Flowers of Invention: Patent Protection and Productivity Growth in US Agriculture[*]

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Abstract

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 physiology 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 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, could come with potentially significant costs to the consumers of technology and distortions to downstream production. Nevertheless, I document that 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 technological progress and increased downstream productivity and profits.

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1 Introduction

Patent protection is often listed among a set of institutions that drive long run development, and the ability to profit from new ideas is at the heart of modern models of economic growth (e.g. Romer, 1990; Acemoglu and Robinson, 2012). Nevertheless, our understanding of the impact of the patent system on technological progress and productivity growth remains limited and the subject of intense debate (e.g. Lerner, 2009; Boldrin and Levine, 2013; Williams, 2017).[1] Moreover, even if the prospect of patent protection spurs innovation, patent rights come with potential costs to the consumers of technology; this trade off between *ex ante* incentives for innovators and *ex post* costs and distortions to downstream production is the key determinant of the economic impact of patent rights (Nordhaus, 1969). Thus, evaluating the economic effects of patent protection—one of the primary policy levers used to encourage technological progress—requires understanding its effect on innovation, on productivity, and on the downstream consumers of technology.

This paper investigates the impact of patent rights on technology development and downstream production by analyzing the introduction of patent rights for plant biotechnology in the United States. While patent protection for most innovations has existed since the U.S.'s founding, protection for crop varieties (e.g. seeds) was not permitted because living organisms and genetic material were not considered patentable subject matter (Kloppenburg, 2005, p. 262). Certain crops, however—those for which it was feasible to produce hybrid varieties—had *de facto* patent protection prior to the introduction of formal patent rights (e.g. Butler and Marion, 1985; Fernandez-Cornejo, 2004). Hybrid varieties are generated by combining the genetic material of multiple "parent" plants and can only be produced accurately by the developer with access to both parents. Offspring of the first generation hybrid do not match the traits of the original variety; thus, hybrids cannot be reproduced by farmers or competing inventors. This feature of hybridization afforded innovators of hybrid varieties with "the same commercial right that an inventor receives from a patented article" (Kloppenburg, 2005, p. 102). Non-hybrid varieties, however, once sold, are easily reproducible, and formal contracting is important to prevent them from being saved or sold.

In one fell swoop, the legal regime changed in 1985 and inventors could for the first time claim patent-level protection for non-hybrid varieties.[2] In *Ex Parte Hibberd*, the US Patent and Trademark Office ruled that seeds, plants, and plant tissue were patentable subject matter under the utility patent statute. The ruling was a shock; in the words of William Lesser (1987):

> [V]irtually overnight, and to the great surprise of many, seeds became patentable.

After the decision, *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). This narrative forms the basis of this pa-

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[1] Williams (2017, p. 443) writes that there is "remarkably little empirical research" on whether stronger patent protection induces R&D investment. Boldrin and Levine (2013, p. 3) 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 and were of limited import to inventors. The history of intellectual property protection for varieties is discussed in Section 2.1 and the relative strength of different forms of intellectual property investigated empirically in Section 4.3.

per's empirical design: a difference-in-differences framework that compares crops that received formal patent protection in 1985 with a control group that had "built-in" protection prior to the introduction of patent rights (Gupta, 1998).

In order to analyze the consequences of the introduction of patent protection, I first determine the set of crops that are "hybrid-compatible" and therefore had *de facto* protection prior to 1985. The key determinant of whether hybrid varieties can be generated for a given crop is its flower structure (Wright, 1980; Butler and Marion, 1985; Fajardo-Vizcayno et al., 2014; Bradford, 2017). If a crop has "perfect flowers"—flowers that contain both the male and female reproductive parts—generating a hybrid is technologically infeasible or prohibitively costly. When the male and female flowers are separate and on different parts of the plant, generating hybrid varieties is more straightforward (Wright, 1980; Whitford et al., 2013).[3] I ascertain the flower structure of all crops grown in the U.S. in order to determine their "hybrid compatibility" and hence whether they are part of the treatment or control group. Using this fixed characteristic of flower structure to measure hybrid-compatibility furthermore circumvents the empirical issue that the actual development of hybrid varieties is potentially endogenous to, for example, research effort. Throughout, I refer to "perfect flower" or "hybrid incompatible" crops as treatment crops, and "imperfect flower" or "hybrid compatible" as control crops.

I empirically validate each component of this proposed identification strategy. First, I document the sharp and substantial rise of biotechnology patenting following *Ex Parte Hibberd*. Second, I show that in the biotechnology patent data that there is a strong, positive correlation between being related to a *crop with imperfect flowers* and being a *hybrid variety*. Consistent with the agronomic literature, flower structure is a strong proxy for the ease and prevalence of hybrid development. Third, using a stock market event study design around patent issue dates for all plant biotechnology patents issued to publicly traded firms, I show that being issued a patent leads to positive abnormal returns; however, the effect is substantially lower for hybrid varieties. This result indicates that formal patent protection is indeed substantially more valuable to innovating firms for non-hybrid technologies compared to hybrid technologies, which have built-in protection with or without a patent grant. Finally, I show that treatment and control crops are balanced across a range of other characteristics that determine the location, structure, and demands of variety development. Together, these results indicate that crops with imperfect flowers are an appropriate control group for studying the strong increase in effective intellectual property protection for crops with perfect flowers.

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 measure of innovation is patenting activity; however, since this paper investigates the impact of the introduction of patent rights, patents are not a useful dependent variable. Therefore, a key empirical challenge was the construction of other measures of innovation that are observable both before and after the introduction of patent rights. I overcome this challenge using the United States Department of Agriculture's (USDA) *Variety Name List*.

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[3] Corn is an example of a crop without perfect flowers; nearly all corn production relies on hybrid varieties and corn hybrids have existed since the early 20th century. Other examples are buckwheat, spinach, squashes, and cucumbers. Wheat, on the other hand, has perfect flowers and hybrid varieties are not used. Flower structure is not the only determinant of hybrid development, and Section 2.3 describes hybrid development in greater depth while Section 4.2 documents empirically that flower structure is a strong predictor of hybrid technology development across crops.

The *List*, which I obtained via a Freedom of Information Act request, is designed to be a comprehensive list of all crop varieties released in each year; it is maintained in order to prevent fraud in the seed market.[4] 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 *Variety Name List* with three additional crop-level measures of research investment and its impacts. First, I compile data on research investment by crop from the USDA Current Research Information System (CRIS).[5] The CRIS data contain both public research investment and all private research investment directed toward research projects that received any public funding; thus, while the measure of private investment is incomplete, I am able to (imperfectly) compare the response of private and public investment to the availability of patent protection. Second, I compile data on crop-specific patent grants in non-biological technologies, which were patentable during the entire sample period. I assign patents within relevant patent classes to individual crops if the crop name appears in the patent title, abstract, or keywords. With these data, I estimate spillover effects of patent rights for varieties on innovation in non-biological agricultural technologies. Third, I compile measures of crop yields in order to estimate the impact of patent rights on one component of downstream 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 were on similar trends prior to 1985, treatment crops experienced a dramatic, 119% relative increase in variety development during the ten years following the introduction of patent rights, which corresponds to about 11 additional varieties per year for the mean crop in the sample. 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 patent protection is most profitable to the inventor. Consistent with the historical narrative, the positive effect of patent rights on treatment compared to control crops was driven by the fact that prior to 1985, hybrid compatible crops had a major advantage in variety development which was *brought to zero* in the ten years after *Ex Parte Hibberd*, as variety development for hybrid-incompatible crops increased substantially. The introduction of patent rights thus induced a major shift in technology development.

The prospect of patent protection substantially increased private research investment and did not have a significant effect on public research investment. Thus, the shift in technology development toward newly-protectable inventions seems to have been driven by private investment, consistent with private sector firms being more responsive to profit and patent incentives.

The impact of patent rights for a particular type of technology could be amplified or reduced by spillover effects on innovation in technologies for which the level of protection did not change; in the present context, for example, non-biological agricultural technology was fully patentable throughout the sample period but still might have been affected by the change in incentives for developing crop varieties. Spillover effects could be positive if, for example, improved varieties were complementary to other inputs in production (e.g. a new crop variety makes it possible to improve harvester technology)

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[4] In the words of the USDA, the *List* is compiled ”from sources such as variety release notices, official journals, seed catalogs, and seed trade publications, as well as names cleared for use by seed companies.”

[5] To calculate research investment allocated to each crop in each year, I aggregate the research project-level data reported by CRIS to the crop-by-year level using the commodity (i.e. crop) information associated with each project.

or negative, if improved varieties became substitutes for other inputs that performed related functions (e.g. insect resistant seeds may substitute for insecticide). I find that introduction of patent protection for biotechnology led to an increase in patent grants for some non-biological technologies; the effect is concentrated in mechanical technologies that, anecdotally, had complementarities in production with improved varieties.

While the extension of patent protection increased technology development, the marginal innovation induced by the patent law change may or may not have translated into changes in crop yield. This could be for purely technological reasons or because the ability to enforce intellectual property led to business stealing inventions that did not truly expand the technological frontier. I find, however, that the introduction of patent protection had a discernible positive effect on crop-level agricultural yields measured from nationally representative production data; treatment crops experienced an 11% relative increase in crop yields during the ten years following the introduction of patent rights.

This first set of findings demonstrates that patent protection for plant varieties had a positive impact on innovation. However, the fact that the prospect of patent protection encouraged technology development—which itself could not have been taken for granted—is a *necessary but insufficient* condition for it to have benefitted the users and consumers of agricultural biotechnology (i.e. farmers). First, patent protection allows for monopoly pricing, which may have distorted farmers' 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). Critics of patent protection often argue not that patent rights fail to encourage innovation, but rather that their distortionary effects and costs to the consumers of technology outweigh the benefits of induced innovation.[6] Second, the use of improved technologies could have led to input and land use adjustment, as well as general equilibrium price effects, that together could dampen or amplify the impact of patent protection on downstream profits.[7]

Determining the impact of patent rights on downstream growth requires an analysis that captures its impact on both technological progress *and* consumer costs and distortions. To do this, I focus on fixed geographic units—U.S. counties—and estimate the impact of county-level *exposure* to the change in patent law on agricultural land values. For each U.S. county, using models of maximum potential crop yield from the Food and Agriculture Organization's (FAO) Global Agro-Ecological Zones (GAEZ) database, I predict the optimal crop mix and estimate the share of county land on which the model predicts treatment crops are grown.[8] If the ecological and geographic features of a county make it more suitable for control crops, then the county was relatively less exposed to the change in patent law. If, on the other hand, a county is more suitable for treatment crops, the county was relatively more exposed to the change in patent law. 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 patent law

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[6] For example, see Keteyian (2008). There are myriad news stories of biotechnology companies suing farmers for saving patented seeds; farmers alleged they were unable to compete on the market with old cultivars and unable to afford yearly repurchase of modern seeds. Monsanto, however, argues that its "continuous innovative cycle" is "fueled in part by patents" (see here: `https://monsanto.com/company/media/statements/food-inc-documentary/`).

[7] For example, national productivity growth might have precipitated a decline in producer prices, thus eroding the impact of more productive varieties on farm profits.

[8] See Costinot and Donaldson (2012), who introduce a related methodology. I validate the GAEZ-derived exposure estimates with data on the distribution of production across crops from the 1982 Census of Agriculture. All results are also very similar using crop shares measured from the Census rather than crop shares estimated from the GAEZ-derived model.

change on agricultural land values, capturing the net present value of agricultural profits.

The main county-level result is that exposure to the introduction of patent protection had a large positive effect on the value of 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. According to the most conservative estimates, the introduction of patent protection increased the total value of US agricultural land in 2002 by 7.5%, or roughly $80 billion ($117 billion in 2020 USD).[9] Thus, patent rights were capitalized into a substantially higher value of agricultural land, consistent with the explosion in biotechnology research being a major driving force behind recent decades' productivity growth. (Kloppenburg, 2005).

What mechanisms drove the positive effect on agricultural land values? As might be predicted by a Nordhaus (1969)-style model, more-exposed counties increased input spending on crop varieties.[10] However, the share of land area devoted to crop production and agricultural profits both increased in these counties, while variability in agricultural profits across years declined, suggesting that new technology increased both productivity and resilience in the face of shocks. 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 findings suggest that new technology disproportionately benefitted large farms, which grew to encompass an increasing share of agricultural revenue during the sample period.[11]

This paper's first set of findings contributes to a better understanding of the impact of patent incentives on technology development. Intellectual property protection is central to theories of economic growth and development; yet, because patent rights and enforcement are endogenously determined, estimates of the impact of patent protection on technological progress are limited (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 private cancer research is directed away from long-term projects and argue this distortion is driven by shorter expected patent length. Other studies investigate cross-country changes in patent law and find little evidence of an effect (Lerner, 2002; Qian, 2007), or turn to historical periods to investigate the impact of patent protection on the direction of innovation (Moser, 2005, 2012, 2013, 2016).[12] Moreover, signing the overall relationship between patent rights and innovation is further complicated by evidence that awarding patent protection hinders *follow-on* research (e.g. Murray and Stern, 2007; Williams, 2013).[13]

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[9] For reference, the total value of agricultural output in the US in 2002 was $230.6 billion.

[10] This finding is consistent with producers paying higher prices for patented inputs, but could also be driven by a larger quantity of seed purchases. The Census of Agriculture does not collect data on input quantities; nevertheless, a range of evidence discussed in Section 6.3 suggests that finding is driven by higher prices.

[11] This finding is consistent with the hypothesis that new technology had complementarities with scale, and hence disproportionately benefitted large farms (Willingham and Green, 2019). Small farms were less likely to adopt improved varieties, which often were complementary with scale and non-variety input investment; thus, small farmers of treatment crops may have benefitted less from the productivity potential of new varieties while facing lower output prices as aggregate productivity increased. See the 2005 report by the *Center for Food Safety*, "Monsanto vs. U.S. Farmers," as well as Liptak (2003). Section C.1 investigates raw trends in profits and concentration in the US agricultural sector over the sample period in greater depth.

[12] Also relevant is a growing body of work on copyright protection (Biasi and Moser, 2016; Giorcelli and Moser, 2020)

[13] See also Murray et al. (2016), which implies potentially large costs of intellectual property restrictions in biomedical research. Sampat and Williams (2019), however, find no evidence that patent protection reduces follow on research in an analysis of patents on human genes. The present study is also linked to a related literature that suggests that receiving patent

The second part of this paper's analysis, which documents the relationship between patent rights and downstream profits, builds on theoretical work arguing that the value of patent policy is determined by the extent of *both* induced innovation and *ex post* losses in the form of production distortions and higher costs (e.g. Nordhaus, 1969; Budish et al., 2016). The county-level analysis, moving beyond a sole focus on incentives for innovation, captures both sides of this trade-off.

This paper also deepens our understanding of the growth of agricultural biotechnology, and the role of patent rights in recent decades' explosion of technological progress and productivity growth.[14] Intellectual property protection for plant varieties in the U.S. and other countries has been proposed as an explanation for dramatic productivity growth during the second half of the 20th century, both in the US and around the world (e.g. Evenson and Gollin, 2003, on variety protection and the "Green Revolution"). Since 1960, 74 countries have adopted intellectual property protection for plant varieties; these countries are displayed on the map in Figure A1. Several more are debating whether to introduce it; unsurprisingly, the extension of intellectual property protection is often politically contentious and controversial (e.g. Straub, 2005). The introduction of patent protection in the US has been blamed for declining farm profits, particularly for small farmers, as well as concentration of landholdings and agricultural research investment (e.g. Howard, 2015; Bonny, 2017).[15] This paper directly estimates the impact of patent protection for biotechnology on US agricultural productivity and documents that they explain part of the late-20th century growth of US agricultural biotechnology.

Finally, this paper builds on broad literature investigating endogenous technological progress and the extent to which research investment is re-directed in response to profit opportunities. There is a long and storied history of asking how innovation responds to incentives in the agricultural sector (e.g. Griliches, 1957; Hayami and Ruttan, 1971; Ruttan and Hayami, 1984; Olmstead and Rhode, 1993, 2008). I find that policy induced changes in profit opportunities had a large impact on the direction of technology development and translated into productivity growth; private research investment and novel variety development were narrowly targeted to the crops for which profit opportunities increased the most. This study thus also builds on the relatively small set of empirical studies that investigate the impact of changing profit incentives on the direction of technological change (e.g. Popp, 2002; Finkelstein, 2004; Acemoglu and Linn, 2004; Hanlon, 2015).

The paper is organized as follows. The next section (Section 2) provides information on the history of patent protection for plant varieties and a discussion of the features of plant breeding and biology required for the empirical analysis. Section 3 discusses the data and Section 4 empirically investigates the paper's main identifying assumptions. Section 5 presents the empirical strategy and results for the crop-level analysis while Section 6 does the same for the county-level analysis. Section 7 concludes.

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protection is beneficial to firms and technology developers (e.g. Gans et al., 2008; Farre-Mensa et al., 2016; Gaule, 2018).

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

[15] Other work suggests that in more recent years, the rise of venture capital funding and "agtech" start-ups has pushed the industry away from concentration (Graff et al., 2020). The relationship between patent law and research funding structure is beyond the scope of this paper but a potentially exciting area for future work.

2 Background

2.1 Intellectual Property Protection for Plant Varieties

While most inventions have been considered patentable subject matter since the U.S.'s founding, this was not the case for inventions that are classified as living organisms. Agricultural inventions like new fertilizers, tractors, harvesters, etc. have been patentable since the 18th century; however, utility patent protection for new plant varieties—for example, seeds and runners—was not available until the legal regime changed in 1985 with the USPTO's *Ex Parte Hibberd* decision. This meant that, prior to 1985, farmers were permitted to save seeds from one season to the next, effectively "re-making" the invention and substantially limiting the extent to which inventors could profit from technology development and sale (Kloppenburg, 2005, p. 265-6)

Before *Ex Parte Hibberd*, only certain weaker forms of intellectual property existed for seeds. The Plant Patent Act of 1930 introduced some limited protections for vegetatively propagated plant varieties (i.e. plants that can reproduce asexually).[16] The Plant Variety Protection Act (PVPA) was passed by the US Congress in 1970, and introduced seed certificates that afforded breeders with 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.[17] Consistent with the limited extent of protection, neither the 1930 nor the 1970 law was the subject of substantial infringement litigation (Kershen, 2003). Still in 1982, most non-hybrid varieties were saved from one season to the next, preventing innovators from profiting from selling their inventions; for example, over 90% of planted wheat was saved from the previous year (McMullen, 1987, pp. 86-7).

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 [...] His discovery is not nature's handiwork, but his own." However, the USPTO was still not open to patent protection for plants or plant parts; the few applicants seeking protection for seeds or plant parts were soundly rejected (Kloppenburg, 2005, p. 263). In 1985, a patent examiner rejected a patent application for a maize variety; however, the breeder argued that the variety was patentable subject matter following the *Chakrabarty* decision. The developer appealed the decision, and the US Patent and Trademark Office (USPTO) Board of Appeals and Interferences reversed the rejection in *Ex Parte Hibberd*.

Following the decision, the USPTO released a notice stating that "the Patent and Trademark Office is now examining applications including claims to plant life–e.g., plants per se, seeds, plant parts" (Hodgins, 1987, p. 88). The change in intellectual property regime was a shock and major break from long-standing precedent (Van Brunt, 1985), and was almost immediately taken advantage of by breeders and breeding companies (Lesser, 1987). In 1986, there was a surge of patent applications

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[16] 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.

