, thereby flexibly capturing trends in the characteristic of interest. Although the independent variable is constructed using data on the spatial pattern of crop production, the estimates are very similar controlling for trends in county-level latitude and longitude, thereby absorbing trends in the effect of geographic location (column 2). The estimate is also similar after controlling for trends in pre-period farmland area (column 3) or the pre-period market value of farm production (column 4), suggesting the effects are not driven by differences in the size of the farm sector or specialization in agriculture. The estimate also does not change after controlling for trends in pre-period average farm size (column 5). When all controls mentioned thus far are included on the right hand side of the same regression—amounting to 56 covariates in total—the coefficient of interest still remains positive and significant (column 6). Moreover, the effects are also similar after controlling flexibly for irrigation (Table A14)

Inference Table A15 reports the t-statistic from the baseline county-level estimates (column 3 of Table 5) under a series of alternative strategies for clustering the standard error. Columns 1-5 report the t-statistic using Hsiang (2010)'s implementation of Conley (1999) standard errors for several potential values of the spatial and temporal cut-off values. The five columns use spatial cut-off values (in kilometers) of 250, 500, 1000, 1500, and 2000 respectively. For reference, the distance between New York City and Chicago is about 1300km. The two rows report different values for the temporal cut-off value, five or ten years. Finally, in column 6 I report the *t*-statistic when standard errors are clustered by state.

Measurement and Sample Restrictions Figure A9 reports the partial correlation plot between the share of county-level land area devoted to treatment (hybrid-incompatible) crops and the share of land area devoted to treatment crops as predicted by the Food and Agriculture Organization (FAO) Global AgroEcological Zones (GAEZ) database. The relationship is positive and highly significant. In Table A16, I report a version of the baseline results, structured identically to Table 5, in which the independent variable is constructed from actual crop shares measured in the 1982 Census of Agriculture, rather than predicted crop shares estimated from the FAO-GAEZ derived model. The findings are very similar. Table A17 reports equivalent estimates, except crops for which CMS systems have been developed are assigned to the control group. In Table A18, I report a version of the baseline results restricting the sample period to 1974-1997 (the main results cover 1969-2002).

Additional Outcomes Table A19 reports the impact of exposure to the introduction of patent rights on farmer spending in a range of mutually exclusive input categories, including varieties (column 1), chemicals and fertilizers (column 2), petroleum (column 3), and feed (column 4); column 5 reports the impact on total spending. Exposure to patent protection had a significant positive effect on variety spending, but it had no significant impact on spending in other categories. These findings are consistent with higher variety spending driven by higher seed prices that resulted from patent rights and monopoly pricing, or the requirement that farmers buy patented seed from the breeder each year.

Table A20 reports the relationship between county-level patent law exposure and the change in the standard deviation of agricultural profits between the pre-treatment and post-treatment periods. The pre-treatment value is computed using census rounds from 1969-1982 and the post-treatment value census rounds from 1987-2002. Each is normalized by the appropriate sample mean before computing the difference. The negative coefficient estimate suggests that exposure to the change in patent regime reduced variability in farm profits.

C.2 Aggregating the local effects of patent law exposure

This section explains how I use coefficient estimates from Equation 4 to compute the aggregate impact of patent rights on US agricultural land values. These methods closely follow those used in Moscona and Sastry (2023). For each county i and time period t, I use the regression model from equation (4) and estimates thereof to predict each county's value of agricultural land as a function of exposure to the change in patent law. I define a counterfactual scenario in which patent law never changed (NP) as:

$$\text{logAgrLandPrice}_{it}^{NP} = \hat{\alpha}_i + \hat{\delta}_{s,t_1} + \hat{\phi} \cdot \text{Exposure}_i \cdot \mathbb{I}_{t_0}^{\text{Post 1985}} + \mathbf{X}_{it}'\hat{\Gamma} \tag{5}$$

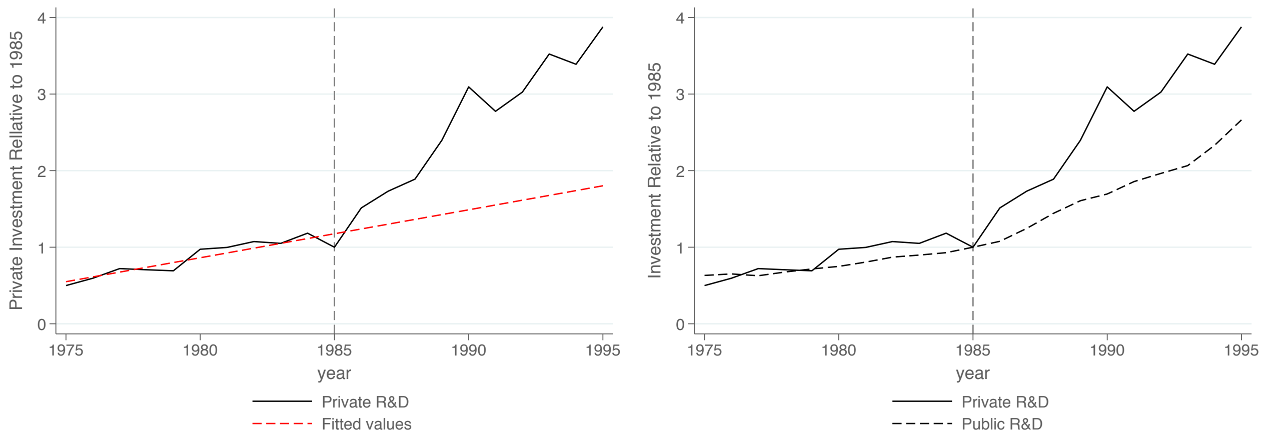
where t_1 is defined as the end of the sample period (in 2002) and t_0 is defined as the start of the sample period. Stated differently, this captures estimated local land value in a world where exposure to the change in patent regime is held at its pre-period level (that is, it is held at zero for all counties). I aggregate estimates of local land value from equation (5) to a national value of agricultural land, weighting each county by its (pre-determined) share of national agricultural land area in the US and using coefficient estimates from the specification in column 2 of Table 5 (i.e., the specification with state-round fixed effects).

Define AgVal^{NP} as the predicted total value of agricultural land under this no-patent counterfactual, and AgVal as the total value of agricultural land in the realized state of the world. The percent increase in the total value of US agricultural land in 2002 due to the introduction of patent rights is then given by:

$$\text{Percent Increase} = \frac{\text{AgVal} - \text{AgVal}^{NP}}{\text{AgVal}^{NP}}$$

This estimate relies on the assumption that there was zero effect of the extension of patent rights in counties whose land was 100% devoted to hybrid compatible crops; this is the key "intercept" assumption, implying that patent-induced technology had zero benefits for control crops and also that any benefits for treatment crops were not a result of reallocating R&D resources from control crops. There are several reasons why this assumption may be reasonable in the studied context and, if anything, conservative. First, agricultural R&D investment, and investment in biotechnology in particular, experienced unprecedented growth during our sample period. From 1960 to 2000, private sector R&D investment in crop breeding increased nearly 1500%. Thus, the industry does not seem to have been facing a binding aggregate resource constraint. Second, I find no evidence that the main results are driven by the substitution of research effort across crops or technologies; instead, they seem to be driven by an absolute increase in biotechnology development for treatment crops. Finally, the assumption that patent-induced technology had *zero* benefits for control crops is conservative. Nevertheless, absent a full general equilibrium model, it is not possible to estimate the intercept directly and these empirical estimates should be interpreted with this in mind.

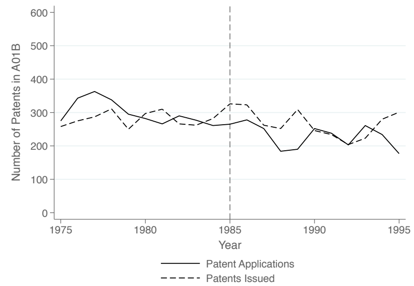
D Supplementary Figures and Tables



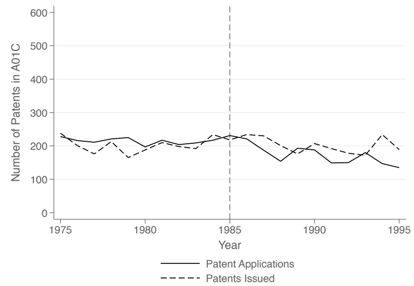
(a) Private Investment vs. Pre-Trend

(b) Private vs. Public Investment

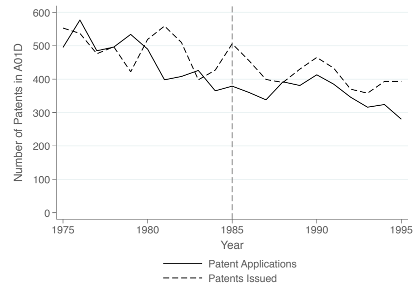
Figure A1: **Research Investment: Time Trend.** Figure A1a displays the trend in private research investment relative to 1985, averaged across crops in the sample and reported in the USDA CRIS. The dotted red line is the linear trend estimated from 1975-1984. Figure A1b displays the trend in both private and public research investment relative to 1985, also from the USDA CRIS, averaged across crops in the sample.



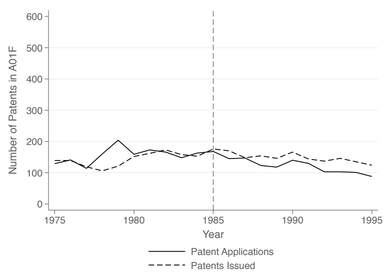
(a) Soil Working (CPC A01B)



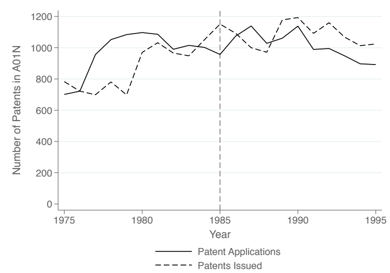
(b) Plant. and Fert. (CPC A01C)



(c) Harvesting (CPC A01D)

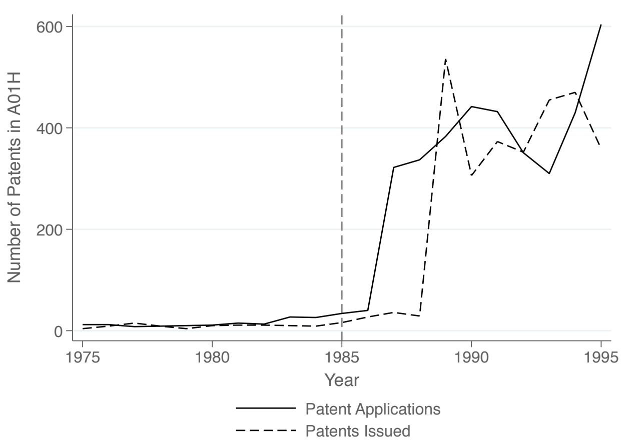


(d) Post-Harvest (CPC A01F)

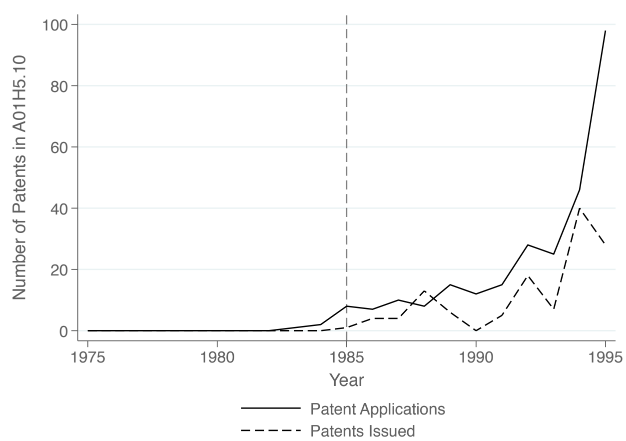


(e) Chemicals (CPC A01N)

Figure A2: **Non-Biological Patents: Time Trends.** Each figure displays the count of patent applications and patents issued for the CPC class denoted in the caption. Data were collected from the PatSnap database.



(a) All Plant and Plant Part Patents (A01H)



(b) All Seed Specific Patents (A01H.5.10)

Figure A3: **Biotechnology Patents: Time Trend for Alternative Measurements.** This figure displays the count of patent applications and patents issued in CPC classes A01H ("new plants or processes for obtaining them") in (A3a) and A01H.5.10 ("seeds") in (A3b). Data were collected from the PatSnap database.