[17] Section 4.3 empirically investigates the value to innovating firms of PVP certificates compared to patents.

due to the *Ex Parte Hibberd* ruling, followed by a surge in patent grants in the years that followed (see 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).[18] Section A.2 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, hybrid plant varieties have *de facto* intellectual property protection (e.g. Butler and Marion, 1985; Fernandez-Cornejo, 2004; Fajardo-Vizcayno et al., 2014; Bradford, 2017). In the words of Fernandez-Cornejo (2004), hybrid seeds "provided the private sector a natural method of protecting plant breeding investments" since the saved offspring of hybrid seeds "produc[e] substantially lower yields, encouraging farmers to repurchase seeds every year."[19] The relationship between this feature of hybrids and intellectual property protection is explicit. Fernandez-Cornejo et al. (1999) juxtapose protection for non-hybrid and hybrid varieties: "[A]ccording to the Patent Act of 1790, seeds were considered 'products of nature' and could not be patented. Hybrid seed technology, however, required farmers to repurchase seeds each year," allowing breeders and inventors to circumvent the absence of formal protection (p. 19).

As a result, according to Kloppenburg (2005, p. 102), hybrid varieties have "the same commercial right that an inventor receives from a patented article." Gupta (1998, p. 1320) refers to this as "built-in" patent protection that is available for some crops but not others. He notes that in self-pollinated crops "like wheat, rice, barley, beans, etc [...] the commercially grown cultivars are actually 'pure lines' so that the yield does not decline and harvested seeds can be used for sowing the next crop." Prior to the introduction of formal intellectual property, breeders of certain crops could reap the rewards of their innovation by making use of hybrids' "built-in" patent protection. Developers of other crops for which hybrid varieties were not feasible to produce, however, had little if any recourse.

Therefore, when formal patent protection was introduced, it affected non-hybrid varieties and crops for which hybrid varieties were scarce or difficult to generate (Lesser, 1987). Agricultural firms and researchers are keenly aware of this distinction. Facing criticism for enforcing patent protection by suing farmers who saved its patented seeds under the new regime, Monsanto Company responded that farmers had not been saving hybrid seeds for decades and that patent protection was merely an extension of the protection that hybrid varieties had always received.

Why do hybrid varieties have *de facto* protection? Hybrid varieties are produced by crossing two parent plants to produce the first generation hybrid (F1). Seeds produced by the F1 hybrid—those that could be collected 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

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[18] Kloppenburg (2005, p. 266) discusses the several enforcement strategies available to seed companies after *Ex Parte Hibberd*, including monitoring of farmers, collecting information from dealer networks or neighbors, and selective prosecutions to demonstrate the potential cost of being found in 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."

[19] This is still relevant for farming today. According to the University of Illinois Extension program, for example, hybrid seeds are "sterile or [do] not reproduce true to the parent plant" (Bhalsod, 2021). As a result, hybrids are "bad for seed saving and you will need to buy new seeds every year."

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, seed marketing firms, or researchers to reproduce or sell the F1 variety. When farmers use non-hybrid varieties, on the other hand, they can save seeds for many seasons without sacrificing the beneficial characteristics of the purchased seed and need not re-purchase the seed from the developer. Moreover, other breeders can use non-hybrid varieties directly in the breeding process and build on the varieties' favorable characteristics.

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; indeed, the F2 hybrid can even have worse performance than either of the original parent varieties (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 quite stylized, this example illustrates that the probability that a farmer reproduces the desired characteristics of the hybrid variety are vanishingly small. Non-hybrid varieties, however, can be reproduced exactly generation after generation and do not need to be re-purchased from the developer.

Moreover, even if by random chance the second generation plant *were* comparably productive to the original hybrid, the farmer would have no way to re-produce or breed it. As the stylized example illustrates, hybrids can only be uniformly produced because the parent strains are highly inbred (that is, they are homozygous at all alleles); when two highly inbred strains are hybridized, the offspring will be uniform and identical. In the case of the example, the F1 hybrid will always carry Aa. However, subsequent breeding of non-inbred strains which are heterozygous at many alleles will not generate uniform, predictable, or necessarily productive offspring (McMullen, 1987).[20]

2.3 Hybrids and Flower Structure

The key characteristic that determined whether or not a hybrid variety could be developed is the crop's flower structure, and in particular, whether the crop has "perfect" or "imperfect" flowers (e.g.

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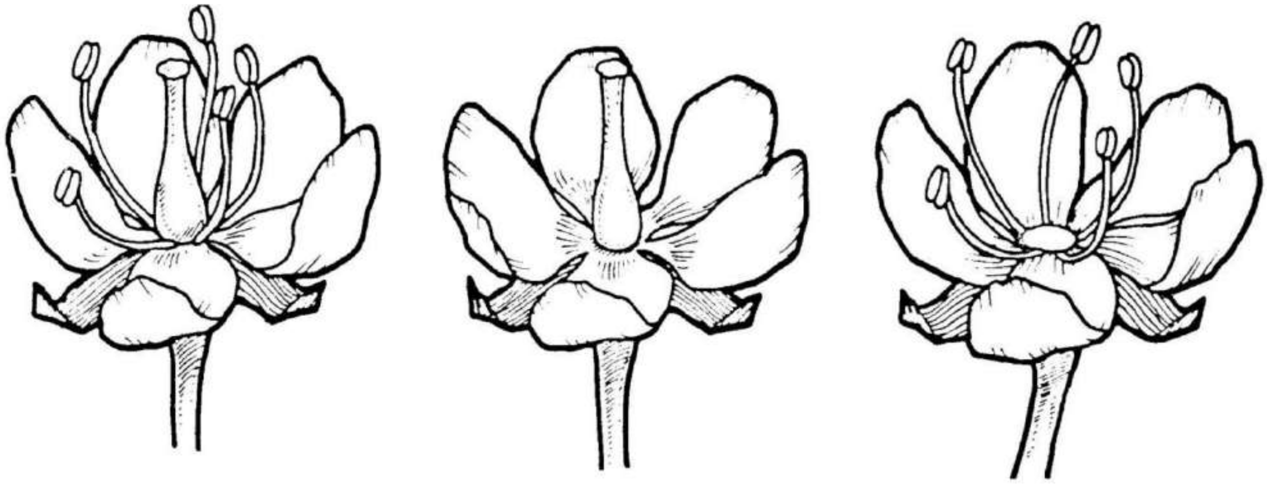
[20] Early seed companies often marketed F2 hybrids, which were the offspring of two specifically chosen F1 hybrid varieties, each of which was generated from two highly in-bred parents. The reason that F2 hybrids were commercialized was not because they were as productive as their F1 counterparts, but because it was easier to breed them at scale. Since the F2 hybrid is the cross between two hybrid varieties, the parent plants of the F2 are themselves productive hybrids and can be produced in large quantities; the parent plants of the F1 hybrids, which are in-bred, are more challenging to produce at scale. Thus, while F2 hybrids have been marketed, they are the offspring of very specifically targeted and chosen F1 hybrids parents, and are themselves not as productive as the F1 generation (McMullen, 1987, p. 47).



(a) Perfect Flower (b) Imperfect Flower (Pistillate) (c) Imperfect Flower (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.

Wright, 1980; Butler and Marion, 1985; Fajardo-Vizcayno et al., 2014; Bradford, 2017).[21] The distinction between perfect and imperfect flowers is displayed in the image in Figure 1. 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. Crops with 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.

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; Bradford, 2017). Separating and re-combining the male and female reproductive material (e.g. preventing self-pollination, separately isolating the genetic material, etc.) is often technologically infeasible or extremely costly in crops with perfect flowers. Wheat is a crop with perfect flowers, and the penetration of hybrid varieties is very limited; as a result, 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. This is strikingly different from the case of corn, a staple crop with *imperfect* flowers; just 5% of land area devoted to corn was planted with saved seeds and breeders of hybrid corn varieties could profit from selling their invention to farmers each season (McMullen, 1987, pp. 86-7).[22] Other examples of crops with perfect flowers are barley, beans, carrots, and turnips, while examples of crops with imperfect flowers include corn, squashes, cucumber, and spinach.

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[21] See also McMullen (1987, pp. 43-45) on hybrid development in the 1980s and its largely exclusive focus on crops with imperfect flowers (referred to as "monoecious" crops in the text).

[22] The shares for cotton and soybeans, which have perfect flowers, were somewhat smaller than wheat, at 50% and 45% respectively; however, the land planted with saved seed corresponded to the overwhelming majority of market value, at 97.6% for cotton and 82.8% for soybeans. 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*.

Flower structure is not the only determinant of hybrid development. Hybrid varieties have been developed for some crops with perfect flowers, most prominently using a technique referred to as cytoplasmic male sterility (CMS), which prevents open pollination (Havey, 2004). However, hybrids for crops with perfect flowers were mostly developed recently and have far more limited penetration in production.[23] Section 4.2 documents empirically that this simple feature of flower structure—having imperfect flowers—is a strong predictor of hybrid variety development. Moreover, since flower structure is fixed, it is not biased by endogenous investment in crop-specific technology and efforts to develop advanced breeding techniques; this makes it an ideal pre-determined measure of the potential impact of patent rights. Consistent with this, I show in Section 4.4 that perfect flower structure is not correlated with a broad range of crop-specific characteristics that might otherwise affect breeding. Finally, I document below that the main results are robust to categorizing crops for which CMS systems have been developed as control-group crops, or excluding these perfect-flower crops for which hybrids have been developed from the analysis entirely.

Throughout the paper when I refer to a crop as "hybrid compatible" or in the "control group," this means that the crop has imperfect flowers. When I refer to a crop as "hybrid incompatible" or in the "treatment group," this means that the crop has perfect flowers.[24]

3 Data

3.1 Crop Treatment Status and Other Biological Characteristics

In order to identify which crops were affected by the introduction of patent protection, I constructed a data set of the structure and reproductive process of all crops produced in the United States. The main independent variable is an indicator variable that equals one if a crop is not hybrid compatible. To measure this, for all crops grown in the United States I determined whether or not the plant has perfect flowers. This is used throughout the empirical analysis as a reduced form measure of hybrid compatibility. In total, this information was compiled from 339 separate sources. This information is used to construct the key independent variables in the analysis.[25]

In order to investigate whether crop-level treatment is correlated with other crop-level characteristics that affect crop breeding, I compile crop-level covariates from the ECOCROP Database, which contains information about plant-specific characteristics and growing conditions for over 2,500 species. The database, discussed at greater length in Moscona and Sastry (2021a), was compiled from a sweeping set of agronomist and expert surveys conducted during the early 1990s and contains a range of

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[23] The first hybrid soybean, for example, was bred in 2003 by a team of Chinese scientists who claimed that the key challenge that had faced global efforts to develop a soybean hybrid was the "difficulty involved in changing the plant's trait of self-pollination" (See the news release here: `http://en.people.cn/200301/17/eng20030117_110279.shtml`). The first hybrid variety for barley, despite being a globally important crop, did not occur until it was released, following years of research investment, by Syngenta in 2003, which is after this paper's main sample period (See here: `https://www.cabi.org/agbiotechnet/news/2886`). Even still, the penetration of hybrid varieties for barley remains limited.

[24] Because vegetatively (i.e. asexually) reproducing crops can also be re-produced by the farmer, I also categorize all crops that can reproduce vegetatively in the treatment group, but show throughout that the results are robust to controlling for vegetative reproduction.

[25] Table B1 reports treatment status of all seed crops in the *Variety Name List*, discussed below, along with a series of crop-level characteristics.

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.

3.2 Crop-Level Innovation

I combine multiple sources to compile a consistent data set of crop-specific measures of technology development, research investment, and productivity. First, to estimate the number of new varieties developed in each year for each crop, I rely on the USDA *Variety Name List*. The *Variety Name List*, obtained through a Freedom of Information Act (FOIA) request for this paper, is a list of all released crop varieties known to the USDA. The USDA collects data on all released varieties in order to prevent fraud in the seed market; while the list likely has omissions, it is designed to be as comprehensive as possible and uses a broad range of sources in order to identify crop varieties.[26] Breeders have an incentive to report new varieties to the USDA for inclusion in the list because farmers frequently check the *List* to make sure that varieties they purchase were cleared. The *List* is structured as a series of PDF files with separate columns for the crop name (e.g. alfalfa, sorghum), variety name (e.g. 13R Supreme, Robinson H-400 B), and the year when the variety was released.[27] I digitized the full list and use it to compute the number of varieties released for each crop in each year. This data set is essential, because it makes it possible to track biotechnology development for each crop, both before and after the introduction of patent rights.

Second, to measure crop-specific research investment, I rely on data on project-level R&D spending from the USDA Current Research Information System (CRIS).[28] CRIS began reporting research investment data in 1970, at the request of the US Secretary of Agriculture, in order to better document research funding in agriculture and how it changes over time. Crucially, the CRIS data also report the commodity or commodities that are the focus of each research project. For each project focusing on plants or crops (as opposed to livestock, machinery, etc.), funding is broken down by crop; if the project covers multiple crops, then the share of funding devoted to each crop is also reported. I aggregate the project level data to compute a crop-level measure of R&D investment for each crop over time.[29] CRIS compiles project-level data on R&D expenditure for all research projects that received any public support; for all projects that received funding from any public source, the CRIS data also asks researchers to report private funding received for the project.[30] Therefore, for the set of projects in the data, it is possible to investigate the impact of patent rights on both private and public investment. A 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, and I am not aware of any other data set measuring crop-level private research funding.

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[26] According to the USDA, it is compiled "from sources such as variety release notices, official journals, seed catalogs, and seed trade publications, as well as names cleared for use by seed companies."

[27] While sometimes the day and month are listed, in most cases during the sample period, only the year is included. While in later years, the *List* often reports the company or breeder name for each variety, unfortunately this did not begin until after the period under investigation. For recent years, the names of varieties in the *List* are publicly available; however, the release years and all the data for the earlier part of the sample period required the FOIA request.

[28] For a description of the raw data, see here: `https://cris.nifa.usda.gov/aboutus.html`

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

[30] Sources of public investment include the USDA and its research agencies, the National Institute of Food and Agriculture (NIFA), state agricultural experiment stations, land grant universities, and other state and local institutions

Third, to measure crop-level innovation for all technologies other than crop varieties (i.e. non-biological technologies), as well as investigate trends in biotechnology patenting itself, I use patent data. Using the patent database *PatSnap*, I computed the number of patents in Cooperative Patent Classification (CPC) classes that correspond to agriculture, excluding husbandry.[31] To match patents to crops, I searched for the name of each crop in the *Variety Name List* in all patent titles, abstracts, and keyword lists. Thus, for each crop, CPC class, and year in the sample period, I estimate the number of patented technologies.

Finally, I measure the average yield of each crop in the US using data from the Food and Agriculture Organization (FAO) and the USDA. These crop-level production data sets are both standard.

3.3 County-Level Data

I construct a county-level panel from the 1969-2002 rounds of the US Census of Agriculture (Haines, 2005).[32] The Census of Agriculture contains a range of information about the US agricultural sector and agricultural production, 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.

In order to construct the county-level treatment variable, I used data on the predicted maximum potential yield for all crops available from the Food and Agriculture Organization (FAO) Global Agro-Ecological Zones (GAEZ) database. These data are reported by the FAO as a (roughly) 9.25km × 9.25km raster grid, with each grid cell containing the maximum attainable yield for a given crop in that grid cell based on ecological and topographical characteristics of the cell and characteristics of the crop in question.[33] The potential yield model is constructed using parameters derived from controlled experiments, and not from data on actual agricultural inputs and output (Costinot et al., 2016, p. 18). In Section 6.1, I use these crop-specific maximum potential yield data in concert with the crop-level treatment variable to construct a *county-level* measure of exposure to the introduction of patent rights.

4 Descriptive Evidence and Validation of the Empirical Strategy

This section empirically investigates the historical narrative and features of innovation in plant biotechnology that underpin the paper's empirical framework. I document that the rise of biotechnology patenting after 1985, and differences across crops in the characteristics of patent grants, are both consistent with the time-series and cross-crop variation described in Section 2.

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[31] This includes CPC classes A01B, A01C, A01D, A01F, A01G, A01H, and A01N, i.e. all CPC classes that relate to non-livestock agriculture.

[32] The census years included in the analysis are 1969, 1974, 1978, 1982, 1987, 1992, 1997, and 2002.

[33] The FAO GAEZ maximum potential yield data "...reflect yield potentials with regard to temperature, radiation and moisture regimes prevailing in the respective grid-cells. The model requires the following crop characteristics: Length of growth cycle (days from emergence to full maturity); length of yield formation period; maximum rate of photosynthesis at prevailing temperatures, leaf area index at maximum growth rate; harvest index; crop adaptability group; sensitivity of crop growth cycle length to heat provision; development stage specific crop water requirements, and coefficients of crop yield response to water stress" (FAO GAEZ)

(a) All Angiosperm Patents (CPC A01H.5 & A01H.6)

(b) Non-Biological Patents (A01B & C & D & F & N)

Figure 2: **Patents: Time Trend.** Figure 2a displays the count of patent applications and patents issued in CPC classes A01H.5 and A01H.6 (novel 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.

4.1 Biotechnology patenting burgeoned after *Ex Parte Hibberd*

Figure 2a displays the time series trends in Cooperative Patent Classification (CPC) classes most closely linked to new plant varieties (see Section A.3 for a more detailed description).[34,35] There is no evidence of patents being issued prior to 1985; patent applications increase in the year following *Ex Parte Hibberd* and the surge in patent issuing occurs shortly thereafter, following an appropriate lag. Figure 2b documents the time series trend in patenting for CPC classes related to non-biological agricultural technologies; Figure A2 shows the same for each non-biological patent class individually. No marked change after 1985 is apparent and the trend is relatively flat throughout the sample period, suggesting the pattern in Figure 2a is not related to any aggregate trend in technological progress.

The sharp change in patent protection policy was mirrored by a marked trend break in crop-specific research investment. Figure 3a displays the trend in research investment relative to 1985, averaged across crops in the USDA CRIS data. The dotted red line extends the linear trend estimated from the pre-period (1975-1984) time series. While private research investment increased throughout the

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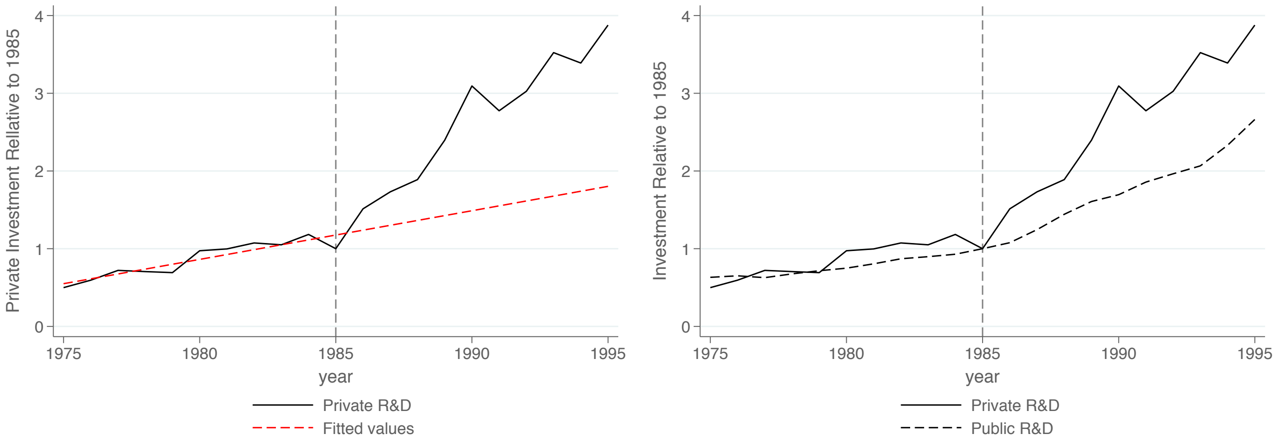
[34] Some other work attempts to identify all patents related to plant biotechnology using a combination of restrictions based on patent class and the identity of the applicant, after combing through patent texts. These analyses also do not identify any utility patents issued for plant biotechnology in the US until 1985 (Graff et al., 2003). An alternative strategy pursued by Kloppenburg (2005) is more subjective, and relies on a range of sources and readings of individual patent grants; this process identified 12 relevant patent grants issued from 1980-1984, all of which were related to *process* innovations and none of which protected an individual variety or plant part (p. 264). *Ex Parte Hibberd* represented a clean break from pre-existing policy.