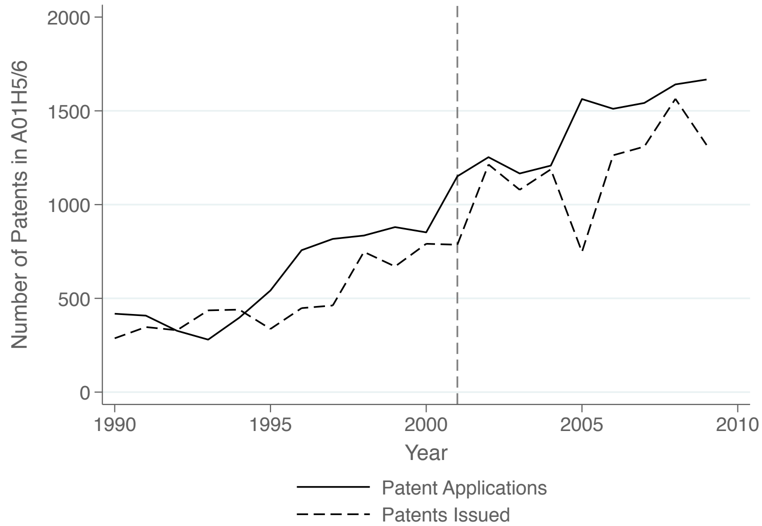
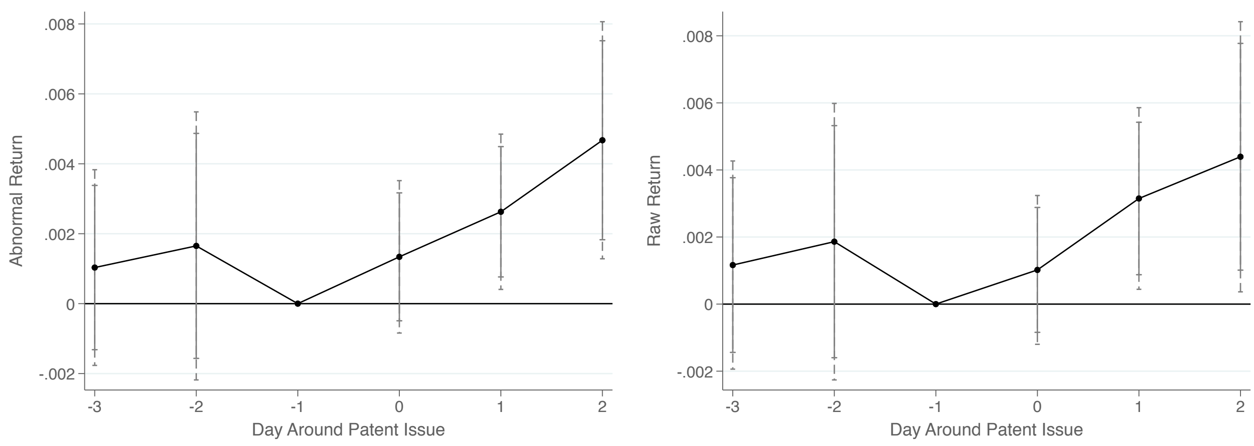


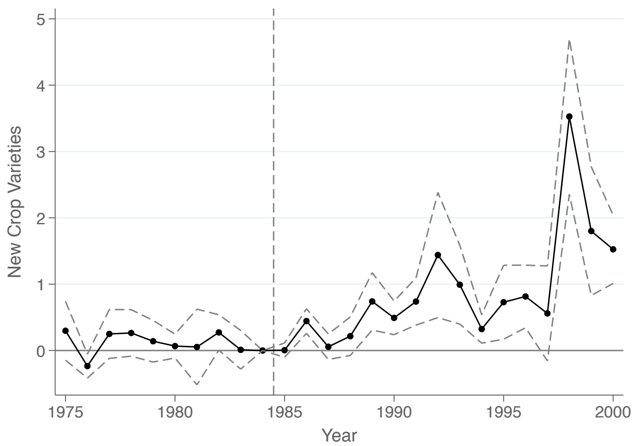
Figure A4: **Biotechnology Patents: Time Trend, 1990-2010.** This figure displays the count of patent applications and patents issued in CPC classes A01H.5 and A01H.6. The vertical dotted line denotes the year of the Supreme Court decision in *J. E. M. Ag Supply, Inc. v. Pioneer Hi-Bred International*. Data were collected from the PatSnap database.



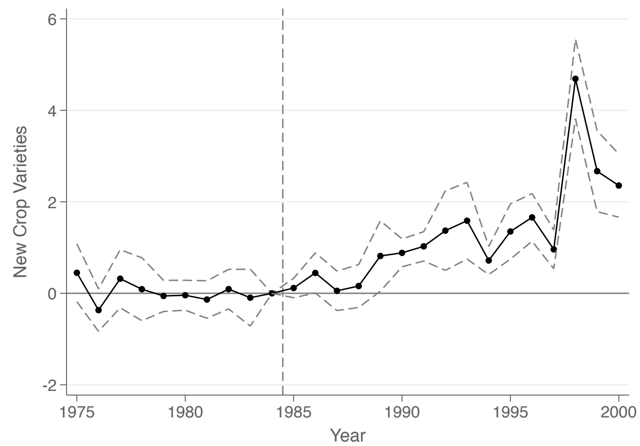
(a) Abnormal Returns

(b) Raw Returns

Figure A5: **Patent Issue Date Event Study.** This figure displays event study estimates of the baseline stock market results. In A5a, the dependent variable is abnormal returns and in A5b it is raw returns. Days relative to the date of patent issue are noted on the x-axis. The solid lines report 90% confidence intervals and the dotted lines report 95% confidence intervals.

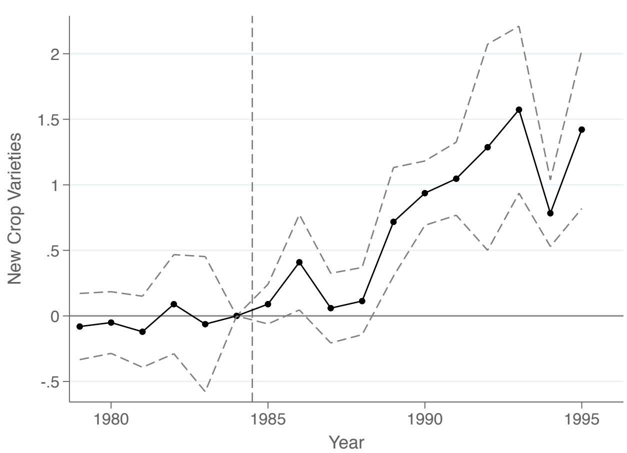


(a) No Controls

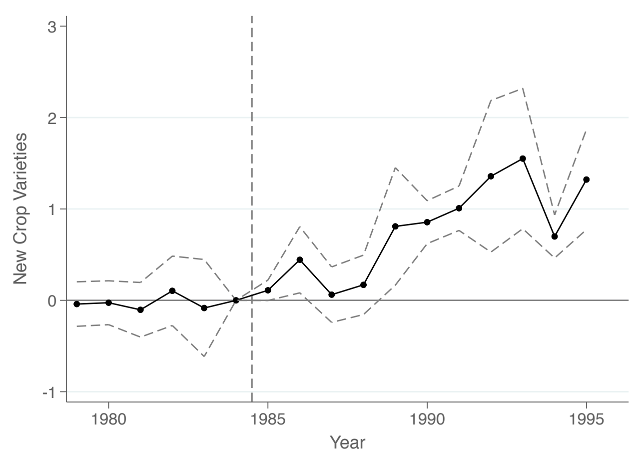


(b) All Baseline Controls

Figure A6: **Patent Protection and Novel Plant Varieties: Dynamic Estimates on Extended Sample.** Coefficient estimates from PPML estimates of Equation (3). The dependent variable is the number of novel plant varieties in the crop-year. Standard errors are double clustered by crop and year. 95% confidence intervals are reported.