[35] While 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, which is reassuring because it confirms that the pattern documented in Figure 2a is not driven by any detail of patent classification or the failure to re-classify patents related to plants and plant parts into the correct CPC class after the fact. Figure A3b shows a similar pattern on a sample of patents categorized only as angiosperm *seeds* (CPC class A01H.5.10). This definition of affected patents is certainly too restrictive, since (as noted in the USPTO CPC scheme handbook), many seed patents have been re-classified under a series of different sub-classes. However, the pattern of virtually zero patents prior to 1985 and a large surge thereafter is very similar.



(a) Private Investment vs. Pre-Trend

(b) Private vs. Public Investment

Figure 3: **Research Investment: Time Trend.** Figure 3a displays the trend in private research investment relative to 1985, averaged across crops in the sample; the dotted red line is the linear trend estimated from 1975-1984. Figure 3b displays the trend in both private and public research investment relative to 1985, averaged across crops in the sample.

sample period, there was a marked trend break after 1985. Figure 3b displays the same trend in private research investment alongside the trend in public research investment. There is a weaker uptick in public investment after 1985, consistent with patent incentives disproportionately affecting the private sector. Together, these findings highlight that the 1985 decision precipitated a marked shift in US patent policy and in the perceived strength of intellectual property protection.

4.2 Flower structure strongly predicts hybrid variety prevalence

This study's identification strategy relies on the fact that a crop's flower structure is a key determinant of the crop-level ease of hybrid development, and hence of the importance and penetration of hybrid technology (see Wright, 1980; Butler and Marion, 1985; McMullen, 1987; Gupta, 1998; Fajardo-Vizcayno et al., 2014; Bradford, 2017, discussed in Section 2.3). While this characteristic of breeding has strong agronomic and scientific underpinning, it can also be verified empirically in the patent data. I first identified patents related to all crops with imperfect flowers—the control group in the main analysis—by searching for the crop name (and related synonyms) in each patent title and abstract.[36] I also identified 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. In 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*. Thus, the vast majority of new varieties for crops with imperfect flowers are hybrids. The correlation between an indicator that equals one if a patent title or abstract

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[36] Unfortunately, this analysis is not possible using the *Variety Name List* since the *List* does not contain any additional descriptive information about each variety. Conducting the analysis on the patent data will likely bias this section's estimates downward. The next section documents that patent protection is less valuable to innovating firms for hybrid varieties, which would plausibly make them less likely to obtain patent protection in the first place, since obtaining protection is costly. This leads the patent data to under-represent the differential prevalence of hybrid varieties across treatment and control crops.

contains the name of a crop with imperfect flowers, and an indicator that equals one if a patent title or abstract contains the word "hybrid," is reported in Table A1. The coefficient of interest is positive, large in magnitude, and highly significant. The F-statistic of the relationship is over one thousand.

These findings suggest that the simple and observable distinction between crops with imperfect versus perfect flowers is a strong predictor in the patent data of whether or not hybrids are developed for each crop. Moreover, these estimates likely under-represent the relationship between flower structure and hybrid development because 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, or that, once developed, they do not confer the same productivity benefits.[37]

4.3 The value of patent protection across crops

Next, I present empirical evidence highlighting 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 non-hybrid varieties. 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. If a particular form of intellectual property or if intellectual property protection for a particular invention is profitable for the innovating firm, the firm's stock price should increase in response to the announcement that protection was issued. It was often the case that knowledge about the *technology itself* existed prior to the date of patent issue since firms, and particularly the large firms that comprise the present sample of publicly traded biotechnology and agro-chemical firms, publicize new products and patent applications extensively.[38]

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.[39] 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 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 for all p if t is greater than zero (that is, the observation is within the two day window following 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 in order 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.

I first investigate the average impact of being issued either a PVP certificate or a utility patent for

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[37] See the discussion of soybeans and barley in Section 2.3.

[38] See, for example, Kogan et al. (2017, p. 673). Thus, we can interpret changes in firm value around the patent issue date as the effect of the patent itself and its value to the firm, *not* the scientific or social value of the technology itself.

[39] Further data and estimation details are discussed in Appendix Section A.3.

Table 1: Stock Price Responses to Intellectual Property Grants

	(1)	(2)	(3)	(4)
	Dependent Variable is Abnormal Returns			
	PVP Certificates	Utility Patents		
I (Post Issue Date)	-0.00154	0.00354**	0.00614***	0.00614***
	(0.00238)	(0.00140)	(0.00156)	(0.00156)
I (Post Issue Date) x Imperfect Flowers			-0.00543**	
			(0.00221)	
I (Post Issue Date) x Imperfect Flowers x "Hybrid" in Title/Abstract				-0.00607***
				(0.00200)
I (Post Issue Date) x Imperfect Flowers 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.

biotechnology. Column 1 of Table 1 reports estimates of (1), estimated on the sample of PVP certificates; ξ is statistically indistinguishable from zero and the coefficient estimate is negative and small in magnitude. This finding is consistent with qualitative accounts suggesting that PVP certificates were relatively weak forms of intellectual property and of limited value to innovating firms (Kershen, 2003; Kloppenburg, 2005).[40] Column 2 reports estimates for the full set of utility patents, and documents a large and positive impact on abnormal returns of being issued a patent.[41] Event study estimates are reported in Figure A5. Thus, the introduction of patent rights markedly increased the effective strength of available intellectual property and the value of protected inventions to firms.[42]

Next, I use the same framework to document a key component of the empirical strategy: that formal patent protection was substantially less valuable to the innovating firm when the patented

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[40] It is possible that the potential for add-on licensing, which could be used to strengthen the protection afforded directly by the certificate, complicates this narrative. In the end, the relative value of each form of IP is an empirical question and the stock price approach is useful because, by capturing the value of intellectual property to firms' expected value, it incorporates both the direct impact of the PVP certificate itself as well as any anticipated impact of add-on licensing.

[41] The estimates are very similar using raw (instead of abnormal) returns, as well as restricting the sample to utility patents in A01H.5 and A01H.6 or to utility patents in CPC class A01.5.10 (not reported).

[42] Another possibility is that, while patent protection was introduced for plant biotechnology in 1985, it only became truly 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 the Supreme Court decision does 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.3.1.

technology was a hybrid.[43] As in Section 4.2, I identify all patents related to control crops (i.e. crops with imperfect flowers) via text analysis of the patent title and abstract. Column 3 of Table 1 estimates an augmented version of (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. These estimates suggest that formal patent protection is on average substantially less valuable to innovating firms for crops in the control group.

Last, in order to corroborate the mechanism described above, I investigate whether the difference in stock price response between technologies related to crops with perfect vs. imperfect flowers is driven by hybridization itself. 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 corresponding to crops with imperfect flowers is driven by hybrid technologies (column 4), which have built-in protection regardless of whether the patent office decides to issue a formal patent grant. When the patent does not explicitly relate to a hybrid variety, there is no significant difference in the stock price response across treatment and control 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 was significantly more valuable for non-hybrid technology compared to hybrid technology. These findings corroborate the key underlying logic of this paper's empirical design.

4.4 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. I investigate whether there are level differences between treatment and control crops across a range of fixed crop-level characteristics other than flower structure that affect variety development. I rely primarily on the ECOCROP Database, described above, which reports information about a broad set of crop characteristics and growing constraints. Plant physiological characteristics determine plant growth and the structure of breeding and reproduction; moreover, much of plant breeding is designed to adapt crop production to changing environmental conditions, so crop-specific environmental growth constraints are informative about the location and demands of variety development (Olmstead and Rhode, 2008; Moscona and Sastry, 2021a).

Table A3 reports estimates of the following specification:

$$x_c^i = \gamma^i \cdot \text{Not Hybrid}_c + \epsilon_c^i$$

where $\text{Not Hybrid}_c = 1$ if a crop has perfect flowers (i.e. is not hybrid compatible). The x_c^i are crop-level characteristics listed in columns 1 and 4; the sample mean of each characteristic is displayed in

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

columns 2 and 5.[44] These characteristics i include an indicator if a plant has a single stem, an indicator if a plant is perennial, minimum and maximum crop cycle length (days of the year), optimal soil depth and salinity, as well as a range of "cut-off" values for temperature, rainfall, and soil pH at which crop productivity changes. For each crop and environmental characteristic, ECOCROP reports two ranges: (i) a range within which crop performance is "optimal" (i.e. an inner range) and (ii) a range within which crop cultivation is possible (i.e. an outer range). Thus, for each crop and environmental characteristic, ECOCROP reports four separate numbers capturing the crop's sensitivity to the environmental characteristic; I include all four numbers for each environmental characteristic in the set of crop characteristics. Finally, I also include (log of) area harvested and the per-unit producer price in both 1975—ten years before the change in patent regime—and 1984—one year before the change in patent regime, since market size and prices are additional potential determinants of research focus.

Estimates of the γ^i are reported in columns 3 and 6 of Table A3. I find no evidence of systematic differences between treatment and control crops along these dimensions; estimates of γ^i are consistently small in magnitude compared to the sample mean. Furthermore, only one of the twenty-two coefficient estimates is significant at the 10% level or less, which is to be expected from random chance given the number of regression estimates. Thus, treatment and control crops appear similar across a range of observable characteristics that affect the location, structure, and demands of variety development.

5 Patent Rights and Innovation

5.1 Empirical Strategy

My empirical approach compares treatment to control crops, before and after the introduction of patent rights in 1985 using a difference-in-differences design. The main estimating equation is:

$$y_{ct} = \alpha_c + \delta_t + \beta \cdot \text{Not Hybrid}_c \cdot \mathbb{I}_t^{\text{Post 1985}} + \mathbf{X}'_{ct}\Gamma + \epsilon_{ct} \tag{2}$$

For each outcome, the regression is estimated on a balanced panel of crops for the years 1975-1995. Throughout the analysis, c indexes crops and t indexes years. α_c and δ_t are crop and year fixed effects respectively. $\mathbb{I}_t^{\text{Post 1985}}$ is an indicator that equals one in all years after the extension of patent rights (i.e. after and including 1985) and NotHybrid_c is a crop-specific indicator that equals one if a crop has perfect flowers (i.e. is a treatment crop). The coefficient of interest is β, the impact of the introduction of patent rights on crop-specific innovation in treatment relative to control crops. Standard errors are double clustered by crop and year.

In order to ensure that treatment and control crops were on similar trends prior to the introduction of patent protection, I also present estimates of the following estimating equation:

$$y_{ct} = \alpha_c + \delta_t + \sum_{\tau \in \mathcal{T}^{pre}} \beta_\tau \cdot \text{Not Hybrid}_c \cdot \delta_\tau + \sum_{\tau \in \mathcal{T}^{post}} \beta_\tau \cdot \text{Not Hybrid}_c \cdot \delta_\tau + \mathbf{X}'_{ct}\Gamma + \epsilon_{ct} \tag{3}$$

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[44] The sample included is all crops in the ECOCROP database which also appear in the *Varieties Names List* analysis. This changes slightly across variables in Table A3 due to missing data in ECOCROP.

Table 2: Patent Protection and Novel Plant Varieties

	(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
Not Hybrid Compatible$_i$ x $\mathbb{1}_t^{Post\,1985}$	0.795***	0.920***	0.931***	0.919***	0.109***	0.204**	0.275**	0.320***
	(0.240)	(0.322)	(0.327)	(0.329)	(0.0334)	(0.0837)	(0.111)	(0.105)
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 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.

Here, the coefficients of interest are the β_τ. The identification assumption is that prior to the introduction of patent protection, hybrid compatible and incompatible crops are on similar trends; 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.

5.2 Results

5.2.1 New Crop Varieties

Estimates of Equation 2 in which the dependent variable is the number of new crop varieties are reported in Table 2. Since the number of variety releases is a count variable, and since there zeroes on the left hand side of the regression, I report a Poisson pseudo-maximum likelihood estimate (columns 1-4), in addition to OLS specifications after computing the inverse hyperbolic sine of the dependent variable (columns 5-8).[45] In columns 1 and 5, I control for only crop and year fixed effects. Both specifications indicate a positive and significant relationship between the strength of patent protection and new biotechnology development. The estimate from column 1 implies that, compared to control crops, treatment crops experienced a 119% increase in variety development following the introduction of patent rights. For the mean crop, this corresponds to 11.2 additional varieties.

The remaining columns explore the robustness of these estimates to the inclusion of an increasing

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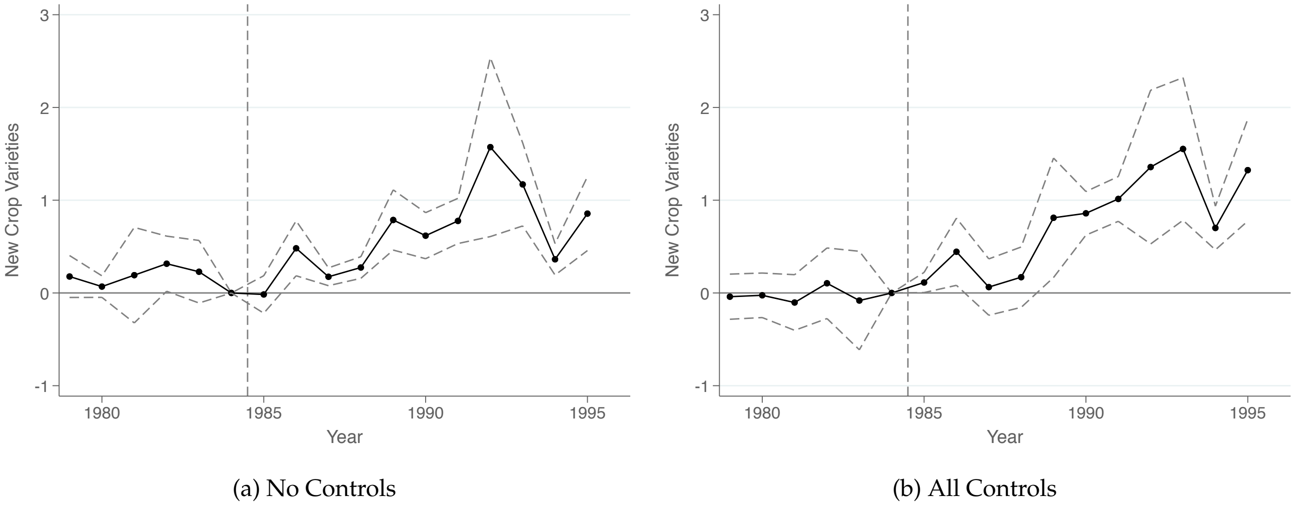
[45] Whenever Poisson estimates are reported, I use pseudo-maximum likelihood estimators in order to ensure appropriate standard error coverage; see Wooldridge (1999).



(a) No Controls

(b) All Controls

Figure 4: **Patent Protection and Novel Plant Varieties Over Time.** Coefficient estimates from poisson 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.

number of controls. The end of the 20th century was witness to major advances in agricultural science, chief among them the development and eventual widespread adoption of genetically modified organisms (GMOs). The actual release and adoption of GMOs did not occur until *after* the main sample period of this analysis, and could have been an outcome of stronger patent protection.[46] In order to ensure that the results are not driven by any breakthrough in genetic modification technology unrelated to patent incentives, I directly account for GMO development in the regression model. There are just ten crops for which genetically modified versions have been introduced in the US, and only a slightly larger set of crops for which GMOs have been developed but never approved for production.[47] In columns 2 and 6, I control for separate indicators that equal one if a crop has a *released* GM version and if a crop has a *developed* GM version, both interacted with a full set of year indicators in order to capture dynamics in these fixed crop-level indicators. The estimates are very similar.

While the results in Table A3 show no systematic evidence of physiological differences between treatment and control crops, there is weak evidence that treatment crop productivity is somewhat more sensitive to low levels of rainfall (column 4, row 7). In order to document that this feature of the data is not affecting the results, in columns 3 and 7 of Table 2 I control for the crop-specific rainfall tolerance cut-off values from the ECOCROP database interacted with a full set of year indicators. Finally, in columns 4 and 8, I control for an indicator that equals one if a crop can re-produce vegetatively, interacted with a full set of year fixed effects, since asexually propagated varieties may experience different trends of development and release. The estimates are again very similar.

The main identifying assumption is that, absent the change in patent law, innovation in treatment

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[46] The rise of genetic modification and its relationship to this paper's estimates are discussed in detail in Section B.2.

[47] The crops for which GMOs have been approved for production in the US are: alfalfa, apples, canola, corn, cotton, papaya, potatoes, soybeans, summer squash, and sugar beets.

and control crops would have been on similar trends. Figure 4 displays coefficient estimates from the event study analysis (Equation 3), both with and without the full set of controls from Table 2. Innovation in the treatment and control group are on very similar trends prior to 1985. This baseline figure focuses on years close to the policy change; Figure B1 reports estimates using an extended pre and post-period and again, no pre-trend is apparent while the positive effect after 1985 is persistent.[48,49] Thus, the introduction of patent rights had a large, positive impact on technology development.

The historical narrative suggests 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, Figure B2a documents that the positive difference-in-differences estimate is driven by biotechnology development for treatment crops rapidly increasing to catch up to the level of control crops in the years following the extension of patent rights. Figure B2a reports the relationship between an indicator that equals one if a crop is in the control group and variety development in each five year bin. During the pre-period, variety development in control crops—those with *de facto* intellectual property protection—is significantly higher (column 1-2). However, the gap declined by over one third during the period 1985-1989 and was eliminated entirely by 1990-1994. Figure B2b shows the rise in variety releases for treatment and control crops separately, over the same period and binned in the exact same way. Mirroring Figure 4, treatment and control crops begin to diverge over the period 1985-1989, and grow apart even more sharply following an appropriate technology development lag from 1990-1994, driven by a substantial increase in variety releases for treatment crops.[50]

Evidence of the profit motive Patent protection provided *ex ante* incentives to invest in research because it allowed innovators to sell new non-hybrid varieties to farmers at a price that exceeded marginal cost. 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, farmers were forced to purchase seeds from the developer. This made the potential profits from developing a new variety much higher. However, other features of patent protection—for example, the disclosure requirement and the fact that patent holders had to provide information about the details of their invention—might have also contributed to the growth in variety development after 1985.

Certain crops in the sample 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 to a given farmer are more limited. Table B2 examines heterogeneity based on whether a crop is perennial or not. I estimate the

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[48] Figure B4 reproduces the event study estimate after controlling for a “major field crop indicator” (i.e. an indicator that equals one for corn, wheat, soy, and cotton) interacted with year fixed effects, in order to make sure the findings are not driven by comparisons between field and non-field crops; if anything, the result is more dramatic.

[49] 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 very close to zero, statistically insignificant, and, if anything, trends in the opposite direction it would need to in order to explain the findings.

[50] A similar pattern is apparent focusing only on the three main field crops: corn, wheat, and soy (Figure B3). Variety releases in wheat and soy increase dramatically relative to corn after the mid-1980s, with some evidence of a small absolute decline in corn variety development over 1985-1995. The main pattern in the variety release data is thus apparent in just the three largest crops.

impact of patent protection separately for non-perennial and perennial crops (columns 1-2, 4-5), and also estimate the heterogeneous impact of the introduction of patent protection from a single regression model (columns 3 and 6). Across specifications, the effect is driven by non-perennial crops; patent rights increased variety development by 129% in non-perennial crops and had an effect indistinguishable from zero for perennial crops. This is consistent with new profit opportunities from the ability to protect varieties from re-sale and re-use as an important causal mechanism.

Sensitivity and Robustness While Figures 4 and B1 do not indicate that there were pre-existing trend differences in variety development between treatment and control crops, it is nevertheless possible that pre-existing trends affect the esitmates despite not being statistically detectable in the event study analysis (see Freyaldenhoven et al., 2019). To rule out this possibility, I control for pre-period innovation explicitly. The results are similar 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 B3, 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 suggest that the baseline findings are not driven by any pre-existing trend in technology development.

I next investigate whether the findings are driven disproportionately by small or large crops, and whether the estimates are driven by extreme observations. In columns 1-2 of Table B4, I report estimates weighted by (log of) the number of varieties released for each crop during the pre-period; the estimates are, if anything, slightly larger in magnitude, suggesting that the findings are not driven by crops that occupy a small share of overall research focus. A related strategy could be weighting the estimates by the crop-level market size, as proxied by the land area on which each crop is grown. Data on land area harvested are only available for a subset of the crops in the *Variety Name List*; however, on this sample, the area-weighted estimate is $\beta = 1.331$ (0.434) and the un-weighted estimate is $\beta = 1.292$ (0.450). In columns 3 and 4, I exclude from the sample crops in the bottom 25% of the pre-period variety development distribution and the top 25% of the pre-period variety development distribution respectively. The coefficient of interest is positive and significant in both cases and, if anything, is larger when the smaller crops are excluded. Next, I estimate the baseline specification after excluding the most influential observations as measured by their Cook's Distance.[51] This estimate is presented in column 5 and is very similar to the baseline findings.

Flower structure strongly predicts hybrid technology development (see Section 4.2); nevertheless, hybrid varieties have been developed for several 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-pollenate, making hybridization more straightforward. Crops with perfect flowers for which CMS systems have been developed often still have limited hybrid variety penetration in production (Havey, 2004), and the use of flower structure in order to determine crop-level treatment is unbiased by potentially endogenous investment in CMS

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[51] Following Bollen and Jackman (1985), I drop observations with Cook's Distance greater than $4/n$ where n is the number of observations in the regression sample.

system development. Nevertheless, the role of CMS supported hybrid development is potentially interesting to investigate. Table B7 reproduces the baseline estimates after reassigning crops for which CMS systems have been developed to the control group (columns 1-4) or after excluding these crops from the sample entirely (columns 5-8).[52] The estimates of interest remain similar in both cases.

Finally, I investigate the robustness of the findings to expanding the standard error cluster level and unit of observation definition. In the baseline results, standard errors are double-clustered by crop and year. The definition of a "crop" in this context was taken from the *Varieties Names List*; however, it could be possible that regression errors are correlated across crops that are biologically similar. For example, broccoli, cauliflower, and turnips are in the data as separate crops; however, all three crops are genetically similar and indeed part of the *Brassica* genus. Moreover, since the definition of a crop is taken from the *Varieties Names List* which follows crop definitions used in the vernacular rather than taxonomic classifications, it could be that some crops are "smaller" or "larger" taxonomic categories than others; this could be intuitively unappealing.

To investigate this feature of the data, 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 (results are very similar if standard errors are just clustered by genus). In the example above, this would mean broccoli, cauliflower, and turnips would all be part of the same cluster. The precision of the estimates, reported in Table B5, are very similar using this alternative clustering strategy. I also reproduce the baseline results after collapsing the data to the genus-level; estimates in which the unit of observation is the genus-year are reported in Table B6 and the results are quantitatively very similar.

Additional robustness tests and sensitivity analyses are reported in Section B.1.

Discussion of Magnitudes While the magnitude of the estimated effects 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). To make progress on identification, however, 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. The estimates therefore do not necessarily reflect the causal effect of patent rights on the aggregate level of innovation; this is sometimes referred to as the "intercept problem."

A range of evidence, however, lends support to the interpretation that the results are driven by an absolute increase in treated technologies. First, I find no evidence of an absolute decline in variety development or research investment in the control group. Second, discussed in greater detail below, I find no evidence that innovation related to treatment crops in non-biological technology classes declined following the introduction of patent rights for biotechnology, suggesting the results are not driven by shifting research investment across technology types. Finally, there is no reason to think that breeders and agricultural biotechnology firms—particularly large firms, which made up a growing share of total research investment after 1985—were financially constrained in terms of their ability to

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[52] 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. The estimates in columns 1-4 are, intuitively, somewhat smaller than the baseline estimates since the crops newly assigned to the control group are not complete controls.

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

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent Variable:	Public Research Investment (asinh)			Private Research Investment (asinh)		
Not Hybrid Compatible$_i$ x $\mathbb{1}_t^{\text{Post 1985}}$	-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 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

expand total research investment. Indeed, total private spending on crop breeding increased dramatically throughout the sample period (see Figure B6). In all of these cases, however, it is not possible to know the counterfactual trends in the absence of the change in patent law, and as a result the estimated magnitudes should be interpreted with necessary caution.

A related question is what lessons these estimates might have for industries other than agricultural biotechnology. There are several reasons why this context is one in which the prospect of patent protection might have a particularly large effect on innovation. Absent patent protection, new non-hybrid seeds can be easily re-used, replicated, and re-sold. Without formal patent protection, there is little a breeder could do to extract rents from her innovation. In other industries, innovators may be able to recoup some of their profits by, for example, maintaining trade secrets (see e.g. Png, 2017). Non-hybrid plant varieties may be a context where one might expect the most dramatic impact of the introduction of patent rights on incentives to innovate.

5.2.2 Research Investment

The previous section documented that patent protection increased novel variety development. Table 3 investigates the impact of patent rights on crop-specific research investment in order to probe the mechanisms underpinning the shift in technology. First, I investigate the impact of patent protection on public research investment. I find a negative but statistically insignificant relationship between the availability of patent protection and pubic investment (column 1), which is further attenuated and very close to zero after controlling for pre-period public investment in 1975, 1980, and 1984 interacted with

(a) Public Research Investment

(b) Private Research Investment

Figure 5: **Research Investment.** Coefficient estimates from 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. All baseline controls are included in each specification. Standard errors are double-clustered by crop and year; 95% confidence intervals are reported.

year fixed effects (column 2).[53] The estimate remains small in magnitude and statistically insignificant after adding the full set of baseline controls from Section 5.2.1 (column 3).

However, 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).[54,55] The positive effect of patent rights on variety development was driven by a substantial increase in private research investment in the years following the strengthening of patent protection.

Figure 5 investigates the impact of patent availability on research investment over time. I find no evidence of a difference in trend in public or private research investment between treatment and control crops prior to 1985. After 1985, the parallel trends continue for public sector investment, and the effect even dips slightly in later years (Figure 5a); however, the trends in private research investment sharply diverge following the change in patent law, and are already significantly different by 1986 (Figure 5b). The increase in private investment seems to decline slightly in later years, which could be due to the fact that the CRIS investment data only include data on private investment for projects that also received public investment; thus, if part of the mechanism is that over time, patent protection led to an increasing share of research being fully privately funded, the observed pattern would result.[56]

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[53] I parameterize all measures of research investment x as $\text{asinh}(x)$ because there are zeroes, but the results are very similar using $\log(1+x)$ instead or using the total level of investment x (in dollars) as the dependent variable.

[54] The sample size decreases slightly in columns 3 and 6 due to availability of the optimal rainfall cut off data. The coefficient estimate from the estimation sample from column 6 but without the full set of controls is 0.925 (0.367), suggesting that the increase in coefficient magnitude is due more to the different sample than the addition of controls.

[55] The estimated linear pre-trend for each specification is small and statistically insignificant; for columns 4-6 respectively, the estimates are 0.0382 (0.0589), 0.0340 (0.0217), and 0.0476 (0.0277).

[56] To my knowledge it is not possible to track private research investment by crop outside of the CRIS data, so this limitation is not possible to surmount. This logic implies that the estimated impact on private research investment from Table 3 might under-estimate the true effect. This feature of the CRIS data also makes it impossible to interpret the effect of patent

Aggregate increases in private investment in biotechnology after 1985 are also consistent with an increase in private sector innovation and show no evidence of reverting back to their pre-period level. Total private sector investment over time in both breeding and chemicals, relative to investment in 1984, is displayed in Figure B6.[57] While private sector investment in breeding and chemicals are on similar trends prior to 1985, they diverge in 1986 and investment in breeding accelerates. 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, the introduction of patent rights concentrated research investment in a smaller set of researchers, while having a limited effect on the number of researchers working on each crop. Table B10 documents that while patent protection has no significant effect on the total number of crop-specific scientist years, it has a positive and significant impact on investment per scientist year.[58] The extension of patent protection led to a dramatic increase in private investment and greater investment per scientist, rather than any net movement of scientist labor across crops.

5.2.3 Spillover Effects: Non-Biological Technology

The impact of patent protection for plant varieties might extend beyond biotechnology if it had spillover effects on other technology classes. There are major complementarities between different agricultural inputs, for example, and new seed technologies might give rise to the development of complementary non-variety inputs. A famous example is the development of the tomato harvester by two scientists—engineer Coby Lorenzen and crop breeder Gordie Hanna—at the University of California in 1959. It was widely viewed that tomato production could be made more productive with more efficient harvesting mechanisms; however, existing tomato varieties would not have been tough enough to survive being handled by most modern harvesters. Thus, 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.[59]

Spillover effects, however, need not be positive. While it is intuitive that there may be positive spillover effects from variety innovation to harvester development, the same is not necessarily true for agricultural chemicals and biocides. Although certain new seed technologies, including herbicide or insecticide tolerant varieties, may increase incentives to invest in chemical development, Robinson and Cowling (1996) explain how in many contexts modern crop breeding has reduced and may continue to reduce pesticide dependence (see also e.g. Leppik, 1970; Ratnadass et al., 2012). Thus, we might expect a limited or even negative impact of additional variety innovation on improvements in agricultural chemicals on average. Investigating the sign and magnitude of these spillovers is important for

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protection on *total* research investment since, while all public investment is in the data, private investment is systematically underestimated.

[57] 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).

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

[59] Another example of this phenomenon is the widespread increase in development and adoption of corn harvesting technologies following the development of hybrid corn. The genetic uniformity of hybrid varieties, in addition to physiological characteristics of the plant stalk and structure, made it possible to develop mechanical harvesters that drastically increased productivity; see Kloppenburg (2005, p. 117) for a discussion.

Table 4: Spillover Effects on Non-Variety Crop Technologies

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Pre-Harvest and Harvest Technology				Post-Harvest Technology	Multiple Technologies	
Dependent Variable is the Number of Patents 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)
Not Hybrid Compatible$_i$ x $\mathbb{1}_t^{\text{Post 1985}}$	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

understanding the overall impact of patent protection on innovation.

Table 4 reports estimates of Equation 2 in which the outcome variables are crop-specific patent grants. All columns report Poisson pseudo maximum likelihood estimates.[60] The first five columns report the effect of patent protection for varieties on patent grants in a series of mutually exclusive patent technology classes. Column 1 suggests that there were positive and significant spillover effects on harvester technology development, consistent with the intuition provided by the tomato harvester anecdote. Innovation in crop-specific harvester and mower technology increased disproportionately for hybrid-incompatible crops following the change in patent regime.

Columns 2-3 tell a similar story for planting technologies. In column 2, the outcome variable is patent grants related to planting, sowing, and fertilizing, while in column 3 it is patents related to soil working machinery. In both cases the coefficient estimate is positive and similar in magnitude; in column 3, it is statistically significant. I find no evidence of spillover effects on crop-specific chemicals; this result is presented in column 4. While the point estimate is negative, the coefficient estimate is small and statistically insignificant.

All outcome variables thus far were pre-harvest or harvest technologies. Using the patent data it is also possible to measure crop-specific post-harvest technologies (these correspond to CPC class A01F). I estimate a negative but small and statistically insignificant relationship between variety patent availability and post-harvest technology development in column 5. This null result suggests that the

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[60] The sample in each specification was determined by searching the patent data for patents in each CPC class related to all crops in the *Variety Name List*. Thus, in some cases the sample size is slightly reduced when there was not a patent during the sample period within the given CPC class explicitly linked to each crop in the *Variety Name List*. The noted sample size varies across specifications because in some specifications, part of the variation is fully absorbed by the included fixed effects.

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, columns 6 and 7 report the impact on crop-specific patent totals, aggregated across patent classes. In column 6, the dependent variable is the total number of crop-specific patents and in column 7, it is the same after excluding 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 spurred new technology development in non-biological crop technologies, and particularly those related to harvesting and soil working, potentially amplifying the productivity consequences of patent incentives. I find no evidence of declining technology development in any patent class, suggesting that the impact of patent protection for seeds was not simply to pull innovative activity from other sectors.

5.2.4 Physical Productivity

Did the technology development that resulted from the change in patent law have a discernible impact on crop productivity? There are several reasons that this might not have been the case. The marginal investment and new technology induced by patent incentives might have been of low quality; indeed, its possible that patent incentives had an especially large impact on business stealing or "copy-cat" invention that had limited effects on productivity. Therefore, I directly estimate the crop-level relationship between exposure to the patent law and national agricultural yields.[61]

Columns 1-3 of Table 5 report estimates of Equation 2 in which (log of) national crop yield is the dependent variable. I find a positive and significant relationship between the availability of patent protection and crop yields, which is similar after controlling flexibly for crop-specific pre-period yield trends (column 2) or including the full set of baseline time-varying controls (column 3).[62] The estimates suggest that patent rights for innovation increased downstream crop yields by 10-11%.

In column 4, I investigate the pre-existing trend in crop yields (i.e. before the change in patent law) by estimating the relationship between the crop-level treatment variable and the change in (log of) crop yields from 1970-1985, where yield at each endpoint is calculated as an average over the five year period. The coefficient estimate is small in magnitude and statistically indistinguishable from zero. This stands in sharp contrast to column 5, which reports the relationship between the crop-level treatment indicator and the change in crop yields from 1980-1995. Together, these results indicate that the introduction of patent rights had a discernible, positive impact on crop yields.

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[61] Of course, it would be possible for the new technology induced by patenting to lead crop production to expand to *ex ante* less productive land; this would mean that new technology did indeed increase productivity, but this mechanism would be difficult to discern from data on national yield. New technology could also improve quality (e.g. taste) or reduce the need for other input costs. These additional margins through which technology improved downstream production are captured by the analysis in Section 6.

[62] In all specifications, the positive impact on crop yields is driven by positive (albeit imprecise) impacts on area planted and total output, with the impact on output dominating.

Table 5: 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
Not Hybrid Compatible$_i$ x $\mathbb{1}_t^{\text{Post 1985}}$	0.106*	0.108**	0.119*		
	(0.0505)	(0.0513)	(0.0652)		
Not Hybrid Compatible$_i$				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.

6 Downstream Effects: County-Level Analysis

The previous set of results documented that the introduction of patent rights for agricultural biotechnology spurred research investment and technology development. However, the fact that patent incentives encouraged innovation does not necessarily imply that they benefitted agricultural production—providing *ex ante* incentives for innovation is a necessary but insufficient condition for patent rights to have had a positive impact on the consumers of technology. This is due to the fact that: (i) monopoly pricing of patented technologies may have increased the cost of inputs faced by farmers and/or distorted input choice decisions and (ii) general equilibrium price effects could have dampened the impact of productivity on profits.

To fully capture the impact of patent protection on agricultural production, I estimate the effect of patent rights on agricultural land values and profits downstream. I turn to an analysis in which the units of observation are fixed geographic locations—US counties—and measure the extent to which each county was *exposed* due to their ecological and geographic suitability for the cultivation of treatment (versus control) crops. Finally, I estimate the extent to which county-level exposure to the introduction of patent rights was capitalized into agricultural land values, thus capturing the benefits of patent rights—documented in detail in the previous sections—alongside their potential costs.

6.1 Empirical Strategy

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 in the GAEZ data, I determine the optimal crop $c(g)$ as

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

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 according to the USDA.[63] 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 determine crop-specific productivity incorporated into the FAO-GAEZ model.

The GAEZ-derived predicted share is strongly correlated with the actual share of hybrid-incompatible crops planted in each county measured directly in the Census of Agriculture from 1982 (the closest year); this relationship is documented in Figure C3 (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 the map in Figure 6. The map is 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 protection using the following estimating equation:

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

where i indexes counties and t indexes census rounds. α_i and δ_{st} denote county and state-by-round fixed effects respectively, and the coefficient of interest is ϕ, which captures the impact of exposure to the introduction of patent protection on the dependent variable, y_{it}. The baseline estimates are weighted by (log of) pre-period county farm land, but un-weighted estimates are very similar for all results. Standard errors are double clustered by county and state-census-round pair; the baseline sample period is 1969-2002. The sign of ϕ is theoretically ambiguous, and depends on the relative magnitudes of the costs and benefits of the patent system (Nordhaus, 1969; Budish et al., 2016).

In order to make sure that more- and less-exposed counties are on similar trends prior to the in-

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

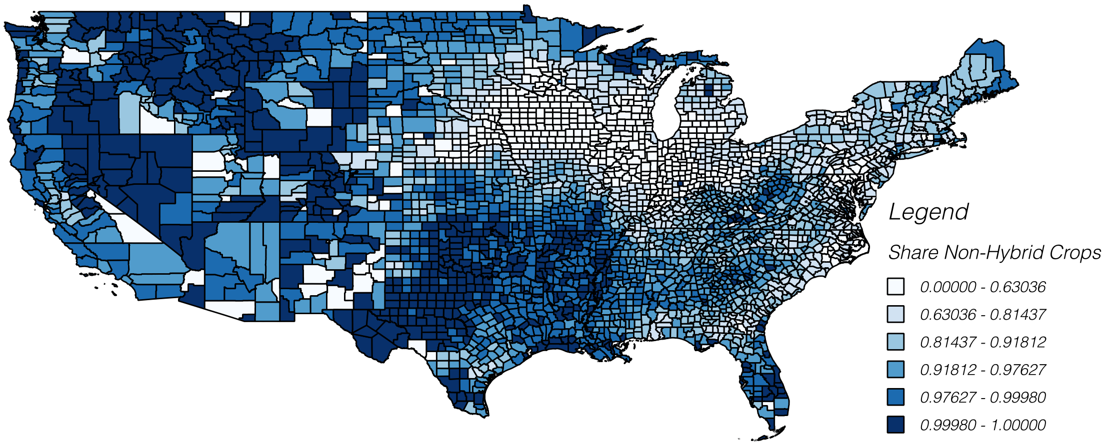

Figure 6: **Share of Cropland Devoted to 'Hybrid Incompatible' Crops Across US Counties** Counties are color-coded based on the share of cropland devoted to hybrid incompatible crops in the 1982 Census of Agriculture, where hybrid compatibility is defined as described in Section 2.

troduction of intellectual property protection, I also report estimates from an event study specification analogous to (3), and document that exposure to the change in patent rights does not predict changes in the value of agricultural land prior to 1985.

6.2 Main Results

The main county-level estimates investigate the relationship between exposure to patent protection and agricultural land values, which capture the net present value of agricultural profits. 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. Mendelsohn et al., 1994; Hornbeck, 2012; Donaldson and Hornbeck, 2016).[64] Baseline estimates of Equation 4 are reported in Table 6.[65] 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 significantly different from zero, suggesting that county-level exposure to the introduction of patent rights for agricultural biotechnology had a positive average effect on the value of agricultural land.

Column 2 adds state-by-census round fixed effects, thereby fully absorbing all time trends at the state level. This restricted specification exploits only within-state variation in suitability to treatment and control crops, and the coefficient estimate remains positive and precise. Column 3 controls directly for the pre-existing trends in agricultural land values by including (log of) land value in 1974 and 1982, both interacted with census round fixed effects, on the right hand side of the regression. In column 4, I report the estimate form an un-weighted specification; the coefficient is similar and slightly smaller, suggesting that the effect is, if anything, driven by more agricultural counties. The result also remains

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[64] Other work using a related framework focuses instead on farm profits (e.g. Deschênes and Greenstone, 2007). While there are issues with this approach (see Fisher et al., 2012), I also explore the impact on profits in the next section.