(a) Major Field Crop Control



(b) C4 Photosynthesis Control

Figure A7: **Patent Protection and Novel Plant Varieties: Dynamic Estimates, Controlling for Large Crop Groups.** Coefficient estimates from PPML estimates of Equation (3). In panel (a), I include on the right-hand side a major field crop indicator (i.e., corn, wheat, soy, cotton) interacted with year fixed effects. In panel (b), I include a C4 photosynthesis indicator interacted with year fixed effects. The dependent variable is the number of novel plant varieties in the crop-year. Standard errors are double clustered by crop and year; 95% confidence intervals are reported

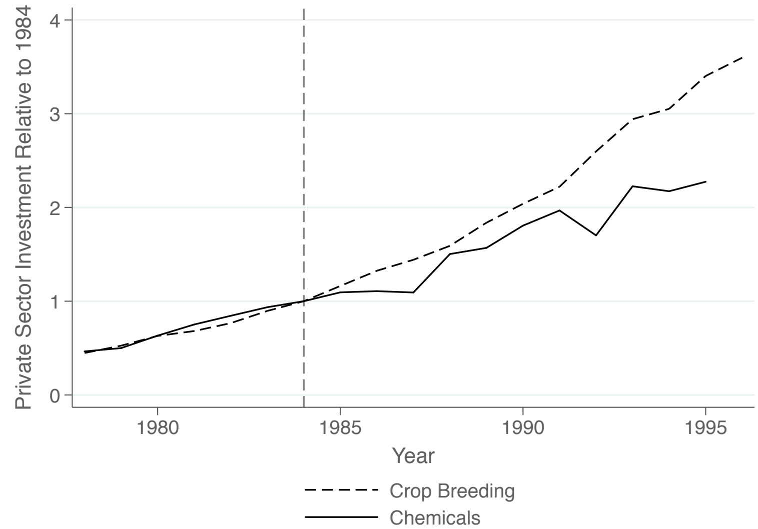


Figure A8: **Private Sector Investment in Breeding and Chemicals.** This figure plots total private sector research investment in (i) crop breeding and (ii) agricultural chemicals, relative to investment in 1984. The data were compiled from Klotz et al. (1995) and Fernandez-Cornejo (2004).

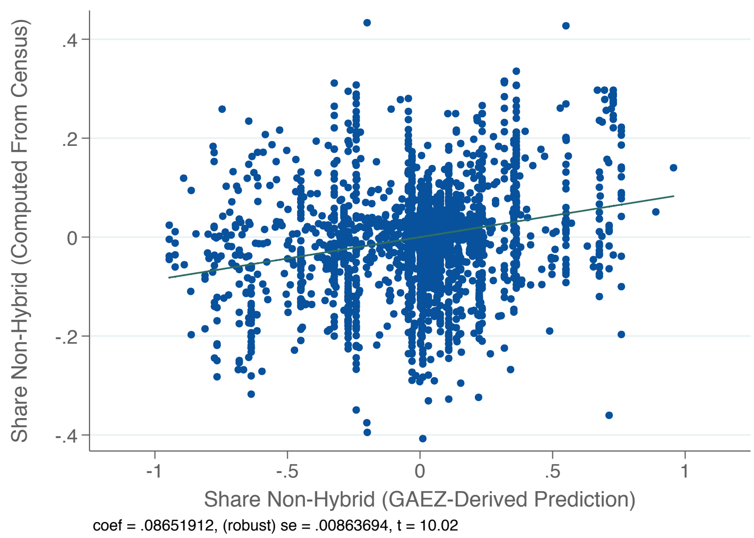


Figure A9: **GAEZ-Derived Prediction vs. Actual Share Hybrid Incompatible Cropland.** The graph displays a partial correlation plot between county-level GAEZ-derived prediction of the treatment crop share and the treatment crop share computed from the 1982 US Census of Agriculture. State fixed effects are included on the right hand side. The coefficient estimate, standard error, and t-statistic are reported at the of the graph.

Table A1: Imperfect Flowers and Hybrid Technology in the Patent Data

	(1)	(2)
	Word "Hybrid" in Title or Abstract (=1)	
Sample includes all patents in CPC class:	A01H	A01H.5 or A01H.6
Control Crop (=1)	0.597***	0.622***
	(0.0169)	(0.0171)
F-statistic	1247.13	1332.38
Month Fixed Effects	Yes	Yes
Observations	7,096	6,685
R-squared	0.268	0.284

Notes: The unit of observation is a patent and the sample includes all patents applied for prior to 2000 in CPC class A01H (column 1) or CPC classes A01H.5 or A01H.6 (column 2). All specifications include month fixed effects and robust standard errors are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

Table A2: Stock Price Response to Patents, Before vs. After the 2001 SCOTUS Ruling

	(1)	(2)
	Dependent Variable is Abnormal Returns	
	1985-2010	1985-2005
𝟙(Post Issue Date)	0.00297**	0.00297**
	(0.00141)	(0.00141)
𝟙(Post Issue Date) x I(Post SCOTUS Decision)	-0.00160	-0.00182
	(0.00195)	(0.00322)
Firm x Month Fixed Effects	Yes	Yes
Issue Date Window Fixed Effects	Yes	Yes
Observations	2,827	1,172
R-squared	0.216	0.221

Notes: The unit of observation is a firm-day and the sample is restricted to a two-day window around the issue date of each patent. Post Issue Date an indicator variable that equals one following the certificate or patent issue date within the two-day window. Post SCOTUS Decision is an indicator that equals one after the Supreme Court decision *J. E. M. Ag Supply, Inc. v. Pioneer Hi-Bred International* . Standard errors, clustered by firm-year, are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