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

Table 6: 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_{i} x $\mathbb{1}_{t}^{\text{Post 1985}}$	0.161***	0.0980***	0.0968***	0.0830**		
	(0.0317)	(0.0297)	(0.0306)	(0.0388)		
Exposure_{i}					-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.

highly statistically significant using a range of alternative strategies for clustering the standard errors to account for spatial and temporal correlation (Table C1).[66]

Column 5 reports the cross-sectional relationship between county-level exposure and the pre-period change in (log of) agricultural land values, from 1969-1982. The coefficient estimate is negative, small in magnitude, and statistically indistinguishable from zero, suggesting that the main results are not driven by pre-existing trends in land values. Exposure to the patent law change is highly positively correlated with increases in agricultural land values between 1982-1997, the period during which the change in patent law took place (column 6). Event study analysis further confirms the absence of pre-existing trends. Figure 7 documents that more- and less-exposed counties were on similar trends prior to 1985, but their trends diverged following the law change and remained relatively level thereafter.[67]

The baseline coefficient estimate with the state-by-round fixed effects included (column 2) 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 and weighting each county by its share of national farmland, 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.[68] This magnitude is consistent with the

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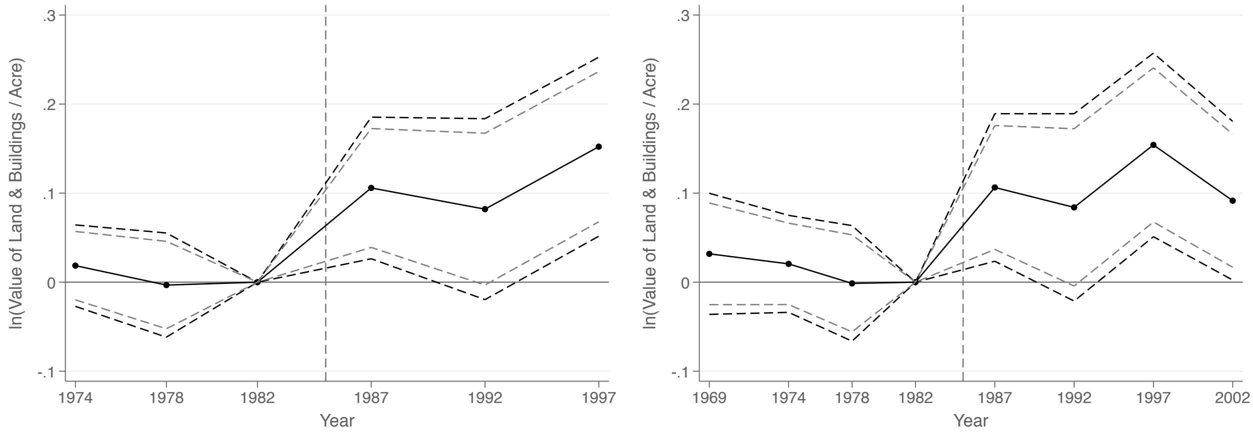
[66] Table C1 reports the estimated *t*-statistic using Hsiang (2010)'s implementation of Conley (1999) standard errors, for several possible values of the spatial and temporal kernel cut-off values.

[67] The same pattern is apparent in the raw data on agricultural land values, comparing counties with high and low levels of patent law exposure without any regression estimation or the inclusion of any controls (Figure C2).

[68] The aggregation procedure is described in more detail in Section C.3. The estimate relies on the assumption that there



(a) 1974-1997

(b) 1969-2002

Figure 7: **Exposure to Patent Rights and Agricultural Land Values.** Coefficient estimates from Equation (3) using a shorter (7a) or longer (7b) sample period. The dependent variable is the log of agricultural land value. The dotted lines display 90% and 95% confidence intervals.

widespread conclusion that advances in agricultural biotechnology were a major force behind agricultural productivity growth in recent decades (Kloppenburg, 2005). However, the estimates also suggest that innovation induced by patent protection, while an important component of new profits, does not explain close to all of the growth of the US agricultural sector that took place during the studied period (see Section C.1).

Table 7 explores the robustness of the baseline estimates to the inclusion of a series of additional controls; these controls take the form of interactions between fixed or pre-period county-level characteristics and a full set of year indicators, thereby flexibly capturing trends in the county-level 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 county-level latitude and longitude interacted with census round fixed effects, 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 across counties. 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). Finally, the results are similar when the dependent variable is calculated from actual crop shares in the 1982 Census rather than the FAO-GAEZ derived model (see Table C2), or doing the same after re-assigning CMS crops to the control group (see Table C3). The estimates are also similar when

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was zero effect of the extension of patent rights in counties whose land was 100% devoted to hybrid compatible crops; the need for such an assumption is sometimes referred to as an "intercept problem" when estimating aggregate effects from regional exposure to a shock. The finding in Table 1 that patent protection for hybrid varieties had approximately zero impact on expected firm profits lends support to the assumption that counties that grew exclusively hybrid-compatible crops were unaffected by the change in patent law.

Table 7: Patent Rights and Agricultural Land Value: Additional Controls

	(1)	(2)	(3)	(4)	(5)	(6)
	log Value of Land and Buildings Per Acre					
Exposure_i x $\mathbb{1}_t^{\text{Post 1985}}$	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.

the sample period is restricted to a narrower window around the policy shift, 1974-1997 (see Table C4). Appendix C.2 reports and discusses a range of additional sensitivity checks of the main estimates.

Together, these results suggest that strengthened patent rights had a robust positive effect on agricultural land values in counties that were exposed to the change in legal regime. Next, I turn to the mechanisms that drove this positive long-run net effect of patent-induced innovation.

6.3 Mechanisms and Trade-Offs

The positive effect of the introduction of patent rights on land values suggests that, in the long run, the benefit of biotechnology patent rights were expected to outweigh their cost to the agricultural sector. What mechanisms underpinned this positive net effect? To investigate this question, I turn to direct measures of input spending and profits during the sample period.

Column 1 of Table 8 reports a positive and significant relationship between exposure to the patent law change and spending on crop varieties; the event study is displayed in Figure C4a and shows no indication of pre-existing trends in seed spending. More exposed counties did *not* increase spending on any agricultural input category other than varieties (see Table C6), suggesting that the increase in seed spending was not driven by any across-the-board increase in spending or expansion of production, and the effect on total input spending is positive but statistically insignificant (Table 8, column 2).[69] Thus, the extension of patent rights *did* seem to have a discernible positive impact on farmers' expenditure

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[69] On average, about 6% of spending is devoted to seeds with a standard deviation of 10%. If spending on livestock and livestock feed are excluded from the denominator (i.e. to more closely approximate seed spending as a share of input spending for crop production), on average about 18% of spending is devoted to seeds with a standard deviation of 7%. This share increased throughout the sample period, and particularly after 1985; the time-series trend is reported in Figure C1.

Table 8: Spending, Land Use Adjustments, and Profits

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent Variable:	log Spending on Seeds	log Total Spending	log Cropland	Share Cropland	Total Profits (asinh)	
$\text{Exposure}_i \times \mathbb{1}_t^{\text{Post 1985}}$	0.0979**	0.0270	0.0374**	0.00745*	0.290**	0.259**
	(0.0393)	(0.0291)	(0.0190)	(0.00383)	(0.125)	(0.122)
log(cropland)						0.628***
						(0.219)
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	23,894
R-squared	0.911	0.972	0.976	0.970	0.743	0.746

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.

on the newly patentable technology: seeds.[70]

Columns 3-4 turn to land use adjustments, and document that the extension of patent protection led to an increase in crop production, measured either as (log of) total cropland (column 3) and the share of county farmland devoted to crops (column 4). The increase in cropland as a share of total farmland likely contributed to the increase in total agricultural land values documented in the previous section.

In columns 5-6, the dependent variable is (aisnh of) total agricultural profits, measured as total revenue net of non-labor input costs.[71] The coefficient of interest is positive and significant—even in the short run, exposure to the change in patent law increased farm profits, consistent with significant productive benefits from new technology. The event study estimates are displayed in Figure C4b and show no evidence of differential trends in agricultural profits prior to 1987. In column 6, I also control directly for (log of) total cropland to investigate whether the increase in profits is driven by the

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[70] In theory, the impact of patent rights on variety spending could be driven by the fact that patented seed inputs became more expensive or by changes in total cropland. However, controlling for total land devoted to crops on the right hand side does not eliminate the effect ($\phi = 0.0842$, $p = 0.022$); while this is a "bad control," it suggests that county-level crop area changes do not mediate the relationship between patent law exposure and variety expenditure. The fact that I find no evidence of greater spending on other inputs is also inconsistent with the finding being driven by an overall expansion of agricultural production (Table C6). Data on seed prices are scarce, particularly for years prior to 1985 and for crops in the control group. However, consistent data on seed prices for corn (a major control crop) and cotton (a major treatment crop) have been collected systematically; the trend for both crops is presented in Figure B9, and is consistent with patent protection increasing seed prices on average.

[71] An advantage to focusing on profits is that they directly capture changes in agricultural productivity, and are not affected by other developments that might affect the value of land, for example urban encroachment, land degradation, and changes in amenity value.

Table 9: The Largest Farms

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

expansion of land devoted to crops. While the coefficient attenuates slightly, it remains positive and significant, suggesting that the impact of patent rights on downstream profits was driven by higher productivity conditional on planted area.

Finally, new technology can affect not only the level of profits, but also profit volatility, by increasing production resilience in the face of shocks; this could be driven, for example, by improved pest or drought resistance. Table C7 reports the relationship between the county-level exposure measure and the change in the standard deviation of agricultural profits between the pre-treatment and post-treatment period. The coefficient estimates are negative and significant, suggesting that exposure to new patent incentives both increased the level of agricultural profits and also reduced profit fluctuations across census years.

There are potentially large complementarities between improved varieties and farm scale. Several qualitative accounts have argued that large farms benefitted disproportionately from the growth in improved seed varieties, while higher potential profits on small farms have been substantially eroded by higher seed prices (e.g. Willingham and Green, 2019). This has been explained by production complementarities between new seed varieties and other farm inputs, as well as farm scale, and the fact that prior to 1985 many small farms remained profitable only by saving seeds from one season to the next.[72] Column 1 of Table 9 documents that the positive impact of patent rights on downstream profits

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[72] This second point has been disputed, however, and it is often argued that farmers growing hybrid crops were never able

is driven especially by counties with the largest pre-period average farm size.[73] I report the estimate from an augmented version of (4), in which the independent variable is interacted with indicators for whether average farm size is in the bottom three quartiles or the top quartile; the effect is significantly stronger for counties in the top quartile of the farm size distribution.[74] Consistent with new technology increasing the relative productivity of large farms, the introduction of patent rights also 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).

Together, these estimates suggest that patent rights had a positive effect on the value of land by increasing the level and consistency of agricultural profits, despite the fact that farmers also increased spending on seeds. The direct effect of more productive varieties on land values was plausibly amplified by the expansion of farmland in more exposed counties. Despite the positive effect on land values *on average*, new profits disproportionately accrued to the largest farms, which expanded to earn a larger share of agricultural revenue.

A final question is whether any profits flowed to the eventual consumers of *food*, or whether it all accrued to innovating firms and farmers. While this question is largely outside the scope of the present study, Section B.3 investigates the relationship between patent protection and food prices and reports suggestive evidence that the extension of patent rights led to a relative decline in food prices. This finding suggests that not all surplus was captured by seed companies and agricultural producers, but that final good consumers also stood to gain.

7 Conclusion

Institutions that protect intellectual property are potentially of central importance for economic growth and development. The role of patent protection in spurring innovation features prominently in growth theory. However, since patent regimes are endogenously determined, our understanding of the impact of patent rights on technological progress or—of perhaps greater interest—the impact of patent rights on downstream productivity and profits, is limited.

This paper investigates the impact of the introduction of patent rights on technological progress and productivity by exploiting unique features of plant biology and intellectual property protection in agricultural biotechnology. A plant having imperfect flowers facilitates the development of hybrid plant varieties, which have *de facto* intellectual property protection even in the absence of formal patent rights. This physiological difference across crop species, combined with the extension of patent rights

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to save seeds, so the ability to save seeds could not be important. See, for example: `https://geneticliteracyproject.org/2016/08/17/why-activists-but-few-farmers-complain-they-cant-save-patented-seeds/`. This does not necessarily imply, however, that the *switch* from a regime in which it is possible to save seeds to a regime in which it is not possible to save seeds did not have distributional consequences.

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

[74] One explanation for this heterogeneity is the decline of producer prices following the introduction of more productive inputs. If small farmers experienced more muted productivity increases from new varieties (or chose not to adopt them), but large farms became more productive, price effects could precipitate a larger relative decline in small farm profits. While producer price data were collected by the USDA for only a small set of crops (22-25 depending on the year), comparing the evolution of prices for treatment and control crops yields a striking pattern, displayed in Figure B8. While the prices of treatment and control crops were on similar trends prior to 1985, the (relative) price of treatment crops decreased after 1985. These results, however, should be taken as suggestive since, due to the small sample size, statistical precision is low.

to crop varieties in 1985, makes it possible to estimate the causal impact of patent rights on technology development and productivity in US agriculture.

I find that the introduction of patent protection led to a substantial increase in novel variety development in treatment relative to control crops. 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. Patent rights were thus successful at providing *ex ante* incentives for technology development and growth in physical productivity. Patent rights, however, can come with significant trade-offs for consumers of technology, and an increase in technological progress is a necessary but insufficient condition for downstream benefits. I show, however, 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.

The idea that patent rights are a source of productivity growth has been challenged in recent years, both in academic writing and across other outlets. While the costs of the patent system have been extensively reported, perhaps nowhere more than in the context of biotechnology, its benefits are more challenging to observe and the counterfactual level of technology in a world without patent rights more difficult to quantify. The present study stands in contrast to claims that patent rights are inconsequential by documenting that the extension of patent protection to plant biotechnology led to a dramatic increase in technology development and shaped patterns of productivity and profits across the US. Understanding the effects of patent protection outside of a high-income, research intensive country like the US, as well as the impact of patent protection on the characteristics and diversity of new technology, which could shape the longer-run consequences of patent incentives, are important goals for future research.

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A Patent Protection in the US, Stock Market Analysis, and Balance Tests

A.1 Intellectual property protection around the world

Figure A1 displays all countries in the world with some form of intellectual property protection for plant varieties that is recognized by the International Union for the Protection of New Varieties of Plants (UPOV), the international organization tasked with promoting, standardizing, and facilitating the enforcement of intellectual property protection for varieties. Several additional countries, including India, are engaged in ongoing political debate about whether to introduce similar protection. While much of the world has introduced protection for varieties since 1960, notable exceptions include much of sub-Saharan and North Africa, the Middle East, and South Asia.

Introducing intellectual property protection for plant varieties has been a politically contentious process in almost all cases (e.g. Straub, 2005). Some interest groups argue that the productivity benefits and incentives to innovate would outweigh the potentially higher costs, while others argue that higher prices for seeds and lower output prices would hurt farmers. Still today, in countries where intellectual property protection is not enforced, breeders and seed companies use hybridization as a way to enforce *de facto* intellectual property protection (see e.g. Pulla, 2018, on India).

A.2 *Ex Parte Hibberd* and patent protection in the US

Qualitative accounts suggest that the USPTO's *Ex Parte Hibberd* decision had a sudden and substantial impact on the effective strength of intellectual property protection for plant varieties in the US. As noted in the Introduction, 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 could "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, including PVP certificates.[75] Ewens

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[75] For example, Blair (1999, p. 318) writes: "Plant utility patents offer the greatest protection when compared to plant patents or PVPA certificates. Plant utility patents allow the inventor-breeder to claim not just one claim on the plant as a whole, as is the case with Plant Patents and PVPA, but the inventor-breeder can also claim the individual components of the variety. In addition to the components of a variety such as the DNA sequence, gene, tissue culture, seed, or specific plant part, the inventor-breeder can claim methods to use the variety to make other varieties [...] Patenting multiple components or uses of an inventive plant allows for the licensing of those individual components, which is an important factor in genetic

(1999) concurs that *Ex Parte Hibberd* marked the critical moment when plants became eligible for patent protection. Stein (2005) avers that "[e]ven though [Ex Parte Hibberd] was an agency decision, it had a profound effect on germplasm patenting," as evidenced by both the number of patents for germplasm issued in the subsequent years and the wave of merger and acquisition activity that began in the seed industry after 1985. More recently, Peschard and Randeria (2020) write that, despite substantial international debate on the validity of plant patents, 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."

The major impact of the *Ex Parte Hibberd* decision was also reflected in the US's approach to international patent law. In negotiating for 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 at TRIPS negotiations, as well as a guide for international enforcement.

A.3 Empirical evidence from patent grants and stock market returns

In Section 4, I use plant biotechnology patent data to investigate trends in patenting and the impact of patent grant announcements on firm value. To identify plant biotechnology patents, I use each patent's Cooperative Patent Classification (CPC) class. The broadest CPC category I use is the A01H class, which is defined as *New plants or processes for obtaining them; plant reproduction by tissue culture techniques*. I also use two refinements of this class-based 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 home in on seeds in particular, I present results using only patents classified in A01H.5/10, titled *Seeds*. 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.

While the main results focus on plant biotechnology patents, Figure A2 plots the time series trend in patent grants and patent applications in non-biological technologies related to crop agriculture, i.e. CPC classes A01B, A01C, A01D, and A01F. These classes correspond respectively to: (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). Notably, none show a market shift at or after 1985. The main paper shows the marked trend break in patents in classes A01H.5 and A01H.6. However, 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.

To investigate the relationship between a plant having imperfect flowers and producing hybrids, I

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engineering research."

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.

Next, I investigate the impact of being issued a patent on abnormal stock price returns. Daily stock price data are from the Wharton Research Data Services (WRDS) 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 a review of stock market event study analyses by 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, thus allowing the relationship between S&P 500 movement and stock prices to vary by year. The residual from this estimation (i.e., the movement in stock price that is not predicted by market movement) is defined as the abnormal return. All reported estimates are very similar using raw returns as the dependent variable rather than abnormal returns (not reported).

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 included in the stock market analysis: 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 are 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. The main conclusion is that 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.

A.3.1 J. E. M. Ag Supply, Inc. v. Pioneer Hi-Bred International

While patent protection was introduced for plant biotechnology in 1985, the US Supreme Court did not rule officially on its constitutionality until the 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.[76] 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 all patents issued *after* the Supreme Court decision. If the decision significantly increased the value of patent protection to firms, we would expect the interaction to be positive. However, using the sample of all patents issued to publicly traded firms between 1985-2010 or 1985-2005, the estimated interaction is negative and statistically indistinguishable from zero. The value of being issued a plant biotechnology patent for innovating firms 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 the Supreme Court decision. The same is true in the raw data for private research investment. Whereas between 1985 and 1990, private research investment related to the sample of crops in the analysis increased by 61%, between 2001 and 2006 it increased by just 14%.

A.4 Balance tests

Table A3 reports a series of balance tests comparing treatment and control crops in the analysis. 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 Food and Agriculture Organization (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 (2021a). The bottom two rows use crop-level area harvested and price, estimated separately in 1975 and 1984 and published by the USDA.

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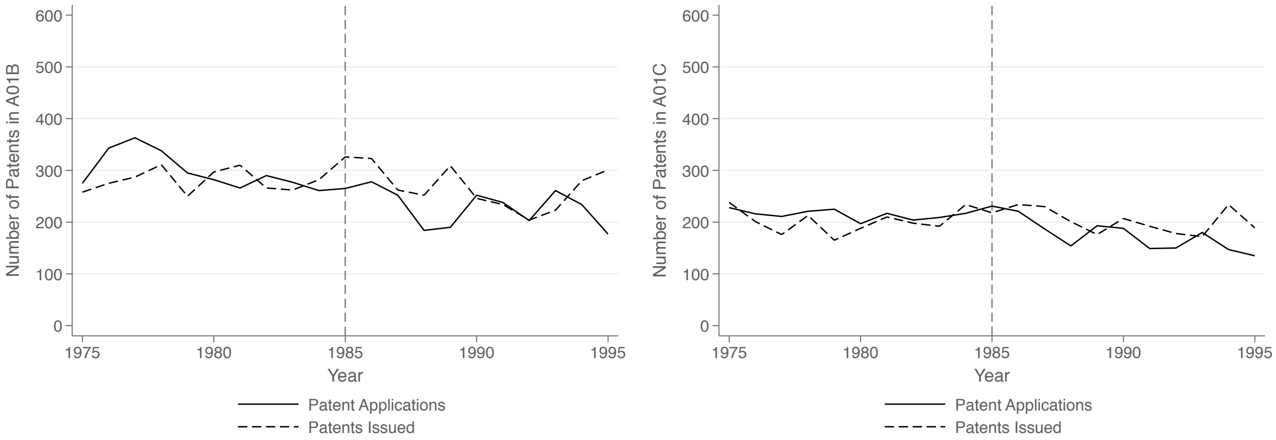
[76] Several pieces of evidence suggest they were valuable to innovating firms *prior* to 2001. First, Figure 2 shows a surge of patenting activity after 1985 and before 2001. Second, the sample period used to estimate the positive effect of being issued a patent on abnormal stock returns in Table 1 is entirely prior to 2001. Third, in his majority decision, Justice Clarence Thomas noted the widespread use and acceptance of utility patents for plant biotechnology to justify his ruling.

Figure A1: **Countries with Intellectual Property Protection for Plant Varieties.** This map displays in green all countries that have adopted intellectual property protection for agricultural biotechnology and plant varieties. These data were compiled by the Union for the Protection of Varieties (UPOV), an international organization that oversees and codifies the international introduction and enforcement of intellectual property protection for plant varieties.

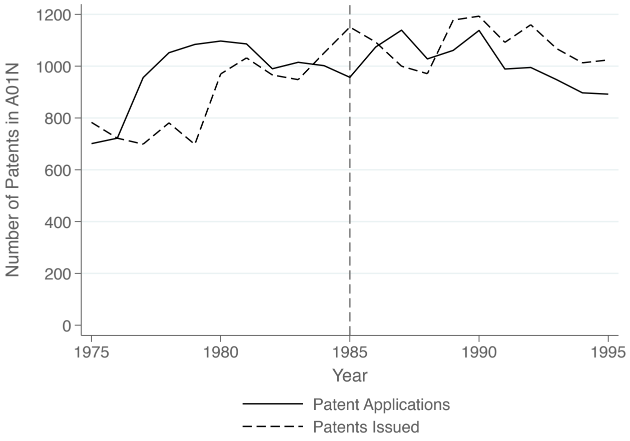


(a) Soil Working (CPC A01B)

(b) Planting, Sowing, and Fertilizing (CPC A01C)

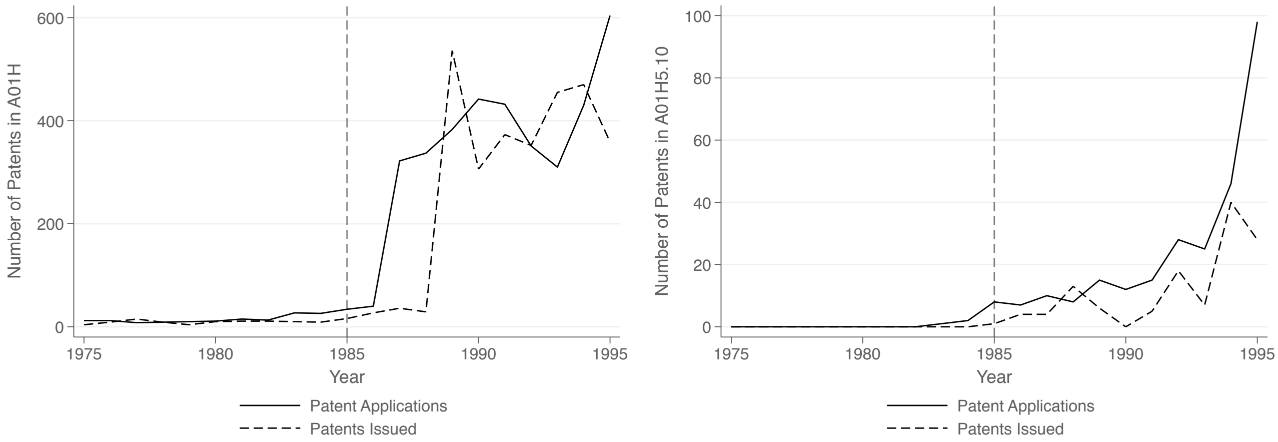
(c) Harvesting and Mowing (CPC A01D)

(d) Processing and Post-Harvest (CPC A01F)



(e) Biocides and 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 dented in the caption.



(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).

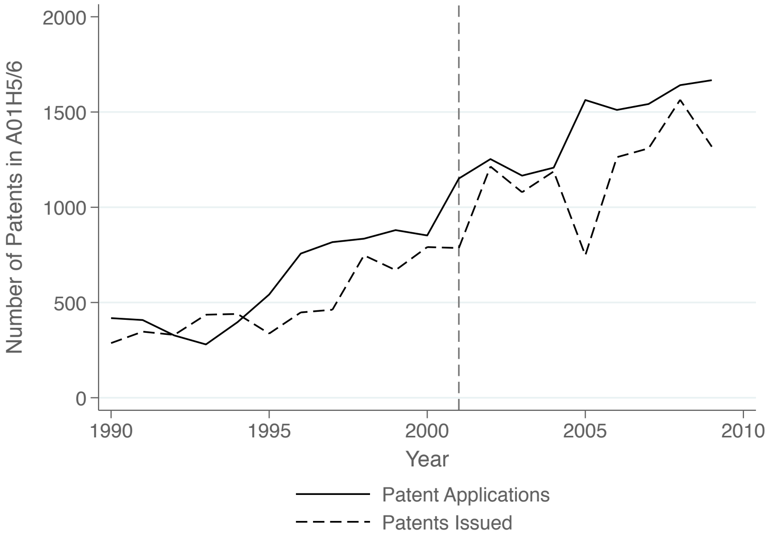
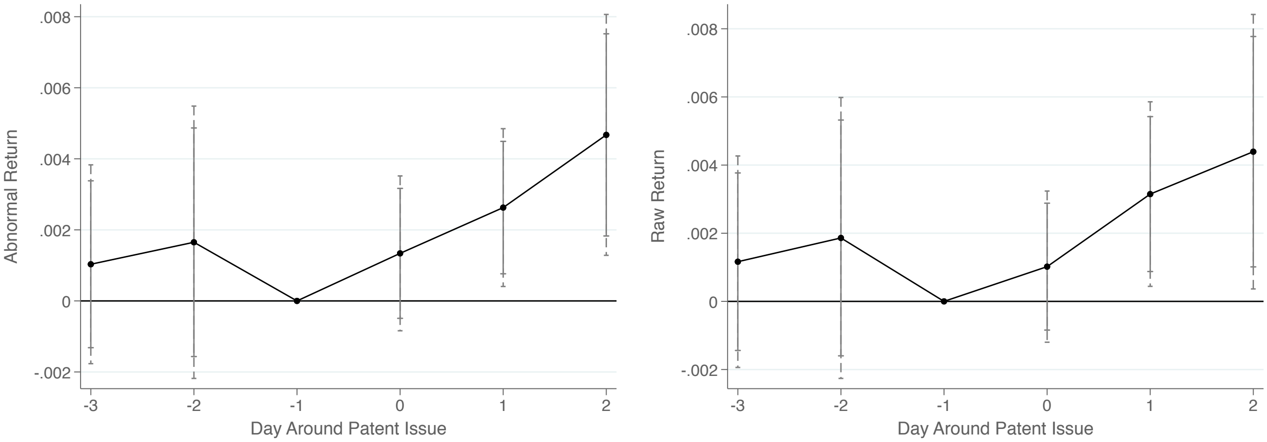


Figure A4: **Variety Patents: Time Trend 1990-2010.** This figure displays the count of patent applications and patents issued in CPC classes A01H.5 and A01H.6. The vertical dotted line denotes the year of the Supreme Court decision in *J. E. M. Ag Supply, Inc. v. Pioneer Hi-Bred International*.



(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.

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
Crop with Imperfect Flowers (=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 Patent Protection, Before and After the Supreme Court Ruling

	(1)	(2)
	Dependent Variable is Abnormal Returns	
	1985-2010	1985-2005
I (Post Issue Date)	0.00297**	0.00297**
	(0.00141)	(0.00141)
I (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) Not Hybrid vs. Hybrid	(4) Variable Name	(5) Sample Mean	(6) Not Hybrid vs. Hybrid
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.

B Crop-Level Analysis: Additional Results and Robustness

B.1 Additional crop-level results and robustness

This section reports the additional results and sensitivity checks that accompany the main crop-level analysis (Section 5). Table B1 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. The first set of estimates investigates the mechanism underpinning the baseline results. Table B2 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.4. 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 (columns 1 and 4) but a much smaller effect that is statistically indistinguishable from zero using the sample of perennial crops (columns 2 and 5). These results are consistent with the potential profits from being able to re-sell varieties to farmers each year being an important driving mechanism.

I also report a range of sensitivity checks of the baseline results on the relationship between patent protection and variety development. Figure B1 reports the event study estimates with an extended pre- and post-treatment period.[77] Table B3 shows that the results are very similar controlling directly for pre-trends; 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. These controls absorb trends in pre-period variety development. Table B4 shows the results are very similar under a series of weighting schemes and sample restrictions. Table B5 documents that the estimates are very similar clustering standard errors by *genus* and Table B6 shows that the results are also similar if the regressions are estimated at the genus-by-year level (rather than the crop-by-year level). Information on the genus of each plant species was obtained by matching each crop to the ECOCROP database. Table B7 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 B8 shows that the results are robust controlling directly for crop-level producer prices, as estimated at the national level by the USDA, suggesting that the findings are not affected by crop-level policy (e.g. price support) or demand.[78]. Finally, Table B9

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[77] Figure B4 documents that the results are very similar controlling for a staple crop indicator interacted with a full set of year fixed effects, suggesting that the findings are not driven by the distinction between staple and non-staple crops. Figure B5 reproduces the baseline event study figure after controlling for a C4 photosynthesis indicator interacted with year fixed effects, and the result is very similar. This suggests that the findings are not driven by differences in photosynthetic potential across crops.

[78] This could constitute a bad control, since producer price changes could no doubt be an outcome of technological progress. Nevertheless, this sensitivity check suggests that the findings are not driven by any demand side or policy forces that directly affect prices.

shows that the results are virtually identical after excluding all crops that reproduce vegetatively.[79]

The rest of the results in this section relate to the additional crop-level dependent variables. Table B10 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). I find no effect on the total number of scientist years but a positive effect on research dollars per scientist-year, suggesting that the main results on spending are driven by individual researchers accumulating resources rather than an expansion in the number of researchers. Figure B7 reports event study estimates for the patent grant dependent variables; the estimating equation is Equation (3), reported in the main text. Figure B8 reports the time series trend in producer prices (relative to 1984) for all crops for which price data are collected by the USDA, separately for treatment and control crops; consistent with patent rights leading to increased productivity, after 1985 we observe a relative decline in the price of treatment compared to control crops. Finally, while I am unaware of systematic seed price data for most crops, Figure B9 displays the trend in corn and cotton seed prices over the sample period. While the two were on similar trends prior to 1985, they diverge around 1990, with cotton (a treatment crop) increasing substantially relative to corn (a control crop).

B.2 Genetic modification and the "biotechnology revolution"

An important conceptual 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 protect intellectual property may have been an important force driving technological progress in GM technology and genetically modified organism (GMO) development. Many GMOs in use today are non-hybrids and require patent protection to prevent farmers from saving and re-using seeds; in the case of GMOs, 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 importance of this protection for GMO sale profitability is thrown into stark relief by the fact that in India, which does not protect intellectual property for plants, seed companies often only sell *hybridized* GMOs in order to protect their inventions, while non-hybridized versions are sold in other countries that protect intellectual property for seeds, like the US and Australia (see Pulla, 2018).

A potential concern, however, would be if there were some reason that treatment crops in the analysis were more likely to be the subject of GM research *for reasons other than changes in patent protection*. The ability to genetically modify organisms had been progressing for years and likely would have been improved even in the absence of changes in patent law; if this shift in the "supply" of scientific knowledge for some reason disproportionately affected treatment crops, this would be cause for concern. Therefore, I address this issue head-on empirically. First, the first GMOs were not released commercially until the end of this paper's main sample period. The first GMO *in the world* was released by Calgene in 1994; the now-ubiquitous (and somewhat infamous) Roundup-Ready varieties produced

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[79] In the baseline results, I show that the findings are robust to including an indicator that equals one if a crop can reproduce vegetatively interacted with a full set of year indicators; here, I show that the results are also similar excluding these crops from the sample entirely.

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).

The main event study figures *end* in 1996 (see Figures B2a and B2b) and across specifications, statistically significant effects are detected prior to 1990.[80] Figure 7 documents significant effects at the county-level prior to the adoption of any genetically modified varieties. Thus, the paper's main findings emerge prior to the release of any GMOs, suggesting the main estimates could not be driven exclusively by GMO development.

Second, as discussed briefly in the main text, 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.[81] I show that all crop level estimates reported in Section 5 are robust to controlling flexibly for whether or not a GMO has 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. These controls capture the dynamic effect of being a crop for which a GMO has been released or developed; all results are robust to the inclusion of these controls.

Third, most GM technology development has directly related to conferring resistance to specific pests and pathogens (see Vanderplank, 2012; Van Esse et al., 2020). GMOs are generally referred to as either "insect resistant" (IR) or "insecticide/herbicide tolerant" (IT/HT) (Perry et al., 2016); as a result, the hostility of the pathogen environment facing each crop—and the particular composition of pests and pathogens—is a key determinant of GMO development (Oerke and Dehne, 2004). Thus, an additional strategy to control for GMO demand is to control directly for features of the pest and pathogen environment.

To do this, I rely on data on the global distribution of crop pests and pathogens in the Centre for Agriculture and Bioscience International's (CABI) Crop Protection Compendium (CPC), compiled by Moscona and Sastry (2021b). The CABI CPC reports which crop-damaging viruses, bacteria, plant-eating insects, fungi, weeds, and protest diseases are present in each country, as well as which crops they affect. Using this information, I estimate the number of pathogens that affect each crop in the U.S. (as well as every other country), as well as the identity of each pathogen. Focusing on the main results with plant varieties as the dependent variable, I find that: (i) $\beta = 0.788$ (0.271) controlling for the number of crop-damaging pests and pathogens in the US interacted with year fixed effects; (ii) $\beta = 1.011$ (0.374) when I also control for the GMO indicators interacted with year fixed effects; and (iii) $\beta = 1.023$ (0.355) when I also control for the number of crop-damaging pests and pathogens in the EU (another important source of agricultural technology demand) interacted with year fixed effects. The results are also similar controlling directly for pest and pathogen *fixed effects*; to select among the thousands of potential controls, I use post-double LASSO and, despite the stringency of this specification, the results are again very similar.

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[80] An interesting observation is that the yearly effects plotted in Figure B1 do seem to increase somewhat after the mid-1990s, suggesting that there could be an important interaction between patent protection and GMO development; this raises the possibility that GMO release was facilitated by patent protection. However, this observation is only suggestive and directly identifying GMOs in the *Variety Name List* is, to my knowledge, not possible.

[81] See the US FDA page on GMO authorization, along with a list of crops for which GMO varieties have been released, here: `https://www.fda.gov/food/agricultural-biotechnology/gmo-crops-animal-food-and-beyond`. The crops for which GMOs have been ether commercialized or developed are also noted in Table B1.

B.3 Food Prices

The main paper investigates the impact of patent rights on technological progress and on downstream agricultural productivity; on average, the consumers of new technology (i.e. farmers) benefitted as a result of the change in legal regime. A question that is not answered in the paper is the impact of patent rights on the final consumers of *food*. Do consumers of food benefit from higher productivity in the form of lower prices? Or are the rents from new technology accumulated by the technology developers, farmers, and intermediaries? Due to the lack of comprehensive consumer price data for a large sample of crops, I leave this analyisis out of the main text.[82] To make some progress on this question, however, I compiled commodity-by-month level consumer price data for all goods included in the US Consumer Price Index (CPI), which are publicly accessible beginning in 1980. I merged these commodities to crops in the baseline varieties data; this yielded 40 unique CPI codes corresponding to 26 crops (several crops, like sugar and coffee, are related to multiple products). I then estimate (2) on this restricted sample, using (log of) the consumer price in the commodity-month as the dependent variable, and month-by-year instead of year fixed effects.

Estimates from this specification are reported in Table B11. While the small sample size means these results will necessarily be imprecise, I estimate a negative effect of patent protection on consumer prices, which is significant at the 10% level when the sample period is extended to 2000. Economically meaningful positive values occupy a small fraction of two standard deviation confidence intervals around either estimate. These results suggest that patent rights and the corresponding downstream productivity growth, if anything, reduced food prices. There is no evidence that patent rights had the perverse effect increasing the price of food faced by consumers, for example through induced changes in market structure. Economically meaningful positive effects occupy a small share of the two standard error confidence interval around the point estimates.

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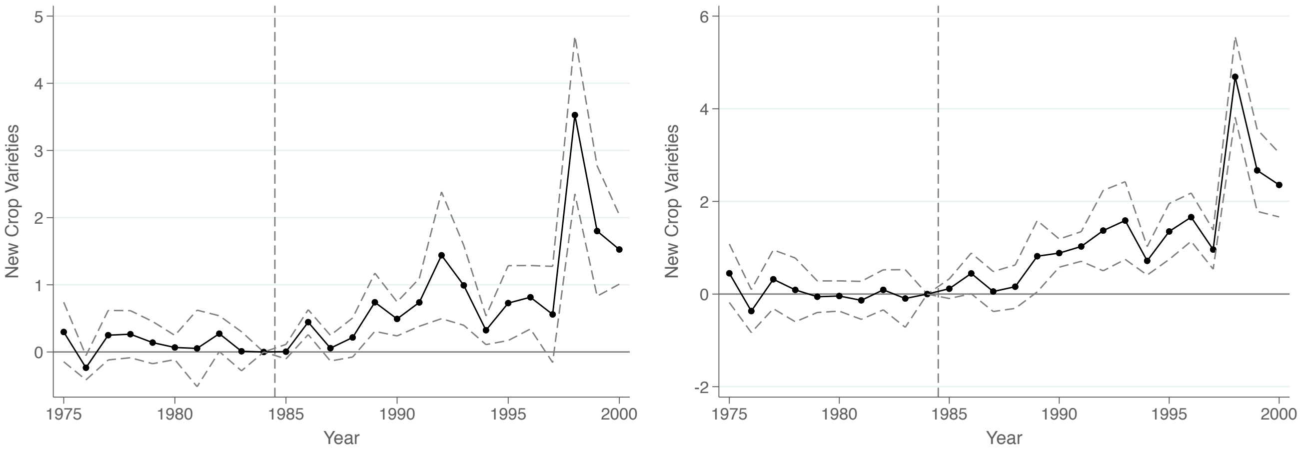
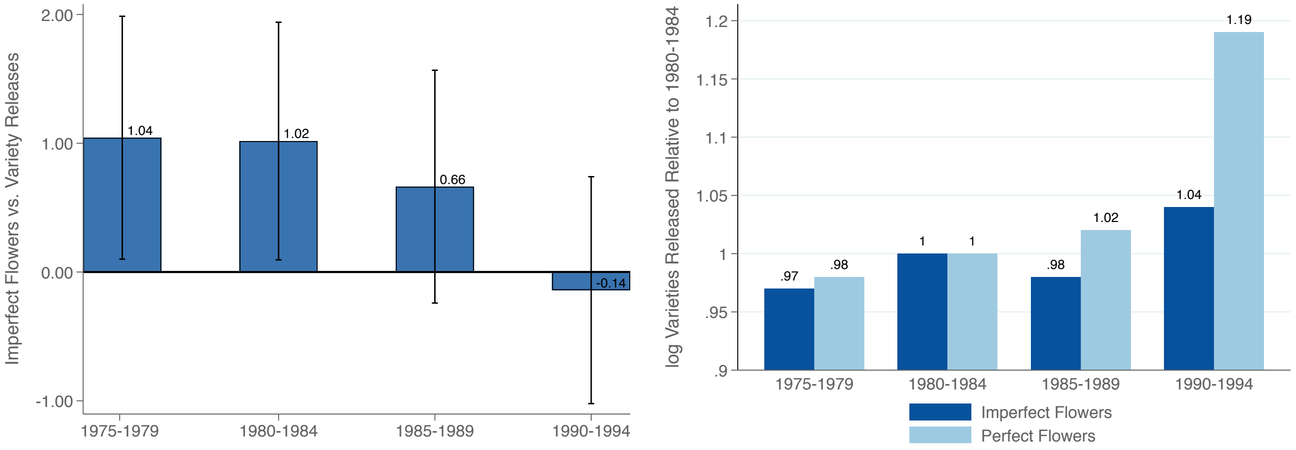
[82] Detailed (e.g. scanner) consumer price data are not available until later years; Nielsen data, for example, are not available until 2006. I thank Jeremy Majerovitz for a discussion on this point.