Table A3: Balance Across Characteristics that Affect Breeding

(1) Variable Name	(2) Sample Mean	(3) Treatment vs. Control	(4) Variable Name	(5) Sample Mean	(6) Treatment vs. Control
Single Stem Plant (0/1)	0.315	-0.0190	Perennial Plant (0/1)	0.350	0.0685
		(0.282)			(0.179)
Min. Crop Cycle (Days)	83.29	8.092	Max. Crop Cycle (Days)	182.9	-22.12
		(16.59)			(42.03)
Opt. Soil Depth (cm)	2.039	0.0417	Opt. Soil Salinity (dS/m)	1.020	0.0213
		(0.296)			(0.0150)
Temp. Opt. Range, Max. (°C)	26.31	-0.893	Temp. Opt. Range, Min.	15.95	-0.205
		(1.951)			(1.171)
Temp. Feasible Range, Max.	33.73	-2.591	Temp. Feasible Range, Min.	6.408	-0.329
		(2.542)			(1.042)
Rain Opt. Range, Max. (mm)	1,176	-10.19	Rain Opt. Range, Min.	668.4	-110.5
		(123.9)			(81.72)
Rain Feasible Range, Max.	2,297	58.50	Rain Feasible Range, Min.	397.1	50.52*
		(414.9)			(29.24)
pH Opt. Range, Max. (0-14)	7.066	-0.0518	pH Opt. Range, Min.	5.868	0.242
		(0.150)			(0.176)
pH Feasible Range, Max.	8.146	-0.0430	pH Feasible Range, Min.	4.936	0.00789
		(0.180)			(0.173)
ln Area Harvested (1975)	10.90	0.431	ln Area Harvested (1984)	10.99	0.457
		(1.228)			(1.231)
Price per unit (1975)	21.100	19.797	Price per unit (1984)	24.790	23.751
		(16.641)			(20.57)

Notes: The unit of observation is a crop. Columns 1 and 4 list a series of crop-level characteristics, and columns 2 and 5 report the sample mean of each corresponding characteristic. Columns 3 and 6 report estimates of the relationship between each characteristic and the "not hybrid compatible" indicator variable. Each coefficient was estimated from a separate regression. Robust standard errors are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

Table A4: Seed Crops in the *Variety Name List*

(1) Crop Name	(2) Varieties Released Before 1985	(3) Area x 10^{-6} from 1982 Census of Agriculture	(4) Perfect Flowers	(5) GMO	(6) GMO (Developed)	(7) Temp. Opt. Range, Min. (C)	(8) Temp Opt. Range, Max (C)	(9) Rain Opt. Range, Min (mm)	(10) Rain Opt. Range, Max. (mm)
Alfalfa	658	48.24094	1	1	1	21	27	600	1200
Barley	880	17.25652	1	0	0	15	20	500	1000
Beans, dry	1026	3.37848	1	0	1	16	25	500	2000
Broccoli	128	0.15793	1	0	0	15	24	900	1500
Brussel Sprouts	8	0.01192	1	0	0	12	20	900	1600
Buckwheat	4	0.15643	0	0	0	17	27	700	1000
Cabbage	218	0.16829	1	0	0	15	24	500	1000
Carrots and Turnips	552	0.17068	1	0	0	17	30	700	1000
Castor oil seed	2	-	0	0	0	20	30	600	1000
Cauliflower	539	0.09412	1	0	0	10	25	600	1100
Celery	162	0.07614	1	0	0	15	21	700	1300
Chickpeas	3	-	1	0	0	15	29	600	1000
Chicory	13	0.00010	1	0	0	10	30	1500	2500
Collards	4	0.01989	1	0	0	15	22	450	1000
Cornsalad	2	-	1	0	0	-	-	-	-
Cotton	107	19.52720	1	1	1	22	36	750	1200
Cow peas	209	0.05787	1	0	0	25	35	500	1500
Crambe	3	-	1	0	0	15	25	800	1500
Cucumbers	558	0.21500	0	0	0	18	32	1000	1200
Dill	3	-	1	0	0	15	18	800	1200
Eggplants	95	0.01030	1	0	1	20	35	1200	1600
Flaxseed	87	1.26335	1	0	0	16	24	500	800
Foxtail	2	0.00328	1	0	0	16	26	500	700
Garden Cress	3	-	1	0	0	14	21	1000	1800
Gourd	4	-	0	0	0	20	30	400	600
Groundnuts/Peanuts	76	2.46918	1	0	0	22	32	600	1500
Guar	5	0.21162	1	0	0	25	35	500	800
Hairy Indigo	1	-	1	0	0	22	30	900	1700
Kale	36	0.00427	1	0	0	15	22	450	1000
Kenaf	2	-	1	0	0	15	28	600	2000
Kochia	1	-	1	0	0	20	30	1000	1600
Kohlrabi	5	-	1	0	0	12	18	900	1300
Lentils	9	0.38945	1	0	0	15	29	600	1000
Lettuce	393	0.45178	1	0	0	12	21	1100	1400
Lupine	13	-	1	0	0	12	18	400	1000
Maize	3441	156.75150	0	1	1	18	33	600	1200
Milkvetch	2	-	1	0	0	20	35	400	500
Millet	60	0.38682	1	0	0	20	32	500	750
Mustard seed	26	0.05023	1	0	0	10	25	600	1400
Oats	546	18.23003	1	0	0	16	20	600	1000
Okra	33	0.00945	1	0	0	16	32	1000	3000
Other Clovers	50	0.01326	1	0	0	16	27	900	1100
Other Grasses	182	0.15095	1	0	0	18	30	900	2100
Parsley	27	0.00780	0	0	0	11	20	900	1500
Peas (dry, green)	410	0.55075	1	0	0	18	38	600	1500
Peppers	516	0.13733	1	0	1	17	30	600	1250
Pumpkins	56	0.04650	0	0	0	-	-	-	-
Rapeseed	237	0.00971	1	0	0	10	25	1000	1500
Rice, paddy	120	6.45737	1	0	1	20	30	1500	2000
Rutabaga	44	-	1	0	0	15	25	500	1000
Safflower seed	19	0.29491	1	0	0	20	32	600	1000
Salsify	3	-	1	0	0	13	19	600	900
Seashore Paspalum	3	-	0	0	0	-	-	-	-
Sesame Seed	20	-	1	0	0	20	30	500	1000
Soft Chess	1	-	1	0	0	-	-	-	-
Sorghum	1038	25.51052	1	0	0	27	35	500	1000
Sorghum-Almum	1	-	1	0	0	19	26	500	800
Soybeans	234	129.58110	1	1	1	20	33	600	1500
Spelt	65	17.25652	1	0	0	10	17	700	1000
Spinach	186	0.05966	0	0	0	13	20	800	1200
Spinach Mustard	3	-	1	0	0	20	25	900	1400
Squash	319	0.09270	0	1	1	16	28	1000	1600
Sunflower	172	8.63341	1	0	0	17	34	600	1000
Sunn Crotalaria	1	-	1	0	0	20	30	500	1500
Sweetclover	13	0.00700	1	0	0	12	24	450	800
Swiss Chard	4	-	1	0	0	15	25	800	800
Timothy	29	0.08280	1	0	0	15	22	800	1100
Tobacco	151	1.86056	1	0	1	15	30	500	750
Triticale	79	0.01205	1	0	0	-	-	-	-
Turnip Rape	5	0.01469	1	0	0	20	25	900	1400
Wheat	980	141.72350	1	0	0	15	23	750	900