(a) No Controls

(b) All Baseline Controls

Figure B1: **Patent Protection and Novel Plant Varieties Over Time.** Coefficient estimates from poisson 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) Perfect vs. Imperfect Crops Over Time

(b) Variey Releases Over Time

Figure B2: **Variety Development: Raw Differences and Time Trend.** Figure B2a reports the relationship between variety releases and an imperfect flower indicator in each five year time period from a Poisson pseudo maximum likelihood regression model. 95% confidence intervals are reported. Figure B2b 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.

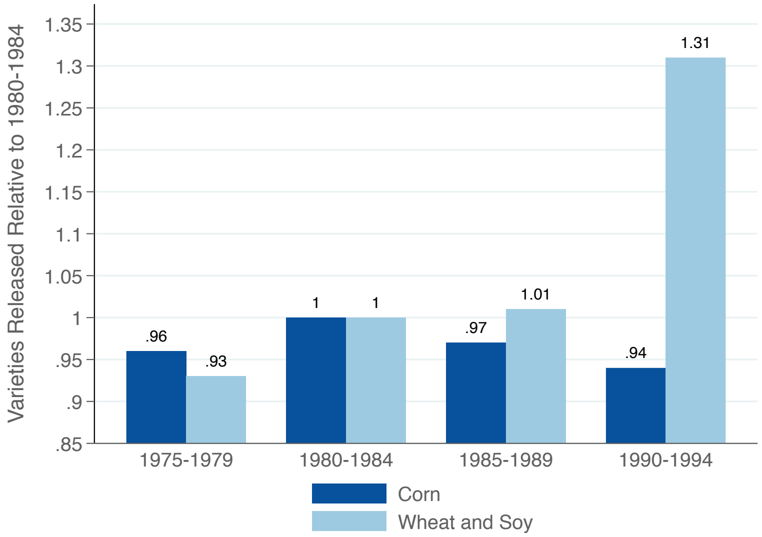


Figure B3: **Variety Development: Time Trend for Corn, Wheat, and Soy.** This figure shows the raw number of varieties released for the two largest crops with perfect flowers (i.e. crops in the treatment group), wheat and soy, and the largest crop with imperfect flowers (i.e. crops in the control group), corn, during each five year window, relative to varieties released during the 1980-1984 period.

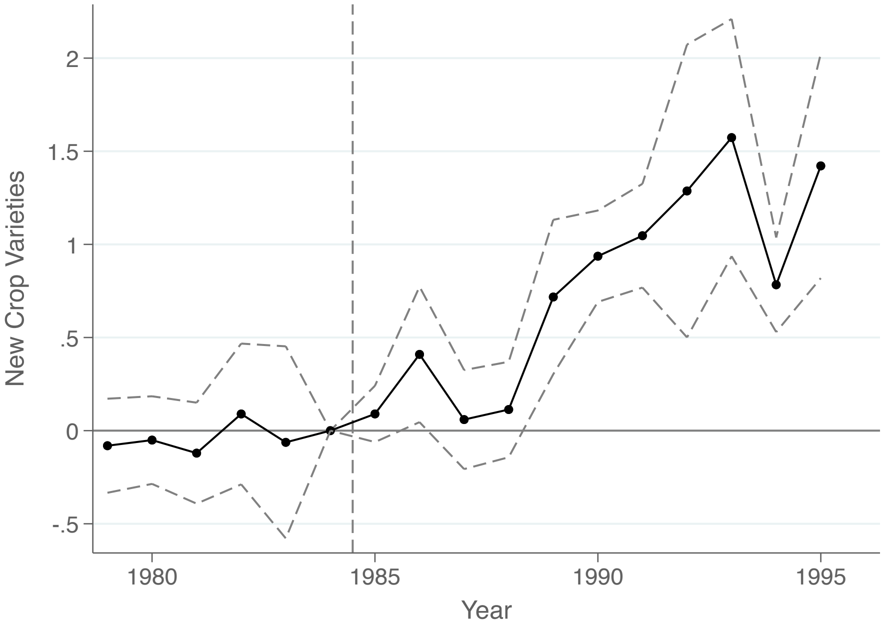


Figure B4: **Patent Protection and Novel Plant Varieties Over Time.** Coefficient estimates from poisson estimates of Equation (3). I also include on the right hand side a major field crop indicator (i.e. corn, wheat, soy, cotton) interacted wth year fixed effects. The dependent variable is the number of novel plant varieties in the crop-year. Standard errors are double clustered by crop and year; 95% confidence intervals are reported.

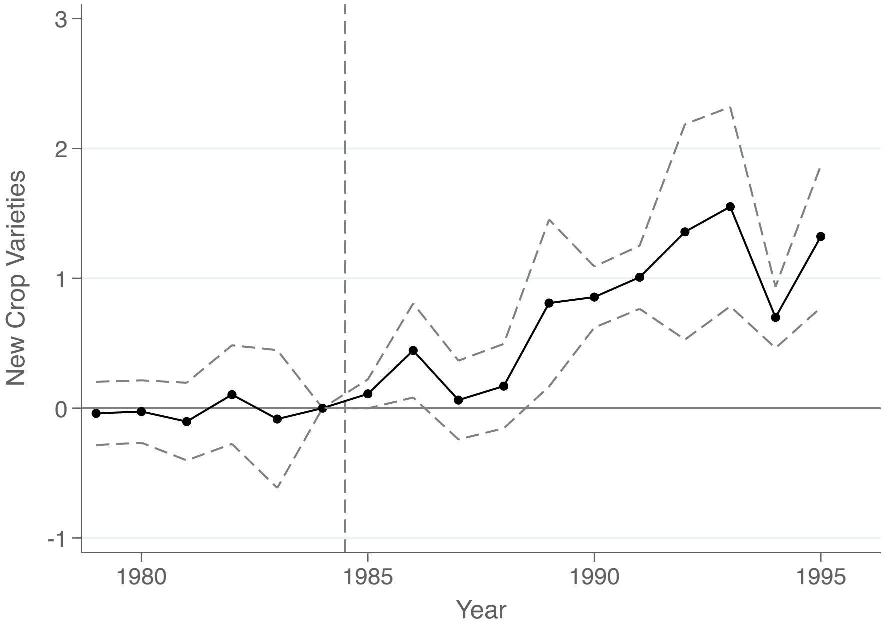


Figure B5: **Patent Protection and Novel Plant Varieties Over Time.** Coefficient estimates from poisson estimates of Equation (3). I also include on the right hand side a C4 photosynthesis indicator interacted with year fixed effects. The dependent variable is the number of novel plant varieties in the crop-year. Standard errors are double clustered by crop and year; 95% confidence intervals are reported.

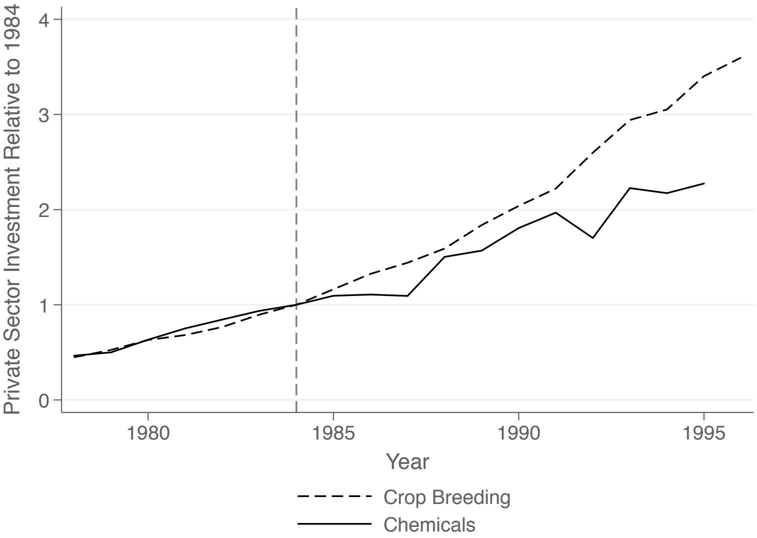
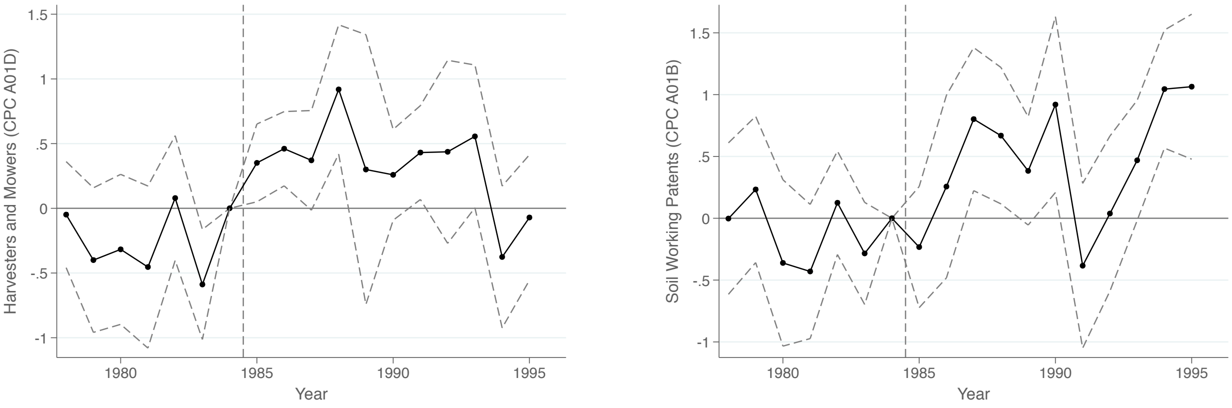


Figure B6: **Private Sector Investment in Breeding and Chemicals.** This figure plots total private sector research investment in (i) crop breeding and (ii) agricultural chemicals, relative to investment in 1984. The data were compiled from from Klotz et al. (1995) and Fernandez-Cornejo (2004).



(a) Harvesting and Mowing Technology

(b) Soil Working Machinery and Accessories

Figure B7: **Patent Protection and Complementary Technologies Over Time.** Coefficient estimates from Equation (3). The dependent variables are noted at the bottom of each sub-figure. Standard errors are clustered by crop and 95% confidence intervals are reported.

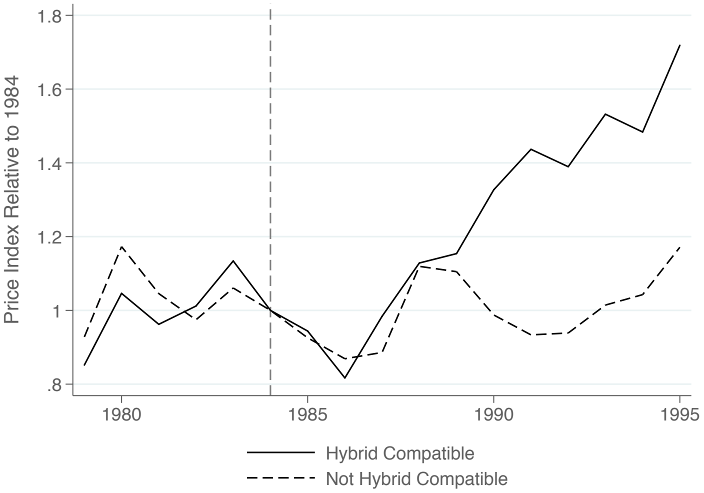


Figure B8: **Producer Prices.** This figure plots producer prices (relative to 1984) for hybrid compatible and hybrid incompatible crops over time. Producer price data were collected by the USDA.

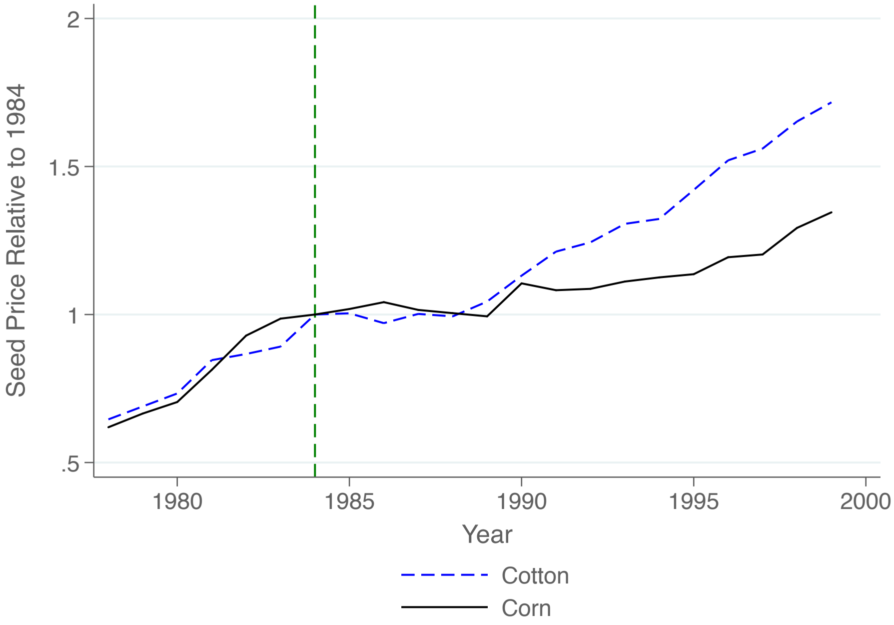


Figure B9: **Corn vs. Cotton Seed Prices.** This figure plots the average price of corn seeds and cotton seeds in the US, relative to the price in 1984.

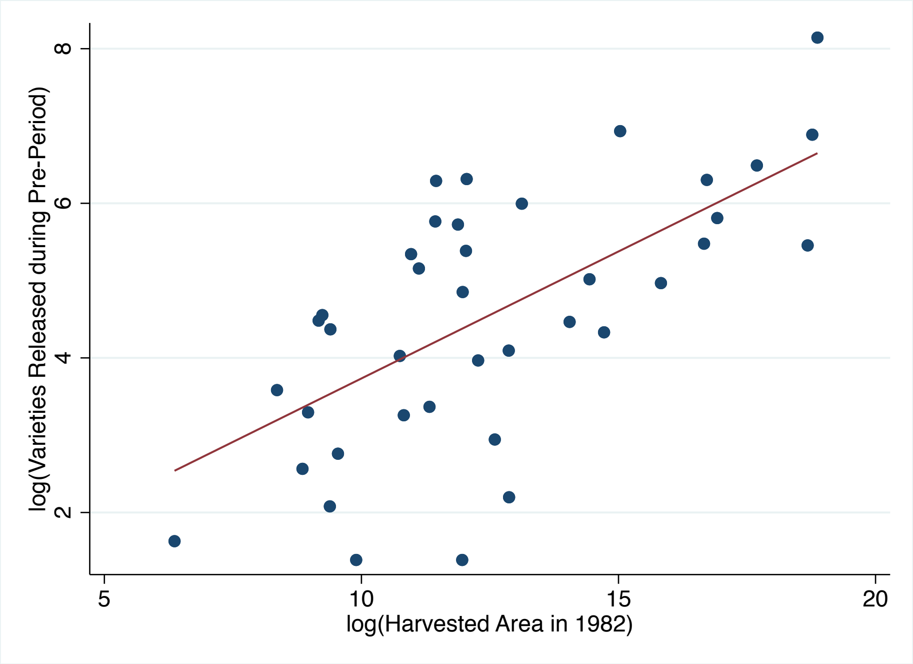


Figure B10: **Pre-Period Harvested Area vs. Released Varieties.** This figure reports the binned scatter plot between (log of) harvested area in 1982 and (log of) variety releases during the pre-1985 period. The coefficient estimate from the equivalent regression is 0.329 with a standard error of 0.063.