Notes: The leftmost column lists all sexually reproducing crops in the *Variety Name List* (VNL) Column 2 lists the number of varieties released for each crop in the VNL prior to 1985 and column 3 records the area of each crop harvested according to the 1982 Census of Agriculture, for all crops for which area was recorded. Column 4 shows the perfect flower indicator for each crop, and column 5-6 report indicators for whether a GMO variety has been commercialized or developed respectively. Columns 7 and 8 report the minimum and maximum temperature within each crop's optimal temperature range according to the ECOCROP database, and columns 9 and 10 report the same for rainfall.

Table A5: Patent Protection and Novel Plant Varieties: OLS Estimates

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Dependent Variable:	New Varieties (asinh)				New Varieties (log)			
Treatment x $\mathbb{1}^{\text{Post 1985}}$	0.109***	0.204**	0.275**	0.320***	0.214**	0.443**	0.555**	0.590**
	(0.0309)	(0.0831)	(0.109)	(0.104)	(0.0978)	(0.178)	(0.218)	(0.210)
Crop Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
GMO Controls	No	Yes	Yes	Yes	No	Yes	Yes	Yes
Rain Sensitivity Controls	No	No	Yes	Yes	No	No	Yes	Yes
Reproduction Type Controls	No	No	No	Yes	No	No	No	Yes
Observations	2,280	2,280	2,060	2,060	1,133	1,133	1,065	1,065
R-squared	0.815	0.819	0.826	0.829	0.780	0.788	0.794	0.802

Notes The unit of observation is a crop-year. All specifications include crop and year fixed effects. In columns 1-4, the outcome variable is the inverse hyperbolic sine transformation of the number of new varieties and in columns 5-8, it is the log of the number of new varieties. All columns report OLS estimates. The controls are listed at the bottom of each column and are included as a fixed crop-level characteristic interacted with a full set of year fixed effects. Standard errors, double clustered by crop and year, are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

Table A6: Patent Protection and Novel Plant Varieties: Heterogeneity by Crop Lifespan

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent Variable:	New Varieties (count)			New Varieties (asinh)		
Sample:	Non-Perennial Crops	Perennial Crops	Full Sample	Non-Perennial Crops	Perennial Crops	Full Sample
Specification:	Poisson			OLS		
Treatment x $\mathbb{1}^{\text{Post 1985}}$	0.828***	0.162	0.828***	0.241**	-0.00709	0.241**
	(0.262)	(0.167)	(0.269)	(0.0965)	(0.0664)	(0.0983)
Treatment x $\mathbb{1}^{\text{Post 1985}}$ x Perennial			-0.666			-0.249**
			(0.488)			(0.113)
Crop Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Perennial Crop x Year Fixed Effects	No	No	Yes	No	No	Yes
Observations	1,340	720	2,060	1,340	720	2,060
R-squared				0.831	0.725	0.830

Notes: The unit of observation is a crop-year. All specifications include crop and year fixed effects. In columns 1-3, the outcome variable is the number of new varieties and in columns 4-6, it is the inverse hyperbolic sine transformation of the number of new varieties. The regression model and sample are noted at the top of each column. Perennial is an indicator that equals one if a crop is coded as perennial in the ECOCROP database. Standard errors, double clustered by crop and year, are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

Table A7: Patent Protection and Novel Plant Varieties: Controlling Directly for Pre-Trends

	(1)	(2)	(3)	(4)
Dependent Variable:	New Varieties (count)		New Varieties (asinh)	
Specification:	Poisson		OLS	
Treatment x $\mathbb{1}^{\text{Post 1985}}$	0.579**	0.594**	0.330***	0.333**
	(0.291)	(0.288)	(0.113)	(0.121)
Crop Fixed Effects	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes
All Baseline Contrls	Yes	Yes	Yes	Yes
1975, 1980, 1984 Varieties x Year FE	Yes	Yes	Yes	Yes
Total Pre-Period Varieties x Year FE	No	Yes	No	Yes
Observations	2,060	2,060	2,060	2,060
R-squared			0.844	0.846

Notes: The unit of observation is a crop-year. All specifications include crop and year fixed effects. In columns 1-2, the outcome variable is the number of new varieties and in columns 3-4, it is the inverse hyperbolic sine transformation of the number of new varieties. The regression model is noted at the top of each column. Standard errors, double clustered by crop and year, are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

Table A8: Patent Protection and Novel Plant Varieties: CMS Hybridization

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Switching CMS Crops to Control Group				Excluding CMS Crops from Sample			
	Dependent Variable is New Varieties (count)							
Treatment x $\mathbb{1}^{\text{Post 1985}}$	0.655**	0.633**	0.660**	0.648**	0.870***	0.972***	0.992***	1.005***
	(0.270)	(0.254)	(0.258)	(0.262)	(0.265)	(0.321)	(0.321)	(0.327)
Crop Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
GMO Controls	No	Yes	Yes	Yes	No	Yes	Yes	Yes
Rain Sensitivity Controls	No	No	Yes	Yes	No	No	Yes	Yes
Reproduction Type Controls	No	No	No	Yes	No	No	No	Yes
Observations	2,260	2,260	2,060	2,060	2,080	2,080	1,880	1,880

Notes: The unit of observation is a crop-year. All specifications include crop and year fixed effects. In columns 1-4, CMS crops are assigned to the control (hybrid compatible) group and in columns 5-8, CMS crops are excluded from the sample. All colums report Poisson pseudo-maximum likelihood estimates. The controls are listed at the bottom of each column and are included as a fixed crop-level characteristics ineracted with a full set of year fixed effects. Standard errors, double clustered by crop and year, are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

Table A9: Patent Protection and Novel Plant Varieties: Clustering by Genus

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Dependent Variable:	New Varieties (count)				New Varieties (asinh)			
Specification:	Poisson	Poisson	Poisson	Poisson	OLS	OLS	OLS	OLS
Treatment x $\mathbb{1}^{\text{Post 1985}}$	0.795***	0.920***	0.931***	0.919***	0.109***	0.204**	0.275**	0.320***
	(0.242)	(0.326)	(0.327)	(0.327)	(0.0197)	(0.0801)	(0.100)	(0.0965)
Crop Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
GMO Controls	No	Yes	Yes	Yes	No	Yes	Yes	Yes
Rain Sensitivity Controls	No	No	Yes	Yes	No	No	Yes	Yes
Reproduction Type Controls	No	No	No	Yes	No	No	No	Yes
Observations	2,260	2,260	2,060	2,060	2,280	2,280	2,060	2,060
R-squared	-	-	-	-	0.815	0.819	0.826	0.829

Notes: The unit of observation is a crop-year. All specifications include crop and year fixed effects. In columns 1-4, the outcome variable is the number of new varieties and in columns 5-8, it is the inverse hyperbolic sine transformation of the number of new varieties. The regression model is noted at the top of each column. The controls are listed at the bottom of each column and are included as a fixed crop-level characteristic ineracted with a full set of year fixed effects. Standard errors, double clustered by genus and year, are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

Table A10: Patent Protection and Novel Plant Varieties: Genus-Level Estimates

	(1)	(2)
Dependent Variable:	New Varieties (count)	New Varieties (asinh)
Specification:	Poisson	OLS
Treatment x $\mathbb{1}^{\text{Post 1985}}$	1.407***	0.326**
	(0.356)	(0.137)
Genus Fixed Effects	Yes	Yes
Year Fixed Effects	Yes	Yes
All Baseline Controls	Yes	Yes
Observations	1,580	1,580
R-squared		0.836

Notes: The unit of observation is a genus-year. All specifications include genus and year fixed effects, as well as the full set of baseline controls. In column 1, the outcome variable is the number of new varieties and in column 2, it is the inverse hyperbolic sine transformation of the number of new varieties. Standard errors, double clustered by crop genus and year, are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

Table A11: Patent Protection and R&D Investment: Scientists and Funding Concentration

	(1)	(2)	(3)	(4)
Dependent Variable:	Scientist-Years Funded, Public + Private (asinh)		Total Investment per Scientist-Year (asinh)	
Treatment x $\mathbb{1}^{\text{Post 1985}}$	-0.160	0.163	0.160**	0.199**
	(0.267)	(0.351)	(0.0727)	(0.0856)
Crop Fixed Effects	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes
All Baseline Controls	No	Yes	No	Yes
Observations	1,220	760	1,148	707
R-squared	0.932	0.936	0.877	0.868

Notes: The unit of observation is a crop-year. All specifications include crop and year fixed effects. The outcome variable is listed at the top of each column. Baseline controls include indicators for any released GMO variety and GMO variety development, an indicator for asexual propagation, and optimal rainfall cut-off values, all interacted with a full set of year fixed effects. All columns report OLS estimates. Standard errors, double-clustered by crop and year, are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels

Table A12: Spillover Effects on Non-Biological Crop Technologies

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Pre-Harvest and Harvest Technology				Post-Harvest Technology	Multiple Technologies	
Dependent Variable is Patenting Related To:	Harvesting and Mowing	Planting, Sowing, and Fertilizing	Soil Working Machinery and Accessories	Biocides and Plant Preservation	Processing of Harvested Produce	All Technologies	All Technologies (Excluding Chemicals)
Treatment x $\mathbb{1}^{\text{Post 1985}}$	0.379**	0.211	0.282**	-0.0735	-0.0820	-0.0215	0.260*
	(0.160)	(0.208)	(0.131)	(0.0608)	(0.195)	(0.0590)	(0.153)
Crop Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1,360	1,620	1,140	1,880	960	1,920	1,780

Notes: The unit of observation is a crop-year. All specifications include crop and year fixed effects. The outcome variable is listed at the top of each column. All columns report Poisson pseudo maximum likelihood estimates and the outcome variable is the number of patents in the listed technology class. Standard errors, double-clustered by crop and year, are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels

Table A13: Patent Rights and Agricultural Land Value: Additional Controls

	(1)	(2)	(3)	(4)	(5)	(6)
	log Value of Land and Buildings Per Acre					
Exposure x $\mathbb{1}^{\text{Post 1985}}$	0.0968***	0.101***	0.0719**	0.0735**	0.0745**	0.0693**
	(0.0306)	(0.0302)	(0.0307)	(0.0306)	(0.0305)	(0.0323)
County Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Census Round x State Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
1974, 1982 log Land Value x Census Round FE	Yes	Yes	Yes	Yes	Yes	Yes
Latitude and Longitude x Census Round FE	No	Yes	No	No	No	Yes
Pre-period log Farm Land x Census Round FE	No	No	Yes	No	No	Yes
Pre-period log Farm Revenue x Census Round FE	No	No	No	Yes	No	Yes
Pre-period log Average Farm Size x Census Round FE	No	No	No	No	Yes	Yes
Observations	24,183	24,167	24,183	24,167	24,183	24,151
R-squared	0.935	0.935	0.936	0.947	0.936	0.949

Notes: The unit of observation is a county-year and the sample includes all census rounds from 1969-2002. All specifications include county and state-by-year fixed effects and are weighted by log of pre-period farmland. Additional controls included in each specification are noted at the bottom of each column. Standard errors, double clustered by state-year and county are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

Table A14: Patent Rights and Agricultural Land Value: Controlling for Irrigation

	(1)	(2)	(3)	(4)
	log Value of Land and Buildings Per Acre			
Exposure x $\mathbb{1}^{\text{Post 1985}}$	0.146***	0.101***	0.0979***	0.118**
	(0.0317)	(0.0366)	(0.0376)	(0.0499)
County Fixed Effects	Yes	Yes	Yes	Yes
Census Round Fixed Effects	Yes	-	-	-
Census Round x State Fixed Effects	No	Yes	Yes	Yes
1974, 1982 log Land Value x Census Round FE	No	No	Yes	Yes
log Land Area Irrigated x Year Fixed Effects	Yes	Yes	Yes	Yes
Weighting	log Area	log Area	log Area	None
Observations	19,980	19,980	19,894	19,915
R-squared	0.902	0.926	0.936	0.921

Notes: The unit of observation is a county-year and the sample includes all census rounds from 1969-2002. All specifications include county and year fixed effects. In columns 1-3, the specification is weighted by pre-period (log of) county-level farmland and in column 4 it is unweighted. Columns 3-4 include log of agricultural land value (the dependent variable) in 1974 and 1982, both interacted with a full set of census round indicators. All columns include log of land area that was irrigated during the pre-period, interacted with a full set of year fixed effects. Standard errors, double clustered by state-year and county are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

Table A15: Standard Error Adjustments for Spatial and Temporal Correlation

	(1)	(2)	(3)	(4)	(5)	(6)
	Coefficient estimate t-statistic					
	Kernel distance for spatial correlation (km):					State-level cluster
	250	*500*	*1000*	*1500*	*2000*	
Period length for temporal correlation (years):						
5	4.44	5.50	4.58	5.62	4.23	2.78
10	3.81	4.41	3.90	4.48	4.23	-
County Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Census Round x State Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
1974, 1982 log Land Value x Census Round FE	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Coefficient estimate t-statistics from the baseline county-level specification (Table 7, Column 3) with alternative standard error clustering strategies. Columns 1-5 follows Hsiang (2010)'s implementation of Conley (2008) standard errors, for five different values of the kernel cut off distance (measured in km) and two values for the temporal kernel cut off (measured in years). In column 6, standard errors are clustered by state.

Table A16: Patent Rights and Agricultural Land Value: Estimates with Actual Crop Shares

	(1)	(2)	(3)	(4)
	log Value of Land and Buildings Per Acre			
Exposure x $\mathbb{1}^{\text{Post 1985}}$	0.271***	0.358***	0.370***	0.374***
	(0.0825)	(0.0918)	(0.108)	(0.115)
County Fixed Effects	Yes	Yes	Yes	Yes
Census Round Fixed Effects	Yes	-	-	-
Census Round x State Fixed Effects	No	Yes	Yes	Yes
1974, 1982 log Land Value x Census Round FE	No	No	Yes	Yes
Weighting	log Area	log Area	log Area	None
Observations	23,917	23,917	23,786	23,838
R-squared	0.903	0.929	0.940	0.933

Notes: The unit of observation is a county-year and the sample includes all census rounds from 1969-2002. All specifications include county and year fixed effects. Exposure is estimated here from actual crop shares measured in the 1982 Census of Agriculture, rather than predicted shares from the FAO-GAEZ derived model. In columns 1-3, the specification is weighted by pre-period (log of) county-level farmland and in column 4 it is unweighted. Columns 3-4 include log of agricultural land value (the dependent variable) in 1974 and 1982, both interacted with a full set of census round indicators. Standard errors, double clustered by state-year and county are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

Table A17: Patent Rights and Agricultural Land Value: Cytoplasmic Male Sterility

	(1)	(2)	(3)	(4)
	log Value of Land and Buildings Per Acre			
Exposure x $\mathbb{1}^{\text{Post 1985}}$	0.297***	0.373***	0.389***	0.390***
	(0.0815)	(0.0915)	(0.109)	(0.116)
County Fixed Effects	Yes	Yes	Yes	Yes
Census Round Fixed Effects	Yes	-	-	-
Census Round x State Fixed Effects	No	Yes	Yes	Yes
1974, 1982 log Land Value x Census Round FE	No	No	Yes	Yes
Weighting	log Area	log Area	log Area	None
Observations	23,917	23,917	23,786	23,838
R-squared	0.903	0.929	0.940	0.933

Notes: The unit of observation is a county-year and the sample includes all census rounds from 1969-2002. All specifications include county and year fixed effects. Exposure is estimated here from actual crop shares measured in the 1982 Census of Agriculture, rather than predicted shares from the FAO-GAEZ derived model, with CMS crops included in the control (hybrid compatible) group. In columns 1-3, the specification is weighted by pre-period (log of) county-level farmland and in column 4 it is unweighted. Columns 3-4 include log of agricultural land value (the dependent variable) in 1974 and 1982, both interacted with a full set of census round indicators. Standard errors, double clustered by state-year and county are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

Table A18: Patent Rights and Agricultural Land Value: Shorter Sample Period

	(1)	(2)	(3)	(4)
	log Value of Land and Buildings Per Acre			
Exposure x $\mathbb{1}^{\text{Post 1985}}$	0.180***	0.105***	0.108***	0.102**
	(0.0332)	(0.0347)	(0.0375)	(0.0448)
County Fixed Effects	Yes	Yes	Yes	Yes
Census Round Fixed Effects	Yes	-	-	-
Census Round x State Fixed Effects	No	Yes	Yes	Yes
1974, 1982 log Land Value x Census Round FE	No	No	Yes	Yes
Weighting	log Area	log Area	log Area	None
Observations	18,267	18,267	18,136	18,184
R-squared	0.876	0.904	0.927	0.910

Notes: The unit of observation is a county-year and the sample includes all census rounds from 1974-1997. All specifications include county and year fixed effects. Exposure is estimated here from actual crop shares measured in the 1982 Census of Agriculture, rather than predicted shares from the FAO-GAEZ derived model. In columns 1-3, the specification is weighted by pre-period (log of) county-level farmland and in column 4 it is unweighted. Columns 3-4 include log of agricultural land value (the dependent variable) in 1974 and 1982, both interacted with a full set of census round indicators. Standard errors, double clustered by state-year and county are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

Table A19: Patent Rights and Agricultural Land Value: Input Spending

	(1)	(2)	(3)	(4)	(5)
Dependent Variable:	log Spending on Seeds	log Spending on Chem. and Fert.	log Spending on Petrol	log Spending on Feed	log Total Spending
Exposure x $\mathbb{1}^{\text{Post 1985}}$	0.0979**	0.0439	0.0190	0.00925	0.0270
	(0.0393)	(0.0320)	(0.0247)	(0.0577)	(0.0291)
County Fixed Effects	Yes	Yes	Yes	Yes	Yes
Census Round x State Fixed Effects	Yes	Yes	Yes	Yes	Yes
All Additional Controls	Yes	Yes	Yes	Yes	Yes
Observations	23,950	20,835	21,063	20,886	24,220
R-squared	0.911	0.959	0.959	0.867	0.972

Notes: The unit of observation is a county-year. All specifications include county and state-by-year fixed effects, as well as all additional controls from Table 9. These include the dependent variable in 1974 and 1982, both interacted with census round fixed effects, and county-level latitude, longitude, and pre-period (log) farmland, farm revenue, and average farm size, all interacted with a full set of census round fixed effects. The outcome variable in each specification is listed at the top of the column. Standard errors, double clustered by state-year and county, are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

Table A20: Patent Rights and Profit Volatility

	(1)	(2)
	Δ Standard Deviation of Agricultural Profits	
Exposure	-0.0472*	-0.0350**
	(0.0239)	(0.0161)
State Fixed Effects	No	Yes
Observations	3,050	3,050
R-squared	0.005	0.117

Notes: The unit of observation is a county. The dependent variable is the change in the standard deviation of county-level agricultural profits from the pre-treatment period to the post-treatment period, normalized by the mean. State fixed effects are included in column 2. Standard errors, clustered by state, are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

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