Table B1: 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 B2: 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		
Not Hybrid Compatible$_i$ x $\mathbb{1}_t^{Post\,1985}$	0.828***	0.162	0.828***	0.241**	-0.00709	0.241**
	(0.262)	(0.167)	(0.269)	(0.0965)	(0.0664)	(0.0983)
Perennial x Not Hybrid Compatible$_i$ x $\mathbb{1}_t^{Post\,1985}$			-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 B3: 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	
Not Hybrid Compatible$_i$ x $\mathbb{1}_t^{\text{Post 1985}}$	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 B4: Patent Protection and Novel Plant Varieties: Weighted Estimates and Sample Restrictions

	(1)	(2)	(3)	(4)	(5)
	Estimates Weighted by (log of) Pre-Period Varieties		Excluding Bottom 25% Pre-Period Varieties	Excluding Top 25% Pre-Period Varieties	Excluding Influential Obs. based on Cook's Distance
Dependent Variable:	New Varieties (asinh)				
Specification:	OLS	OLS	OLS	OLS	OLS
Not Hybrid Compatible$_i$ x $\mathbb{1}_t^{\text{Post 1985}}$	0.152**	0.447**	0.400***	0.168***	0.295**
	(0.0697)	(0.190)	(0.134)	(0.0256)	(0.111)
Crop Fixed Effects	Yes	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes	Yes
All Baseline Controls	No	Yes	Yes	Yes	Yes
Observations	2,280	2,060	1,400	1,540	1,921
R-squared	0.829	0.841	0.818	0.576	0.915

Notes: The unit of observation is a crop-year. All specifications include crop and year fixed effects. In columns 1-2, the regression is weighted by (log of) crop varieties released during the pre-period. In columns 3 and 4, the sample excludes crops with pre-period variety releases in the bottom 25% and the top 25% respectively. Column 5 excludes bservations with Cook's Distance greater than 4/n where n is the number of observations in the regression. Standard errors, double clustered by crop and year, are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

Table B5: 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
Not Hybrid Compatible$_i$ x $\mathbb{1}_t^{Post\,1985}$	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 B6: Patent Protection and Novel Plant Varieties: Genus-Level Estimates

	(1)	(2)
Dependent Variable:	New Varieties (count)	New Varieties (asinh)
Specification:	Poisson	OLS
Not Hybrid Compatible$_i$ x $\mathbb{1}_t^{Post\,1985}$	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 B7: Patent Protection and Novel Plant Varieties: Investigating Cytoplasmic Male Sterility

	(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)							
Not Hybrid Compatible$_i$ x $\mathbb{1}_t^{Post\,1985}$	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 B8: Patent Protection and Novel Plant Varieties: Controlling for Output Prices

	(1)	(2)	(3)	(4)
	New Varieties (count)		New Varieties (asinh)	
	Poisson		OLS	
Not Hybrid Compatible$_i$ x $\mathbb{1}_t^{Post\,1985}$	0.888**	1.855***	0.296*	1.251**
	(0.417)	(0.432)	(0.158)	(0.468)
Producer Price	0.0146	0.0150*	0.00180	0.00168
	(0.0140)	(0.00780)	(0.00377)	(0.00487)
Crop Fixed Effects	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes
All Baseline Controls	No	Yes	No	Yes
Observations	315	307	315	307
R-squared			0.770	0.844

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. All columns also include the crop-specific producer price, as measured at the national level by the USDA, as a control. Standard errors, double clustered by crop and year, are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

Table B9: Patent Protection and Novel Plant Varieties: Excluding Vegetatively Reproducing Crops

	(1)	(2)	(3)	(4)
	New Varieties (count)		New Varieties (asinh)	
	Poisson		OLS	
Not Hybrid Compatible$_i$ x $\mathbb{1}_t^{\text{Post 1985}}$	0.784***	0.871***	0.164***	0.332**
	(0.264)	(0.279)	(0.0425)	(0.122)
Crop Fixed Effects	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes
All Baseline Conctols	No	Yes	No	Yes
Observations	1,280	1,200	1,300	1,200
R-squared			0.830	0.843

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. The regression sample excludes all crops that can re-produce vegetatively. Standard errors, double clustered by crop and year, are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

Table B10: Patent Protection and R&D Investment: Scientist Years and the Concentration of Funding

	(1)	(2)	(3)	(4)
Dependent Variable:	Scientist-Years Funded, Public + Private (asinh)		Total Investment per Scientist-Year (asinh)	
Not Hybrid Compatible$_i$ x $\mathbb{1}_t^{\text{Post 1985}}$	-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 B11: Patent Protection and Consumer Prices

	(1)	(2)
	Dependent Variable is log(Consumer Price)	
	1980-1995	1980-2000
Not Hybrid Compatible$_i$ x $\mathbb{1}_t^{Post\,1985}$	-0.0300	-0.0402*
	(0.0220)	(0.0216)
Commodity Fixed Effects	Yes	Yes
Year Fixed Effects	Yes	Yes
Observations	4,943	6,408
R-squared	0.965	0.967

Notes: The unit of observation is a commodity-month. All specifications include commodity and month-by-year fixed effects. The outcome variable is (log of) commodity-level consumer prices. Standard errors, double-clustered by commodity and year, are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

C County-Level Analysis: Additional Results and Robustness

C.1 Time-Series Trends

This section reports trends in the raw county-level data and puts the paper's findings in the context of longer term trends in US agricultural production. Figure C1 reports time series trends in the raw data for a series of variables in order to characterize changes to the agricultural sector over the sample period. All graphs report the value of each variable in each year, averaged across counties and weighted by total agricultural land (in acres). This was a period of major growth in the agricultural sector. Figure C1a documents that the value of agricultural land was increasing during the sample period (with a slight tip in the late 1980s) and C1b shows a similar pattern for agricultural profits. Figure C1c shows that total input spending was increasing monotonically during this period. Thus, the growth in profits occurred despite the fact that farmers were also spending more on inputs, consistent with an important role of technological progress, which required higher input spending but also increased productivity. Indeed, Figure C1d documents that the share of spending on seed and variety inputs increased substantially during the sample period, with much of the increase happening after 1985; from 1982 to 2002, this share increased by roughly 60%. Longer time-series data published by the USDA show that since 1950, spending on capital and intermediate inputs have increased while the role of land and labor has declined; the authors at the USDA argue that this pattern highlights the importance of "technological advancements" in driving US agricultural productivity growth.[83]

Figures C1e and C1f show that this was also a period of major concentration. C1e displays the time-series trend in the share of land occupied by farms that were at least 1000 acres large, and C1f displays the time series trend in the share of *farms* that were at least 1000 acres large.[84] Both point toward major consolidation over the sample period. The USDA also reports longer run trends in consolidation by combining a range of different sources, including both the Census of Agriculture and the data series *Farms and Land in Farms*. While the process of land consolidation continued during the paper's sample period, a majority of the consolidation happened during prior decades. The number of farms in the US declined from $\sim$ 7 million during the 1930s to $\sim$ 2.5 million in 1985; the steepest decline occurred between 1940 and 1970. Between 1985 and the present, the number of farms declined from about 2.5 to about 2 million.[85] The total amount of land in farms remained relatively stable throughout the 20th century. Thus, concentration of agricultural land was already beginning to stabilize during this study's sample period and much of the consolidation of US agricultural land had already occurred.

This period was also one of substantial concentration in the seed industry. Bonny (2017, p. 9) compiles data showing a substantial increase in the five firm concentration ratio (C5), which picked up after 1985. While the C5 was 10 in 1985, by 2005 it had reached 30. Blair (1999) attributes this pattern to the impact of *Ex Parte Hibberd* and introduction of patent rights directly. She writes, "The seed industry is obviously in a position of flux [...] due to the flurry of acquisitions and mergers. A great

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[83] See the data series here: `https://www.ers.usda.gov/amber-waves/2018/march/agricultural-productivity-growth-in-the-united-states-1948-2015/`.

[84] Greater than 1000 acres is the largest farm size bin reported by the US Census of Agriculture during this period.

[85] See the full data series here: `https://www.ers.usda.gov/data-products/chart-gallery/gallery/chart-detail/?chartId=58268`

deal of this activity is because of the research investment in plant breeding and biotechnology and, more importantly, the protection for the rights to those research efforts through intellectual property protection. [I]t is the largest patent holders that are the most active in purchasing and collaborating with each other to position themselves for the future" (Blair, 1999, p. 326). While directly investigating the impact of patent rights on industry consolidation is beyond the scope of this paper's analysis, it is important background context to keep in mind and a potentially exciting area for future work.

Finally, in Figure C2 I display the time series trend in agricultural land value—the main dependent variable in the county-level analysis—separately for counties with high and low exposure to the change in patent law. As expected from the paper's main results, high and low exposure counties are on similar trends prior to 1985; however, they diverge thereafter and high-exposure counties experience (relatively) faster growth in the value of agricultural land. Also apparent in this graph is the fact that, while the introduction of patent rights had a large impact on land values, it is far from explaining the full increase in agricultural land value during the time period, in both treatment and control counties.

C.2 Additional county-level results and robustness

This section reports additional results corresponding to the county-level part of the main empirical analysis (Section 6). Figure C3 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.

Table C1 reports the t-statistic from the baseline county-level estimates (column 3 of Table 6) 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. Following Conley, I report estimates using a uniform spatial weighting kernel, but the results are very similar using a linearly decaying kernel (not reported). 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. This simple strategy generates more conservative standard errors than the more complex spatial and temporal adjustment strategies from column 1-5.

In Table C2 I report a version of the baseline results, structured identically to Table 6, 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 C3 reports equivalent estimates, except crops for which CMS systems have been developed are assigned to the control group. In Table C4 I report a version of the baseline results restricting the sample period to 1974-1997 (the sample period for the main results is 1969-2002). It is reassuring that the results are so similar focusing on a sample of years very close to the policy shift. Figure C4 reports event study figures when the dependent variable is spending on seeds and agricultural profits.

Table C6 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. Any across the board increase in input spending—for example, driven by an expansion of total cropland—should show up in non-variety input spending as well.

Table C7 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 is computed using 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 the standard deviation in farm profits, one potential measure of profit fluctuations across years.

Next, I investigate the impact of shocks to agricultural production that took place during the sample period. Price and weather shocks have potentially major impacts on farm production. Crop prices are shaped by both domestic and international supply and demand, as well as government policy. Weather, and particularly extreme temperature, which has grown in prevalence in recent years, also has major impacts on agricultural productivity (Schlenker and Roberts, 2009). Moreover, recent evidence suggests that exposure to extreme temperature is also a strong predictor of the local severity of the Farm Debt Crisis, which might have had an independent effect on the value of land (Bergman et al., 2020). For either changing prices or temperature shocks to bias the results, their incidence would have to be correlated with local suitability to treatment compared to control crops, which does not seem plausible *ex ante*; nevertheless, to the extent that accounting for these time varying productivity shocks affect the baseline estimates, it could be cause for concern.

While producer prices could very well be an *outcome* of the change in patent law and therefore be considered a "bad control," in column 2 of Table C8 I control directly for each county's time varying output price bundle. To compute the output price bundle of county i at time t, I combine national producer price data from the USDA and county-level data on the area devoted to each crop:

$$\text{Output Price}_{it} = \sum_{c} \frac{\text{Area}_{it}}{\sum_{c'} \text{Area}_{c'i}} \log(\text{Producer Price}_{ct})$$

While, intuitively, this output price measure is positively correlated with agricultural land values, including this control has virtually no effect on the coefficient of interest. This finding suggests that the baseline estimates are not driven by price changes (or price support policy) during the sample period. In column 3, I control for the average temperature in the county during the decade, as well as the number of extreme growing degree days (GDDs), shown by Schlenker and Roberts (2009) and follow-up work to be the main channel through which temperature changes affect agricultural productivity. Again, the coefficient of interest remains similar, and also remains similar when both output price and temperature controls are included in the same specification (column 4).

Together, these estimates convey the robustness of the main county-level estimates, which are not sensitive to a range of potential strategies for estimating the standard errors, constructing the regressors of interest, or controlling for observables.

C.3 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. 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:

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

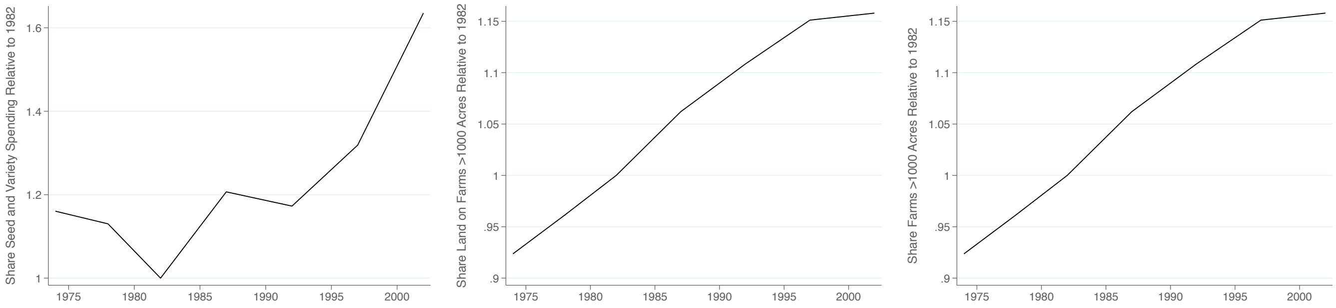
where t_1 is defined as the end of the sample period (in 2002) and t_0 is defined as the start of the sample period. Stated differently, this captures estimated local land value in a world where exposure to the change in patent regime is held at its pre-period level (that is, it is held at zero for all 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 land area in the US and using coefficient estimates from the specification in column 2 of Table 6.

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:

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

As noted in a footnote to the main text, 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; the need for such an assumption is sometimes referred to as an "intercept problem" when estimating aggregate effects from regional exposure to a shock. There is reason to believe that this assumption is reasonable in the present context and, if anything, represents a lower bound. The finding in Table 1 that patent protection for hybrid varieties had approximately zero impact on expected firm profits lends support to the assumption that counties that grew exclusively hybrid-compatible crops were unaffected by the change in patent law. Moreover, I find no evidence that crops in the control group experienced a reduction in innovation in *absolute* terms (see Figure B2) or that counties more exposed to control crops experienced an absolute decline in the value of agricultural land (see Figure C8). 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.

(a) Land Values (b) Total Profits (c) Total Spending



(d) Share Seed and Variety Spending (e) Share Land on Farms Over 1000 Acres (f) Share Farms Over 1000 Acres

Figure C1: **County-Level Time Series Trends.** All graphs report the value of each variable, averaged over all US counties and weighted by agricultural land area, relative to the value in 1982.

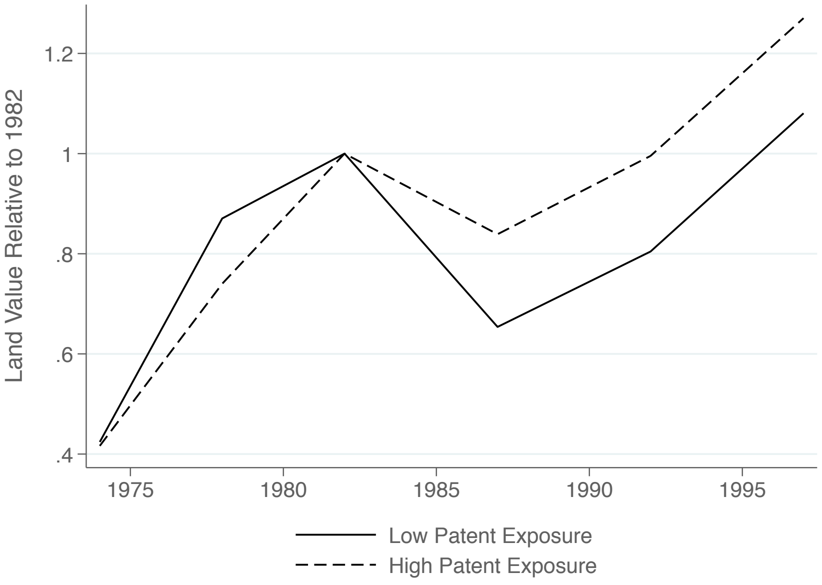


Figure C2: **Land Values Relative to 1982: High and Low Patent Exposure.** This graph reports the value of agricultural land per acre, averaged over all counties and weighted by agricultural land area, relative to the value in 1982 for both high and low patent law change exposure counties. High exposure is defined as all counties with a positive exposure measure.

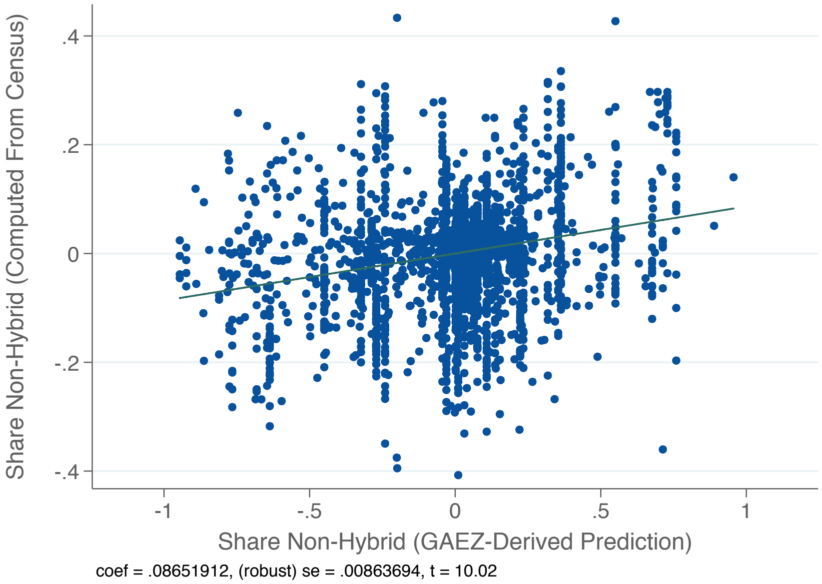
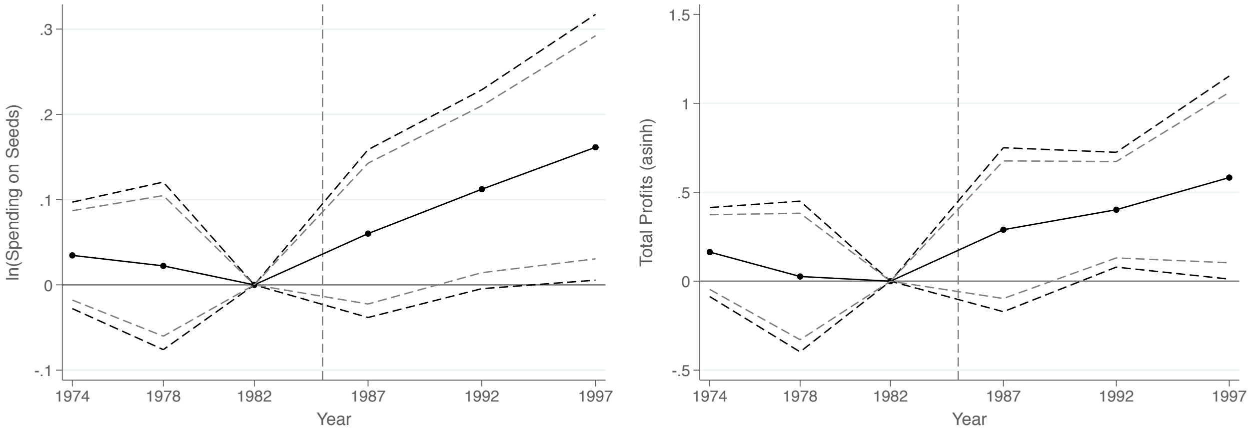


Figure C3: **GAEZ-Derived Prediction vs. Actual Share Hybrid Incompatible Cropland.** The unit of observation is a county. The graph displays a partial correlation plot between county-level GAEZ-derived prediction of the hybrid incompatible share and the hybrid incompatible share computed from the 1982 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 bottom.



(a) log(Spending on Seeds)

(b) Total Profits (asinh)

Figure C4: **County-Level Short Run Effects: Event Studies.** Coefficient estimates from Equation (3). The dependent variable is noted at the bottom of each subfigure and each specification contains the full set of controls from Table 8. The dotted lines display 90% and 95% confidence intervals.

Table C1: 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 C2: Patent Rights and Agricultural Land Value: Estimates with Actual Crop Shares

	(1)	(2)	(3)	(4)
	log Value of Land and Buildings Per Acre			
Exposure_i x $\mathbb{1}_t^{\text{Post 1985}}$	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 C3: Patent Rights and Agricultural Land Value: Cytoplasmic Male Sterility

	(1)	(2)	(3)	(4)
	log Value of Land and Buildings Per Acre			
Exposure_i x $\mathbb{1}_t^{\text{Post 1985}}$	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 C4: Patent Rights and Agricultural Land Value: Shorter Sample Period

	(1)	(2)	(3)	(4)
	log Value of Land and Buildings Per Acre			
Exposure_i x $\mathbb{1}_t^{\text{Post 1985}}$	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 C5: Patent Rights and Agricultural Land Value: Controlling for Irrigation

	(1)	(2)	(3)	(4)
	log Value of Land and Buildings Per Acre			
$\text{Exposure}_i \times \mathbb{1}_t^{\text{Post 1985}}$	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 C6: 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
$\text{Exposure}_i \times \mathbb{1}_t^{\text{Post 1985}}$	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 C7: Patent Rights and Profit Volatility

	(1)	(2)
	Δ Standard Deviation of Agricultural Profits	
Exposure_i	-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.

Table C8: Patent Rights and Agricultural Land Value: Price and Temperature Shocks

	(1)	(2)	(3)	(4)
	log Value of Land and Buildings Per Acre			
$\text{Exposure}_i \times \mathbb{1}_t^{\text{Post 1985}}$	0.0980***	0.0962***	0.101***	0.102***
	(0.0297)	(0.0288)	(0.0290)	(0.0287)
log Output Price Bundle		0.0544***		0.0639***
		(0.0182)		(0.0196)
County Fixed Effects	Yes	Yes	Yes	Yes
Census Round x State Fixed Effects	Yes	Yes	Yes	Yes
Temperature Controls	No	No	Yes	Yes
Observations	24,350	24,082	23,908	23,770
R-squared	0.921	0.937	0.945	0.947

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. The output price bundle is computed using national crop prices and the share of land area in each county devoted to each crop. Temperature controls include average temperature and the number of extreme growing degree days in the decade. Standard errors, double clustered by state-year and county are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels.