Patent Protection, Invention, and Productivity
Evidence from U.S. Agriculture*

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Abstract

Patent protection was introduced for novel crop varieties in 1985, and it affected crops differentially depending on their reproductive structures. Exploiting this variation across crops, I find that the introduction of patent protection increased innovative output, measured as the release of new plant varieties. It also increased private research investment and had positive spillover effects on innovation in complementary non-variety agricultural technologies. Next, I document that the introduction of patent protection increased productivity. First, I show that it led to an increase in crop yields. Second, I show that U.S. counties that, due to differences in crop-specific suitability, were more exposed to the change in patent law experienced an increase in land values following the introduction of patent protection. Even though more exposed counties increased spending on crop varieties, overall profits nevertheless increased, suggesting that productivity gains outweighed the higher cost of patented technologies. Despite these positive effects on average, large farms benefitted disproportionately and agricultural profits in areas with small farms declined following the introduction of patenting. Taken together, the results suggest that patent incentives had a major positive effect on innovation and downstream productivity, but also came with some distributional consequences.

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1 Introduction

What is the impact of being able to protect intellectual property on innovative output and productivity? There is a widespread belief that intellectual property protection underpins technological progress and productivity growth. The ability to profit from new ideas and inventions is at the heart of models of endogenous growth, and intellectual property protection is often listed among a set of institutions that are important for long run development (e.g. Romer 1990; Acemoglu and Robinson 2012). Nevertheless, our understanding of the empirical relationship between the availability of intellectual property protection and innovation is limited and remains a topic of intense debate (Lerner 2009; Moser 2016; Williams 2017). The impact of intellectual property protection on productivity is even less clear. Since patent protection is one of the primary policy levers used to encourage technological progress, understanding the relationship between patent protection, innovation, and downstream production is of critical importance.

This paper provides empirical evidence of the relationship between the availability of patent protection, technological progress, and productivity by investigating the introduction of patent protection for novel crop varieties in the United States. While intellectual property protection for most innovations has existed since the U.S.’s founding, full patent protection for crop varieties (e.g. seeds, runners, etc.) was not introduced until 1985, when the US Patent and Trademark Office (USPTO) ruled that seeds, plant tissue, and plants were patentable subject matter. In the words of William Lesser (1987):

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

Crucially, the change in patent law did not affect all crops equally. Certain crops – those for which it was feasible to produce hybrid varieties – had de facto intellectual property protection prior to the introduction of formal intellectual property protection (e.g. Fernandez-Cornejo et al. 1999; Fernandez-Cornejo 2004; Butler and Marion 2015). Hybrid varieties can only be produced accurately by the developer and, for biological reasons, cannot be reproduced by farmers or competing inventors or producers; this affords innovators with “built-in” intellectual property protection tantamount to patent protection (Gupta 1998). Non-hybrid varieties, however, once sold, are easily reproducible; contracting is required to prevent farmers or competing inventors from saving or selling improved varieties.

This logic forms the basis of the empirical analysis, a differences-in-differences design that compares crops that received formal intellectual property protection with a control group that already had de facto intellectual property protection prior to the introduction of patent rights. In order to analyze the consequences of the introduction of intellectual property protection, I first determined the set of crops that are “hybrid-compatible” and therefore had de facto protection

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1 Indeed, Boldrin and Levine (2013) 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” (p. 3). Also see Heller and Eisenberg (1998) on how “patents deter innovation,” published in Science.

2 See Ex parte Hibberd, 227 U.S.P.Q. 443.
prior to 1985. Since the existence of actual hybrid varieties is potentially endogenous, I instead use characteristics of each crop’s flower that determine the ease with which it is possible to develop a hybrid variety. If a crop has “perfect flowers” – flowers that contain both the male and female reproductive parts – it is much more difficult to generate a hybrid. When the male and female flowers are separate and on different parts of the plant, generating hybrid varieties is much cheaper and simpler (e.g., Wright 1980; Whitford et al. 2013; Bradford 2017). The details of plant reproduction and the relationship between hybridization and intellectual property protection are discussed in much more detail in Section 2.

In order to compare technological progress in hybrid-compatible compared to hybrid-incompatible crops over time, I compile a data set of crop-specific innovation. A common measure of innovation is patenting activity; however, since this paper investigates the impact of introduction of patent rights, patents themselves are not a useful outcome 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. The List, which has been compiled by the USDA since the late 19th century and which I obtained via a Freedom of Information Act (FOIA) request, is maintained in order to prevent fraud in the seed market and is designed to be a comprehensive list of all crop varieties released in each year. 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.” This data set makes it possible to track crop-level innovation in plant varieties – precisely the innovations that became patentable in 1985 – both before and after the introduction of patent rights.

I supplement the Variety Name List with three additional measures of crop-level invention. First, I compile data on research investment by crop from the USDA Current Research Information System (CRIS). To calculate research investment allocated to each crop in each year, I aggregated 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. The key benefit of the CRIS data is that it contains 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 can use the CRIS data to (imperfectly) compare the response of private and public investment to the availability of patent protection. Second, I compile data on crop-specific patenting in non-variety technologies. I assigned patents within relevant patent classes to individual crops if the crop name appears in the patent title, abstract, or keywords; these data make it possible to estimate spillovers of patent availability for varieties on innovation in other crop technologies. Third, I compile measures of crop yields in order to estimate the impact of patent rights on productivity directly. This makes it possible to test whether the innovative activity measured in the varieties data translated into measurable changes in productivity.

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. Wheat, on the other hand, has perfect flowers and hybrid varieties are not used.
I find that the introduction of patent protection led to a dramatic and persistent increase in the development of new crop varieties. While variety development in hybrid-compatible and hybrid-incompatible crop were on similar trends prior to 1985, following the change in patent law they diverged sharply. Compared to hybrid-compatible crops, hybrid incompatible crops experienced a 0.123 standard deviation increase in new variety development during the ten years following the introduction of patenting and a 0.167 standard deviation increase in new variety development during the twenty years following the introduction of patenting. Turning to research investment, I find that the availability of patent protection increased private research investment and did not have a significant effect on public research investment; thus, it also had a positive effect on the share of crop-specific research investment funded by the private sector.

Next, I investigate spillover effects of the introduction of patenting for plant varieties on innovation in crop-specific non-variety technologies. For certain technology classes – and intuitively, technologies like harvesters and planting mechanisms that anecdotally are most complementary with modern varieties – I find that the introduction of variety patenting led to an increase in innovative output. I find no evidence that variety patents led to a significant decline in any technology class, suggesting that the baseline results are not driven by shifting research activity toward variety development and away from non-variety agricultural technologies. Last, I document that the introduction of patent protection had a discernible positive effect on crop-level agricultural yields. The introduction of patent protection affected not only innovative output but also measurable components of agricultural productivity.

This first set of findings demonstrates that in this context, patent protection had a large positive impact on innovative activity. Patent protection, however, comes with potentially significant trade-offs. At least since Nordhaus (1969), models of patenting and innovation have emphasized the need to balance the potential benefits of patent protection with the costs to consumers in the form of higher prices for patented technologies. Understanding whether the innovative benefits outweigh these costs is crucial.

Moreover, figuring out who profits from patents sheds light on the distributional consequences of patenting activity. Do researchers extract all the rents from patented technologies, or are some of those rents passed on to consumers? Farmers may be better off following the introduction of patent protection if the productivity gains from new technology outweigh the potentially higher cost of inputs. Anecdotally, however, this is not always the case. There are myriad news stories of agricultural biotechnology companies threatening to sue or actively suing farmers for saving patented seed technologies and farmers, unable to compete on the market with old cultivars and unable to afford yearly re-purchase of modern seeds, losing their livelihoods. Monsanto, on the other hand, argues that its “continuous innovative cycle” is “fueled in part by patents” and that allowing farmers to save seeds would limit the ex ante incentives provided by patent protection, ultimately making farmers worse off.\footnote{For example, the documentary \textit{Food, Inc.} and other public interest stories have recently documented the potentially devastating economic consequences of companies like Monsanto preventing farmers from saving patented seed varieties. While many farmers had relied historically on the ability to save seeds from one season to the next, this practice...} In the end, they claim, farmers would be worse off without...
the availability of patent protection.

In order to investigate the impact of intellectual protection on downstream production, I conduct a second analysis at the U.S. county-level. 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 based on 1985 producer prices. I then compute the share of county land on which the model predicts hybrid incompatible crops – crops in the “treatment group” – are grown. I treat this share as a measure of each county’s exposure to the introduction of patent protection; I also validate the estimates of county-level exposure using the GAEZ data with actual data on the distribution of production across crops estimated using the 1982 Census of Agriculture. If a county specializes in hybrid compatible crops that already had de facto intellectual property protection, then the county was relatively unexposed to the change in patent law. If, on the other hand, a county specializes in crops for which patents are required in order to prevent seeds from being saved, sold, or used by other inventors, the county was exposed to the change in patent law.

To estimate the impact of patent protection on agricultural production, I combine county-level estimates of exposure to the law change with panel data of county-level characteristics of the farm sector from the 1974-1997 rounds of the US Census of Agriculture. I find that more exposed counties experience an increase in land values, which captures the net present value of future profits; according to the most conservative estimates, a one standard deviation increase in a county’s exposure to the introduction of patenting – as measured by the share of its cropland devoted to hybrid incompatible crops – led to a 0.19 standard deviation increase in land values after 1985. Thus, the long run effect of the introduction of patenting on agricultural profits was positive and significant. Intuitively, more-exposed counties also shifted land into crop production.

While changes in land values reflect long run changes in the profitability of county land, I use additional data from the Census of Agriculture to measure the impact of the introduction of patenting on expenditure and profits in the short run. I find that more-exposed counties experienced an increase in spending on seeds and seed-related inputs. However, farm profits also increased in more exposed counties counties during the sample period, suggesting that the productivity increase from patented technologies outweighed the higher input costs, even in the short run.

Did all counties benefit equally from the introduction of patent protection? Anecdotally and intuitively, large farms benefitted disproportionately from the change in intellectual property regime (Willingham and Green, 2019); I present two sets of results consistent with this narrative. First, it is illegal for patented seeds. Also see: https://www.cbsnews.com/news/agricultural-giant-battles-small-farmers/. The Monsanto quote was taken from its website: https://monsanto.com/company/media/statements/food-inc-documentary/.

See, for example Costinot and Donaldson (2012), who introduce this methodology.

6 An alternative approach to answering this question might be to estimate the impact of the change in patent law on crop-level seed prices. Unfortunately, I have been unable to find or compile data on crop-specific seed prices for the sample period for enough crops to make this exercise worthwhile. The only hybrid-compatible crop for which I was able to find data, for example, is corn. Moreover, the county-level data makes it possible to explore a more varied set of impacts on consumers and understand the net effect of the increase in productivity and input spending.
I show that the positive effect of intellectual property protection on profits is limited to counties with large average farm revenue at the start of the sample period; counties in the bottom farm revenue quartile actually experience a decline in average profits as a result of the introduction of intellectual property protection. Second, the introduction had a direct effect on the farm size distribution. In more exposed counties, the farm size distribution was shifted to the right, consistent with larger farms disproportionately thriving when patent protection became enforced.

This paper contributes to existing work investigating the impact of intellectual property protection on innovative activity. Empirical estimates of the effect of patent protection on innovation are limited (Williams, 2017); the impact of the ability to protect intellectual property on equilibrium innovation is not obvious. While the goal of patent protection is to incentivize research by providing inventors with quasi-rents, awarding patents may hinder follow-on research, thereby reducing overall innovative output (e.g. Murray and Stern, 2007; Williams, 2013). Branstetter and Sakakibara (2002) use time-series data to analyze Japan’s 1998 patent law reform and argue that an expansion of patent scope had a limited impact on firms’ R&D. Also related, Budish et al. (2015) explore the impact of differences in effective patent length across cancer type-by-stage pairs, and find that longer patent length is associated with more type-stage specific clinical trials.

Other papers have studied variation across countries in patent law or law changes (Lerner, 2002; Qian, 2007; Lerner, 2009), or have looked to historical periods in order to investigate the impact of patent protection (see Moser, 2013, 2016 for reviews). Moser (2005), for example, using data from 19th century World’s Fairs, compares countries with and without patent protection and finds that patent protection had a substantial impact on the direction of innovation. Some prior work has investigated the impact of historical changes in intellectual property protection in agriculture, focusing on crop case studies (Alston and Venner, 2002; Naseem et al., 2005; Moser and Rhode, 2011).

While this paper’s focus is narrow, the introduction of patent protection for agricultural varieties and its impact are at the core of several ongoing economic and policy debates. Intellectual property protection for plant varieties in the U.S. and other countries has been proposed as an explanation of dramatic agricultural productivity growth during the second half of the 20th century, dubbed the “Green Revolution” (e.g. Evenson and Gollin, 2003). Since 1960, 74 countries have adopted intellectual property protection for plant varieties, and several countries are currently debating whether to introduce it; unsurprisingly, it has often been a politically contentious process. Policy analysts have also argued that patent protection has contributed to the consolidation of the U.S. and global seed industry, as well as the decline of small farms and concentration of farm

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7See 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.

8This paper is also linked to a related literature that suggests that receiving patent protection is beneficial to firms and technology developers. For example, Gans et al. (2008) on technology licensing, or Gaul (2018) and Farre-Mensa et al. (2016) on the benefit to entrepreneurial firms and startups.

9For example, see here on potatoes in India: https://finance.yahoo.com/news/potato-pepsico-obsessing-over-india-080435284.html. In a companion paper, I investigate this international dimension.
land in the U.S. (Howard, 2015; Bonny, 2017). My results support the latter hypothesis. Thus, intellectual property protection in agriculture has had large and policy-relevant consequences that are currently being debated in countries around the world; the link between the availability of patent protection and these major changes in the agricultural sector, however, has not before been systematically or empirically investigated.

The paper is organized as follows. The next section provides background information on the history of patent protection for plant varieties and a brief discussion of plant biology required for the empirical analysis. Section 3 discusses the data. Section 4 presents the empirical strategy and results for the crop-level analysis while section 5 does the same for the county-level analysis. Section 6 discusses the results and concludes.

2 Background

2.1 Why Agriculture?

This paper focuses on innovation in the agricultural sector because, for both methodological and conceptual reasons, it is an ideal context to study the consequences of intellectual property protection. First, as noted in the Introduction and discussed in detail below, there has been substantial variation over time and across crops in the possibility of protecting intellectual property. This temporal variation, which does not exist in most industries, is very useful for empirically identifying the impact of intellectual property protection. Cross-sectional variation in pre-determined characteristics across crops that determine the benefits of patent protection also make this a methodologically ideal context to study the extension of patent protection.

Second, it is possible to measure crop-specific innovation and productivity over time without using patent data. Since the goal of this study is to examine the impact of introduction of patenting, patents are not a useful measure of innovative activity because they did not exist during the pre-period; however, I overcome this by measuring crop varieties directly. Moreover, crop yields provide a direct measure of crop-specific productivity; in other industries, direct measures of productivity are difficult to estimate.

Third, it is straightforward to figure out who the likely consumers of new crop-specific innovations are. That is, new wheat seeds will be used by farmers who plant wheat. This makes it possible to directly estimate the impact of the introduction of patent protection not only on innovative output but also on downstream production and the consumers of patented technologies. Moreover, the relative suitability of different crops in different parts of the country is, in part, determined by land characteristics. Therefore, it is possible to estimate the exogenous component of crop choice – and hence exposure to the change in patent law – that does not respond endogenously to production decisions.

Finally, intellectual property for plant varieties is at the center of a set of major and ongoing policy discussion. Within the United States, the rights of seed companies to sue small farmers for
saving seeds has been the subject of recent policy and legal debate. Whether the reduced profits and sometimes bankruptcies of small farmers represent extreme cases or the average effect of the patentability of seeds is at the heart of this conversation. Moreover, seventy-four countries have passed a law introducing intellectual property protection for plant varieties since 1968, many after 2000. Several more are in the process of developing or debating such a law. Understanding the impact of patent protection in the US may be informative for the ongoing international debate.

2.2 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 considered living organisms. While agricultural inventions like new fertilizers, tractors, harvesters, etc. have been patentable since the 18th century, utility patent protection for new plant varieties – seeds, runners, etc. – was not available until 1985. While weaker forms of intellectual property protection for plant varieties were introduced by congress in 1930 and 1970, anecdotal and case study evidence suggests that these policies were ultimately of little import.

This 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 the distinction between life and non-life when it came to the patentability of inventions was not relevant. That case involved the patentability of a genetically modified bacterium that was useful for breaking down crude oil, and the Supreme Court wrote that “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.” This opened the possibility of patenting inventions that could plausibly be considered living things.

In 1985, a patent examiner rejected a patent application for a maize variety that the breeder argued 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. Following the decision, the USPTO released a notice stating that “the Patent and Trademark Office is now examining applications including claims to plant life-

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11The list of countries with variety protection can be found here: https://www.upov.int/members/en/. Countries that are currently developing variety intellectual property law are listed here: https://www.upov.int/members/en/status_in_relation_to_upov.html.

12Lesser (1987) notes that the 1970 protections from the Plant Variety Protection Act (PVPA) were considered by breeders to be far inferior to utility patent protection. Alston and Venner (2002), focusing on wheat, find no evidence that the PVPA affected wheat yields. Patenting following the 1930 Act that granted some protection to breeders of vegetatively-derived varieties (i.e. not seeds) was focused predominately on roses, and yet the Act did not increase innovation in rose varieties (see Moser and Rhode 2011). Another indication of this is the fact that, while utility patents for plant varieties has been the subject of extensive litigation and owners of utility patents have taken major action to enforce their intellectual property, this was not the case for earlier forms of seed intellectual property; neither the 1930 nor the 1970 law was the subject of substantial infringement litigation (Kershen, 2003).
e.g., plants per se, seeds, plant parts” (Hodgins, 1987, p. 88). The change in intellectual property regime was a shock, but was almost immediately taken advantage of by breeders and breeding companies (Lesser, 1987). Even by 1987 there were many patents granted as a result of the Hibberd decision, and these new patents were spread across multiple pre-existing patent classes (Hodgins, 1987).

2.3 Hybridization and De Facto Protection

It is common knowledge among farmers and agrochemical companies that hybrid plant varieties have de facto intellectual property protection (e.g. Fernandez-Cornejo, 2004; Butler and Marion, 2015). In the words of Fernandez-Cornejo (2004), hybrid seeds “provided the private sector a natural method of protecting plant breeding investments” since saved hybrid seeds “produce substantially lower yields, encouraging farmers to repurchase seed every year.” The relationship between this feature of hybrids and intellectual property protection is explicit. Fernandez-Cornejo et al. (1999) note: “According 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” (p. 19). Gupta (1998) refers to this as “built-in” intellectual property protection, which “forces the farmers to purchase hybrid seeds every year.” He further argues, “In several self-pollinated crops like wheat, rice, barley, beans, etc., on the other hand, 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” (p. 1320). Prior to the introduction of formal intellectual property, hybrid seed development – and hence, breeding innovation in crops for which hybrid varieties could be developed – already had de facto intellectual property protection.

Therefore, when formal patent protection was introduced, it was widely anticipated to predominantly affect 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, Monsanto responded by asserting that farmers had not been saving hybrid seeds for decades and that patenting served a similar function for a different set of crops. That is, seed companies view hybrid varieties as effectively having intellectual property protection akin to patenting.

Why do hybrid varieties have de facto protection? When farmers use hybrid varieties, they very rarely save seeds to use the following year; the second generation (F2) seeds from hybrid strains do not retain the beneficial characteristics of the first generation (F1) and are often of no use. Therefore, farmers are forced to return to the breeder every time they want a new seed, and cannot save, sell, or replicate the improved variety. Moreover, without access to the parent va-

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13Importantly, this is still relevant for farming today. According to the University of Illinois Extension program, hybrid seeds are “often sterile or [do] not reproduce true to the parent plant.” Therefore, they warn: “never save the seed from hybrids.”

Figure 1: **Perfect vs. Imperfect Flowers.** This figure shows the distinction between perfect flowers (left, color) and imperfect flowers (right, B&W).

varieties used to generate the F1 hybrid, it is almost impossible for other breeders, seed marketing firms, or researchers to steal profits from the original developer. When farmers use non-hybrid varieties, on the other hand, they can save seeds for many seasons without sacrificing the beneficial characteristics of their original seeds and need not re-purchase the seed from the developer. Other developers can use non-hybrid varieties directly in the breeding process and build on their favorable characteristics.

The reason for this 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. The probability that offspring produced by the farmer match the improved variety at this allele is therefore 0.5.

In reality, the beneficial properties of a variety are not stored on a single allele; “hybrid vigor” results from the combination of many alleles and their interactions. 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. If a farmers plants non-hybrid – or, “open pollinated” – varieties, those varieties can be reproduced exactly generation after generation and do not need to be re-purchased from the developer.
2.4 Hybrids and Flower Structure

A final question is what characteristics make breeders better able to generate hybrids from certain crops but not others. The key characteristic that matters during the sample period is the crop’s flower structure, and in particular, whether the crop has “perfect” or “imperfect” flowers (e.g. [Wright, 1980; Butler and Marion, 2015; Bradford, 2017]). The distinction between perfect and imperfect flowers is displayed in the image in Figure 1. In words, perfect flowers have both the male and female parts of the plant in the center of the same flower while crops with imperfect flowers have the male and female reproductive material on different parts of the plant. When a crop has perfect flowers, it is often painstakingly difficult or impossible to generate new hybrids by combining genetic material from multiple plants; this is the case for wheat, for example, which has perfect flowers [Whitford et al., 2013; Bradford, 2017]. Hybridized wheat is very rare, and almost non-existent during the sample period. The opposite is true for corn.

Throughout the paper when I refer to a crop as “hybrid compatible,” this means that the crop has imperfect flowers, facilitating the hybridization process. The benefit of this measure compared to a measure that relied on actual rates of hybridization – aside from the fact that the actual share of hybrid varieties is not possible to measure for more than a small set of crops – is that actual hybrid development is endogenous to crop-specific research investment and demand. Crops’ flower structures, on the other hand, are fixed and do not change with human behavior.

3 Data

3.1 Defining Treatment Status

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 proxy for hybrid compatibility. I also compiled a range of additional information about each crop – including the way it reproduces (i.e. sexually vs. vegetatively) and whether or not the crop is a tuber – that might affect the style and process of innovation in varieties for that crop. In total, this information was compiled from 339 separate sources. This information is used to construct the key independent variables in the analysis.

3.2 Crop-Level Outcome Variables

I combine multiple sources of data to compile a consistent data set of crop-specific measures of R&D that are possible to track over time. 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

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15See also [Jones et al., 1947] for a discussion of flower structure and onion hybridization.
through a Freedom of Information Act request, is a list of all released crop varieties known to
the USDA. The USDA began collecting data on all released varieties during the 19th century in
order to prevent fraud in the seed market; it is designed to be comprehensive and uses a broad
range of sources in order to identify crop varieties. While the list is unlikely to cover every variety
released in the US, it is intended to be as comprehensive as possible; according to 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.” 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. I digitized
the full list and use it to compute the number of varieties released for each crop in each year.

Second, to measure crop-specific R&D investment, I rely on data on project-level R&D spend-
ing since 1970 from the USDA Current Research Information System (CRIS). CRIS’s reporting
and data complication protocol was established in 1966 by the Secretary of Agriculture in order
to better document research funding in agriculture and how it changes over time; however, 1970
was the first year when the full information collection process took place and the data were com-
piled. 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, ma-
chinery, 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. When a single project covers
multiple crops, I assign each crop its corresponding share of the project’s total funding. The CRIS
compiles project-level data on R&D expenditure for all research projects that received any public
support, including funding from 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. For all projects that received funding from any public source, the
CRIS data also asks researchers to report private funding received for the project. Therefore, for
the set of projects in the data set, it is possible to compare the impact of patent protection avail-
ability on private and public investment. However, an important caveat is that the data set does
not contain all private R&D, only private R&D for projects that received any public funding; I am
not aware of a more comprehensive measure of crop-level private R&D investment.

Third, to measure crop-level innovative output for all technologies other than agricultural va-
rieties, I use patent data. Using the patent database PatSnap, I computed the number of patents
in Cooperative Patent Classification (CPC) classes A01B, A01C, A01D, A01F, A01G, A01H, and
A01N (i.e. CPC classes that relate to non-livestock agriculture) that were associated with each

16While 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.
17For a description, see here: https://cris.nifa.usda.gov/aboutus.html
crop. To match patents to crops, I searched for the name of each crop in the Variety Name List in all patent titles, abstracts, and keywords lists. Thus, for each crop, CPC class, and year in the sample period, I estimate the number of patented technologies. Finally, measures of output, area harvested, and yield for each crop are from the Food and Agriculture Organization (FAO) and the USDA.

3.3 County-Level Data

I construct a county-level panel from the 1974-1997 rounds of the US Census of Agriculture. The Census of Agriculture contains a range of information about the U.S. agricultural sector and agricultural production. This includes information about 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. Crucially, the FAO potential yield model is constructed using parameters derived from controlled experiments, and not from data on actual agricultural inputs and output (see Costinot et al., 2016, p. 18). Combining the FAO data with crop-specific producer prices from 1985, I determine which crop would maximize output at the grid-cell level. I then determine the share of grid-cells in each county on which this model would predict that one of the hybrid-incompatible crops should be cultivated. I use measure of the predicted share of county land devoted to treatment crops as the county-level treatment variable. I also compute an analogous measure using the actual composition of crop-cultivation in each county using the 1982 Census of Agriculture. Reassuringly, the actual measure and the GAEZ-derived measure are strongly correlated; I present a version of the county-level results in which the GAEZ-derived measure is used as an instrument for the actual county-level share of hybrid-incompatible crops.

---

18 For crops with multiple possible names, I searched for both and combined them. For example, sometimes corn is referred to as maize; sometimes sorghum is referred to as jowar; etc.
20 To my knowledge, farm-level data with information on the crop-composition of production do not exist for this period so I am restricted to estimating the impact of county-level exposure to new patent protection.
21 The FAO 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)
4 Patenting and Innovation: Crop-Level Analysis

4.1 Empirical Strategy

My empirical approach compares hybrid compatible to hybrid incompatible crops before and after the introduction of intellectual property protection in 1985 using a differences-in-differences design. The main estimating equation is:

\[
\text{Innovation}_{ct} = \alpha_c + \delta_t + \beta \cdot \text{Not Hybrid}_c \cdot \text{Post}^{1985} + X'\Gamma + \epsilon_{ct}
\]

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. \( \alpha_c \) and \( \delta_t \) are crop and year fixed effects respectively. \( \text{Post}_t \) is an indicator that equals one in all years after 1985 and \( \text{NotHybrid}_c \) is crop-specific indicator that equals one if a crop is not hybrid compatible (i.e. has perfect flowers). These are the “treatment” crops in the analysis. The coefficient of interest is \( \beta \), the impact of the introduction of patent protection crop-specific innovation.

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 equation:

\[
\text{Innovation}_{ct} = \alpha_c + \delta_t + \sum_{\tau \in T^{pre}} \beta_{\tau} \cdot \text{Not Hybrid}_c \cdot \delta_\tau + \sum_{\tau \in T^{post}} \beta_{\tau} \cdot \text{Not Hybrid}_c \cdot \delta_\tau + X'\Gamma + \epsilon_{ct}
\]

Here, the coefficients of interest are the \( \beta_{\tau} \). The identification assumption is that prior to the introduction of patent protection, hybrid compatible and incompatible crops are on similar trends; that is, when \( \tau \in T^{pre} \), \( \beta_{\tau} \) should not be statistically distinguishable from zero. When \( \tau \in T^{post} \), the \( \beta_{\tau} \) identify the effect of patent protection crop-specific innovation.

4.2 Results

4.2.1 Innovative Output

This section examines the impact of the introduction of patent protection on the development and release of crop varieties; this is the key outcome variable because varieties were exactly the technology for which patent protection suddenly became available in 1985. Estimates of Equation (1) are reported in Table 3. Since the number of variety releases is a count variable, and since there zeroes on the left hand side of the regression, I report estimates from Poisson (columns 1-2) and negative binomial (columns 3-4) models, as well as OLS specifications after computing the inverse hyperbolic sine of the dependent variable (columns 5-6). Across specifications, I estimate a positive and significant relationship between the availability of patent protection and the development of new varieties. In even numbered columns, I control flexibly for reproduction type of each crop by interacting an indicator for vegetative reproduction with year indicators; if anything, the point estimates are larger and more precisely estimated.
Table 1: Patent Protection and Novel Plant Varieties

<table>
<thead>
<tr>
<th>Dependent Variable:</th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
<th>(5)</th>
<th>(6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not Hybrid Compatible ( \times ) ( \text{Post} , 1985 )</td>
<td>0.795***</td>
<td>0.795***</td>
<td>0.290***</td>
<td>0.348***</td>
<td>0.109*</td>
<td>0.168**</td>
</tr>
<tr>
<td>( \text{Post} , 1985 )</td>
<td>0.245</td>
<td>0.201</td>
<td>0.0928</td>
<td>0.111</td>
<td>0.0624</td>
<td>0.0787</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Specification:</th>
<th>Poisson</th>
<th>Negative Binomial</th>
<th>OLS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crop Fixed Effects</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Year Fixed Effects</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Reproduction Type Controls</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Observations</td>
<td>2,260</td>
<td>2,240</td>
<td>2,280</td>
</tr>
<tr>
<td>R-squared</td>
<td>-</td>
<td>-</td>
<td>0.815</td>
</tr>
</tbody>
</table>

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 5-6, it is the inverse hyperbolic sine transformation of the number of new varieties. The regression model is noted at the top of each column. Reproduction type controls include a full set of year indicators interacted with an indicator if a crop reproduces vegetatively. Standard errors, clustered by crop, are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

Table 5 investigates the robustness of the baseline results; all columns report OLS estimates. For reference, column 1 reproduces column 6 from Table 3. First, I document that the results are similar and, if anything, more precise after controlling flexibly for trends in crop-level innovation during the pre-period (columns 2-3). A potential concern is that the baseline result is driven by a small number of influential observations and not a persistent shift in innovative activity. However, the results are also similar and, if anything, larger in magnitude after omitting the most influential observations as captured by the value of their Cook’s Distance (column 4). Again, the result holds on this restricted sample once the full set of controls is included (column 5). In columns 6-7, I reproduce the baseline results after extending the post-treatment period to 2005, both without (column 6) and with (column 7) the full set of controls; the results are again similar and, if anything, larger in magnitude, consistent with the persistent and accumulating impact of the availability of patents on innovation. Thus, the baseline estimates are not driven by trends in crop-specific innovation or the details of the empirical specification.

The main identifying assumption is that, absent the change in patent law, innovation in hybrid-compatible and hybrid-incompatible crops would have been on similar trends. Figure 2 displays coefficient estimates from Equation (2); reassuringly, I find no evidence of pre-trends. Innovation in the treatment and control group are on very similar trends prior to 1985. They diverge markedly after 1985 and the difference in trends persists. Thus, the baseline results document that

\[ \text{Following Bollen and Jackman (1985), I drop observations with Cook’s Distance greater than} \frac{4}{n} \text{where } n \text{ is the number of observations in the regression sample.} \]
Table 2: Patent Protection and Novel Plant Varieties: Robustness

<table>
<thead>
<tr>
<th></th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
<th>(5)</th>
<th>(6)</th>
<th>(7)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Baseline Sample</td>
<td>Excluding Influential Observations</td>
<td>Post-Treatment Period Extended to 2005</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Not Hybrid Compatible $\times g_{1}$ Post 1985</td>
<td>0.160** (0.0787)</td>
<td>0.149** (0.0739)</td>
<td>0.193** (0.0852)</td>
<td>0.175*** (0.0624)</td>
<td>0.253*** (0.0826)</td>
<td>0.240*** (0.108)</td>
<td>0.262** (0.108)</td>
</tr>
<tr>
<td>Crop Fixed Effects</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Year Fixed Effects</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Reproduction Type Controls</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Pre-Period Innovation Controls</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Observations</td>
<td>2,260</td>
<td>2,280</td>
<td>2,260</td>
<td>2,126</td>
<td>2,106</td>
<td>2,964</td>
<td>2,938</td>
</tr>
<tr>
<td>R-squared</td>
<td>0.817</td>
<td>0.824</td>
<td>0.825</td>
<td>0.908</td>
<td>0.913</td>
<td>0.787</td>
<td>0.804</td>
</tr>
</tbody>
</table>

Notes: The unit of observation is a crop-year. All specifications include crop and year fixed effects and the outcome variable is the inverse hyperbolic sine transformation of the number of new variety releases. Reproduction type controls include a full set of indicators interacted with an indicator if a crop reproduces vegetatively. Pre-period innovation controls include the log of the number of new varieties released for each crop prior to 1985 interacted with a full set of year indicators. In columns 4-5, I exclude observations with Cook’s Distance greater than $4/n$ where $n$ is the number of observations in the regression. In columns 1-5, the post-treatment period is 1985-1995 while in columns 6-7 it is 1985-2005. Standard errors, clustered by crop, are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

The availability of patent protection drastically increased innovative output. When new varieties for specific crops became protectable intellectual property, the development of new varieties for those crops increased.

The estimated magnitudes are quantitatively significant. In the specification with all included controls, the coefficient estimates imply that, compared to the pre-period, hybrid-incompatible crops experienced a 0.123 standard deviation relative increase in variety development after the introduction of patent protection. Estimates of the longer run effect (columns 6-7 of Table 5) are larger and imply that hybrid incompatible crops experienced a 0.167 standard deviation relative increase in variety development. Moreover, it seems likely that these reduced form estimates are a lower bound of the overall effect of the introduction of plant variety patents. It is implausible that crops with imperfect flowers were entirely unaffected by the incentives and legal architecture provided by patents. Since the reduced form estimates only capture the relative increase in innovative output for crops with perfect flowers compared to crops with imperfect flowers, it is unlikely to capture the full effect of the introduction of patenting.

4.2.2 Mechanisms: Shifting Research Investment

While the previous section documented that varietal innovation was directed toward crops for which intellectual property protection for varieties became available, examining changes in crop-specific research investment and its sources makes it possible to probe the mechanisms and char-
characteristics of the innovative shift. First, I investigate whether the re-direction of innovative activity was driven by the public sector, the private sector, or both. Intuitively, the private sector may be more motivated by profit and hence more responsive to incentives provided by patent protection; however, there is some evidence suggesting that the public sector may respond as well, albeit less dramatically (e.g., Budish et al., 2015). Table 3 reports estimates of the impact of patent availability on research investment from various sources. I find a negative but statistically insignificant relationship between the availability of patent protection and public investment (column 1), but a positive and significant relationship between the availability of patent protection and private investment (column 2). Consistent with this, the share of total investment from the private sector also significantly increases for crops exposed to the change in patent regime (column 3). The positive effect on innovative output documented in the previous sections thus seems to have been driven by an increase in private investment.

Figure 6 investigates the impact of patent availability on research investment over time. Focusing on Figure 3b, I find no relationship between hybrid compatibility and trends in private research investment prior to 1985. However, their trends diverge immediately after the change in patent regime. The same is true when the outcome variable is the share of research investment from the private sector in Figure 3c. One question is why the effect on private investment appears to return to its pre-treatment level by 1995; I hypothesize that this pattern is due to the main limitation of the research investment data, which is that it only includes private research investment in research projects that received public funding as well. Thus, it is possible that a substantial

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Figure 2: **Patent Protection and Novel Plant Varieties Over Time.** Coefficient estimates from poisson estimates of Equation (2). The dependent variable is the number of novel plant varieties in the crop-year. Standard errors are clustered by crop; 95% confidence intervals are reported.
Table 3: Patent Protection and Patterns of R&D Investment

<table>
<thead>
<tr>
<th>Dependent Variable:</th>
<th>Public Research Investment</th>
<th>Private Research Investment</th>
<th>Share Private Research Investment</th>
<th>Total Scientist-Years Funded, Public + Private</th>
<th>Total Investment per Scientist-Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not Hybrid Compatible, $x_{1t}$ Post 1985</td>
<td>-0.294 (0.792)</td>
<td>0.479** (0.218)</td>
<td>0.0224** (0.00861)</td>
<td>-0.160 (0.275)</td>
<td>0.160** (0.0701)</td>
</tr>
<tr>
<td>Crop Fixed Effects</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Year Fixed Effects</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Observations</td>
<td>1,220</td>
<td>1,220</td>
<td>1,151</td>
<td>1,220</td>
<td>1,148</td>
</tr>
<tr>
<td>R-squared</td>
<td>0.842</td>
<td>0.927</td>
<td>0.576</td>
<td>0.932</td>
<td>0.877</td>
</tr>
</tbody>
</table>

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; in columns 1-2 and 4-5, the inverse hyperbolic sine transformation of the dependent variable is used. All columns report OLS estimates. Standard errors, clustered by crop, are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

share of research projects in treatment crops shifted over time to entirely private funding by 1995 and hence exited the data. Since the impact on new varieties persists after 1995, it seems unlikely that total private research investment actually returned to pre-treatment levels. However, to my knowledge it is not possible to track private research investment by crop outside of the CRIS data. This logic implies that the estimated impact of the availability of patent protection on private research investment from Table 3 is likely an underestimate and should be considered a lower bound.

An additional piece of evidence lends support to the hypothesis that private investment increased in response to the availability of patent protection. While I am unaware of data on crop-level private sector research investment over time outside of the CRIS data, I compiled data on total private sector research investment in breeding activity and in agricultural chemicals from Klotz et al. (1995) and Fernandez-Cornejo (2004). Total private sector investment over time in both breeding and chemicals, relative to investment in 1984, is displayed in Figure A1. While private sector investment in breeding and chemicals are on similar trends prior to 1985, they diverge in 1986 and investment in breeding accelerates relative to chemicals. While this result is admittedly only suggestive, it is consistent with an increase in private sector breeding research following the introduction of variety patents. Moreover, unlike Figure 6 and consistent with a long-run shift in private sector investment, the relative increase in private sector breeding research is persistent in Figure A1.

Finally, the availability of patent protection seems to have concentrated research investment in a smaller set of researchers. Columns 5-6 of Table 3 document that while patent protection has no effect on the total number of crop-specific scientist-years, it has a positive and significant impact
4.2.3 Spillover Effects: Non-Variety Crop Technologies

The availability of patent protection might have had substantial spillovers to other crop-specific technologies. There are major complementarities between different agricultural inputs, 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. Varietal innovation facilitated innovation in harvester technology.

Spillover effects, however, need not be positive. While it is intuitive there maybe positive spillover effects from variety innovation to harvester development, and this seems to have been the case historically, the same is not necessarily true for agricultural chemicals and biocides. Robinson and Cowling (1996), for example, explain how modern crop breeding has and can continue to reduce pesticide dependence (see also e.g. Leppik 1970; Ratnadass et al. 2012); thus, we might expect a limited of even negative impact of additional variety innovation on improvements in agricultural chemicals. Indeed, Monsanto itself was founded as a chemical company and shifted research investment toward agricultural biotechnology and variety development during...
Table 4: Spillover Effects on Non-Variety Crop Technologies

<table>
<thead>
<tr>
<th>Dependent Variable is the Number of Patents Related To:</th>
<th>Pre-Harvest and Harvest Technology</th>
<th>Post-Harvest Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Harvesting and Mowing</td>
<td>Planting, Sowing, and Fertilizing</td>
</tr>
<tr>
<td></td>
<td>Not Hybrid Compatible; x ( I_{t}^{Post 1985} )</td>
<td>0.400**</td>
</tr>
<tr>
<td></td>
<td>(0.170)</td>
<td>(0.195)</td>
</tr>
<tr>
<td>Crop Fixed Effects</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Year Fixed Effects</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Observations</td>
<td>1,340</td>
<td>1,620</td>
</tr>
</tbody>
</table>

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 then number of patents in the listed technology class. All columns report OLS estimates. Standard errors, clustered by crop, are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

the 1980s and 1990s. Is the increase in variety development driven in part by a shift in innovative resources away from biocides and toward varieties? Understanding the sign and magnitude of these spillovers is important for understanding the aggregate impact of intellectual property protection on innovation.

Unlike crop varieties, other agricultural technologies were patentable through the sample period. Therefore, I use patenting activity to measure the impact of the extension of variety patents on non-variety technologies. I use the CPC class information to determine the “type” of technology. Table 4 documents the impact of the availability of patent protection for varieties on a series of non-variety crop-specific technologies measured in the patent data. Column 1 suggests that there were positive and significant spillover effects to harvester technology development, consistent with the intuition provided by the tomato harvester anecdote. Innovation in crop-specific harvester and mower technology increased following the change in patent regime for crops whose variety intellectual property protection increased.

Columns 2-3 tell a similar story for planting technologies. In column 2, the outcome variable is patents 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. This suggests there were also complementarities between novel varieties and planting technology. I find no evidence of spillover effects on crop-specific biocides; this result is presented in column 4. While the point estimate is negative, the coefficient

23 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.
estimate is small and statistically insignificant. While, intuitively, I do not find evidence of positive spillovers on biocide innovation, I also do not find evidence of significant negative spillover effects. Thus, I do not find that the increase in variety development gave way to a corresponding decline in agricultural chemical and biocide patenting.

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). It seems unlikely that there should be major production complementarities between new seed varieties and post-harvest production and processing. I estimate a negative but small and statistically insignificant relationship between variety patent availability and post-harvest technology development. While this is not a true placebo test, the null result in this column suggests that the positive effects in columns 1-3 were not driven by, for example, an overall increase in crop-level demand or innovative effort.

Estimates of Equation (2) are presented in Figure A2 for the statistically significant results; reassuringly, I find no evidence that patenting of the relevant technologies for treatment and control crops were on different trends prior to 1985. However, patenting activity in both harvesting and mowing as well soil working technologies diverge after 1985, consistent with a causal effect of the introduction of variety patents on innovation in complementary technologies.

4.2.4 Productivity

Did the innovative output that resulted from the change in patent law have a discernible impact on crop productivity? As a first strategy to answer this question, I estimate the crop-level relationship between exposure to the patent law and national agricultural yields. If the availability of patent protection increased downstream agricultural productivity, we would expect the yield – output per area – of more exposed crops to increase. In Table 5, I report estimates of the relationship between the availability of patents and national crop yield, measured as total national output divided by the land area devoted to the crop. I find a positive and significant relationship between the availability of patent protection and crop-specific productivity. This relationship is similar after controlling flexibly for the reproduction type of each crop (column 2). The relationship is also not driven by trends in crop-level output or area harvested; in column 3, I control for pre-period area harvested and total output interacted with a full set of year indicators, and the coefficient estimate is again similar. In column 4, I include both the pre-period output and area harvested controls as well as the reproduction type controls and the result does not change.

Figure A3 investigates the relationship between patent protection and crop yields over time. In Panel A3a, the dependent variable is log of output per area and in Panel A3b it is output per area. Reassuringly, and as in the previous set of results, I find no evidence of pre-trends; yield estimates of treatment and control crops were on similar trends prior to the introduction of patent protection. The trends diverge only after the change in patent regime. Finally, columns 5-6 of Table 5 investigate the impact on output and area harvested separately. I find that patent protection had a positive but small impact on area harvested and a large (albeit imprecise) impact on crop-level
output. Thus, these results document that the introduction of patent protection affected not only crop-level innovative output but also measurable components of crop productivity. The remainder of the paper is devoted to investigating these “downstream consequences” of patent protection in greater depth.

5 Downstream Effects: County-Level Analysis

5.1 Empirical Strategy

I now turn to the downstream consequences of patent protection. While the previous section identified significant benefits of intellectual property protection in the form of innovative output and agricultural productivity, patent protection comes with potential costs to consumers (e.g. Nordhaus, 1969). Developers of patented technologies may retain a substantial share of the profits from new technologies; alternatively, these profits may be passed onto consumers if the productivity benefits from using patented technologies outweighs the costs.

To investigate the county-level impact of the introduction of patent protection, I rely on an analogous empirical strategy to the crop-level analysis. I assign each county a treatment value based on the share of county land on which, in 1985, it was optimal to cultivate crops that are not hybrid compatible (that is, crops that form the treatment group in the crop-level analysis). To estimate this share, I use FAO GAEZ models of crop-specific maximum potential yield, along with 1985 producer prices from the USDA. For each grid cell $g$ in the GAEZ data, I determine the
optimal crop \( c(g) \) as

\[
    c(g) = \arg\max_c \{ A_{cg} \cdot \text{Price}_{1985}^c \}
\]

where \( A_{cg} \) is the maximum potential yield of crop \( c \) in cell \( g \) and \( \text{Price}_{1985}^c \) is the producer price of crop \( c \) in 1985 according to the USDA\(^{24}\). For each county \( i \), I compute the share of county land on which hybrid incompatible crops are predicted to grow as:

\[
    \text{Share Not Hybrid}_i = \frac{\sum_{g \in i} I_{c(g) \in \text{Not Hybrid}}}{\sum_{g \in i} I_{c(g) \in \text{Not Hybrid}}} + \sum_{g \in i} I_{c(g) \in \text{Hybrid}}
\]

where \( I_{c(g) \in \text{Not Hybrid}} \) is a grid-cell-level indicator that equals one if \( c(g) \) is not hybrid compatible. The GAEZ-derived predicted share is strongly correlated with the actual share of hybrid-incompatible crops planted in each county in 1982, displayed in the map in Figure 4. The map is intuitive; the white-shaded region in the upper Midwest and Plains region is the “corn belt” and corn is a large, hybrid-compatible crop in the data. The correlation between the actual share of land devoted to hybrid incompatible crops and the GAEZ-derived prediction is documented in Figure 5. However, the GAEZ-derived measure is unaffected by potentially endogenous production choices. Thus, it is a geographically and ecologically fixed measure of the county-level exposure to the change in patent law.

I estimate the county-level impact of exposure to the introduction of intellectual property pro-
Figure 5: 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 as well as the standard error and t-statistic are reported at the bottom of the graph.

Equation (2) is used to estimate the effect of patent protection on the share of hybrid incompatible cropland in each county over time. The equation is given by:

\[ y_{it} = \alpha_i + \delta_{st} + \phi \cdot \text{Share Not Hybrid}_i \cdot \mathbb{I}^{\text{Post}1985} + \mathbf{X}'\Gamma + \epsilon_{it} \]  

where \( i \) indexes counties and \( t \) indexes time. \( \alpha_i \) and \( \delta_{st} \) denote county and state-by-year fixed effects respectively, and the coefficient of interest is \( \phi \). \( \phi \) captures the impact of the introduction of patent protection in 1985 on outcomes \( y_{it} \). In order to make sure that more- and less-exposed counties are on similar trends prior to the introduction of IP protection, I also report estimates from a second regression equation:

\[ y_{it} = \alpha_i + \delta_t + \sum_{\tau \in T^{\text{pre}}} \phi_{\tau} \cdot \text{Share Not Hybrid}_i \cdot \delta_{\tau} + \sum_{\tau \in T^{\text{post}}} \phi_{\tau} \cdot \text{Share Not Hybrid}_i \cdot \delta_{\tau} + \mathbf{X}'\Gamma + \epsilon_{it} \]  

Analogous to Equation (2), the coefficients of interest are the \( \phi_{\tau} \). When \( \tau \in T^{\text{pre}} \), \( \phi_{\tau} \) should not be statistically distinguishable from zero. When \( \tau \in T^{\text{post}} \), the \( \phi_{\tau} \) identify the county-level effect of the introduction of patent protection over time.
### Table 6: Land Values and Allocation

<table>
<thead>
<tr>
<th>Sample:</th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
<th>(5)</th>
<th>(6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Share Not Hybrid Compatible, x Post 1985</td>
<td>0.166*** (0.0577)</td>
<td>0.136*** (0.0165)</td>
<td>0.0740*** (0.0261)</td>
<td>0.0921*** (0.0326)</td>
<td>0.0365 (0.0223)</td>
<td>0.00870** (0.00395)</td>
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<td>County Fixed Effects</td>
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<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Census Round Fixed Effects</td>
<td>Yes</td>
<td>Yes</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Census Round x State Fixed Effects</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Additional Controls</td>
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<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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<td>Yes</td>
</tr>
<tr>
<td>Observations</td>
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<td>18,115</td>
<td>18,115</td>
<td>9,102</td>
<td>17,831</td>
<td>17,940</td>
</tr>
<tr>
<td>R-squared</td>
<td>0.872</td>
<td>0.898</td>
<td>0.922</td>
<td>0.934</td>
<td>0.969</td>
<td>0.967</td>
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</tbody>
</table>

**Notes:** The unit of observation is a county-year. All specifications include county and year fixed effects. The additional controls include pre-period log of farmland area interacted with a full set of year fixed effects and pre-period log of total farm revenue interacted with a full set of year fixed effects. In columns 1-4, the outcome variable is log of the average value of land and buildings per acre; in column 5, it is the log of the total land area devoted to crop production and in column 6 it is the share of total farmland devoted to crop production. In column 4, the regression sample is limited to counties with above median farmland area in 1978. Standard errors, clustered by county, are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

### 5.2 Results

#### 5.2.1 Land Values

I first investigate the impact of exposure to the availability of patent protection on county-level agricultural land values. The value of land captures the net present value of agricultural profits and hence, is a useful measure of the impact of patenting on farm wealth. I follow a range of prior work that uses agricultural land values as the preferred measure of the impact of policy changes or shocks on farm wealth (e.g. Mendelsohn et al., 1994; Hornbeck, 2012.

Estimates of Equation (3) are reported in Table 6, in which (log of) the value of land and buildings per acre is the outcome variable. In column 1, only county and census round fixed effects are included on the right hand side, along with the independent variable of interest. The coefficient of interest is positive and significantly different from zero, suggesting that county-level exposure to the introduction of variety patenting increased farmland values.

In column 2, I control flexibly for counties’ pre-period involvement in agricultural production by including pre-treatment land devoted to agriculture and total agricultural revenue, interacted with a full set of census round indicators, on the right hand side of the regression; the results are similar. In column 3, I also include state-by-census round fixed effects to absorb any time trends at the state level. Finally, in column 4 I restrict the sample to counties that had above median land devoted to agriculture in 1974, the start of the sample period. This is in order to make sure that

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25 Other work using a related framework focuses instead on farm profits (e.g. Deschénes 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.
the result is not driven by non-agricultural counties. The coefficient estimate is larger using the restricted sample and, despite reducing the sample size by half, the estimate remains statistically significant.

The estimated effects are quantitatively large. IV estimates of the impact of the actual share of cropland devoted to hybrid-incompatible crops are intuitively larger than the reduced form estimates presented in Table 6 and imply that a one standard deviation increase in the share of cropland devoted to hybrid-incompatible crops – i.e. a one standard deviation increase in exposure to the patent law change – was associated with a 0.19 standard deviation increase in (log of) land values (Table A1). Figure 6a displays coefficient estimates from Equation (4), the impact of patent law exposure on land values over time. Reassuringly, more- and less-exposed counties are on similar trends prior to 1985; however, their trends diverge following the law change and level off by 1997.

The direct effect of the change in patent regime on land values via its impact on crop productivity could be amplified by farmers’ shifting land allocation. That is, the introduction of patenting might have a direct effect on the value of land devoted to hybrid-incompatible crops because the innovative output of those crops is expected to (and does) increase. However, this effect could be amplified if farmers in those counties also increase crop production in response to the change in patent regime. This is what I find; in column 5, the dependent variable is (log of) total county farmland and the coefficient estimate is positive albeit imprecisely estimate \( p = 0.102 \). In column 6, the dependent variable is the share of county farmland devoted to crop production and the coefficient of interest is positive and significantly different from zero. Intuitively, farmers more exposed to the introduction of variety patents, and hence the beneficiaries of more crop-specific innovation, also shift land toward crop production.

5.2.2 Input Spending and Farm Profits

The impact of introduction of variety patenting on land values suggests that, in the long run, the benefit of variety patents to the agricultural sector were expected to outweigh the costs. To estimate the short run effect, I measure input spending and farm profits directly in the Census of Agriculture. Conveniently, the Census of Agriculture distinguishes between spending on different input types. In column 1 of Table 7, I find a positive and significant relationship between exposure to the patent law change and spending on crop varieties. Estimates of Equation (4) when log of spending on varieties is the outcome variable are displayed in Figure 6b. I find no evidence that counties differentially exposed were on different spending trends prior to the introduction of patent protection. This is consistent with the availability of patent protection increasing downstream variety costs, as would be predicted by the standard model of patent protection.

The impact of patent availability on variety spending could be driven by the fact that patented seed inputs are more expensive or by the fact that, as documented in Table 6, total cropland increased in more exposed counties. I distinguish between these possibilities in two ways, both of which suggest that the result in column 1 is driven, at least in part, by higher prices for plant
Table 7: Input Spending and Farm Profits

<table>
<thead>
<tr>
<th></th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
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<th>(5)</th>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>log Spending on Crop</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Varieties</td>
<td>0.139***</td>
<td>0.0529</td>
<td>0.00362</td>
<td>0.0124</td>
<td>0.00436***</td>
<td>1.394**</td>
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<td>(0.0397)</td>
<td>(0.0418)</td>
<td>(0.0220)</td>
<td>(0.0255)</td>
<td>(0.00122)</td>
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<td>(0.700)</td>
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<tr>
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<td>Yes</td>
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<td>18,111</td>
<td>18,142</td>
<td>18,142</td>
<td>18,122</td>
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<tr>
<td>R-squared</td>
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<td>0.909</td>
<td>0.964</td>
<td>0.958</td>
<td>0.790</td>
<td>0.848</td>
<td>0.753</td>
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</table>

Notes: The unit of observation is a county-year. All specifications include county and state-by-year fixed effects. The additional controls include pre-period log of farmland area interacted with a full set of year fixed effects and pre-period log of total farm revenue interacted with a full set of year fixed effects. The outcome variable in each specification is listed at the top of the column. Standard errors, clustered by county, are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

varieties in more exposed counties following the introduction of patenting. First, I investigate the impact of exposure to the patent law on spending on non-variety inputs; if the result in column 1 were driven by an increase in land devoted to crops, then spending on other inputs to crop production should increase in comparable proportions. In columns 2 and 3 of Table 6, the outcome variables are spending on chemicals and fertilizers and spending on petroleum respectively; the coefficient is indistinguishable from zero in both cases. In column 4 the outcome variable is total input spending and again, the coefficient of interest is positive but small in magnitude compared to column 1 and statistically insignificant. This suggests that the result in column 1 is not driven by an across-the-board expansion of crop production and input use.

Second, I control for total land devoted to crops on the right hand side; while this is a “bad control,” it is useful for testing whether county-level crop land mediates the relationship between patent law exposure and seed spending. I find that the coefficient of interest in this version of the specification from column 1 remains positive and significant (φ = 0.0842, p = 0.022), suggesting that the increase in land devoted to crops is not driving the result. Finally, while one might ideally compare seed prices for treatment and control crops over time, actual 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. Figure A4 presents corn and cotton seed prices over time, relative to the price in 1984. The two trends are similar prior to 1985 but diverge by 1990; in relative terms, cotton seed prices increase by markedly more than corn seed prices following the introduction of patenting. Since this figure is just a case study and simply compares time series patterns for two crops, it should be interpreted with caution. Nevertheless, this cluster of evidence suggests
that the introduction of patent protection did indeed lead to higher prices faced by consumers of newly patentable technology.

Next, I turn to the impact of variety patents on farm profits (i.e. total revenue — total cost). In column 6 of Table 7, the outcome variable is total county-level profits. The coefficient of interest is positive and statistically significant, suggesting that even in the short run (i.e. by 1997), exposure to the change in patent law increased farm profits and the benefits of new technologies outweighed the increase in variety spending documented in column 1. This is consistent with the positive effect on land values documented in Table 6 but suggests that the positive effect on land values was not driven only by an increase in expected future profits but also an increase in realized profits during the sample period. According to the IV estimates, a one standard deviation increase in the share of a county’s cropland devoted to hybrid-incompatible crops was associated with a 0.155 standard deviation increase in county profits. In column 7, the outcome variable is agricultural profits per farm; again, the coefficient of interest is positive and statistically significant. Even in

Figure 6: County-Level Estimates Over Time. Coefficient estimates from Equation (2). The dependent variables are noted at the bottom of each sub-figure. Standard errors are clustered by county and 95% confidence intervals are reported.
the short run, the average benefit of the introduction of patent protection to the agricultural sector outweighed its costs.

5.2.3 Winners and Losers?

There are potentially large complementarities between the use of improved farm varieties and farm scale. Several qualitative accounts have argued that large farms benefitted disproportionately from the growth in improved seed varieties, and that small farms have been hurt by increased 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 by saving seeds from one season to the next. Thus, while the introduction of patent protection on average had a positive effect on downstream profits, it could have also had major distributional consequences. To investigate this possibility, I estimate heterogeneous effects based on the county-level average farm size during the pre-period. In particular, I estimate versions of the following equation:

\[ y_{it} = \alpha_i + \delta_{st} + \psi_k \cdot \mathbb{I}_k \cdot \text{Share Not Hybrid}_{i} \cdot I^{\text{Post 1985}} + X'\Gamma + \epsilon_{it} \]

(5)

where \( k \) indexes initial farm size bins. The coefficients of interest are the \( \phi_k \), the impact of exposure to patent protection for counties with pre-period farm size in bin \( k \).

These results are reported in Table 8. While the positive effect on land value is larger for larger size bins (column 1), the coefficient estimates are small in magnitude and statistically indistinguishable from zero. As noted above, however, land values capture long run change in expected profits and not necessarily the direct effect on farmers during the sample period; indeed, in the long run the farm size distribution can endogenously adjust. The next set of estimates turn to the heterogeneous impact on farm profits directly, measured either as total profits (column 2) or profits per farm (column 3). In both cases, I estimate large and significant differences across farm size bins. According to the estimates in columns 2-3, for example, a county in the smallest farm size quartile that cultivated only hybrid-incompatible crops experienced a $1.7 million decline in profits as a result of the patent law (or, $1,368 per farm), while a county in the largest farm size bin that cultivated only hybrid-incompatible crops experienced a $4.3 million increase in profits (or, $6,816 per farm). The estimates over time for farms above and below median pre-period farm size are displayed in Figures 6c and 6d. Thus, in the short run, the introduction of patent protection had major distributional consequences downstream.

There are two remaining questions. First, why do the heterogeneous impacts on land value differ from the heterogeneous impacts on farm profits? I already hinted that this may have to do

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26This second point has been disputed, however, and it is often argued that farmers growing hybrid crops were never able 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.

27Farm size is defined as total agricultural revenue per farm.
Table 8: Interactions with Farm Size

<table>
<thead>
<tr>
<th>Dependent Variable:</th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
<th>(5)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>log Value of Land and Buildings Per Acre</td>
<td>Total County Profits</td>
<td>County Profits Per Farm</td>
<td>Farms with Revenue &gt;100k</td>
<td>Farms with Revenue &lt;100k</td>
</tr>
<tr>
<td>Share Not Hybrid Compatible, Post 1985</td>
<td>0.0261</td>
<td>-1.725**</td>
<td>-1.368</td>
<td>0.108***</td>
<td>-0.0348**</td>
</tr>
<tr>
<td>(0.0389)</td>
<td>(771.3)</td>
<td>(1.135)</td>
<td>(0.0308)</td>
<td>(0.0152)</td>
<td></td>
</tr>
<tr>
<td>2nd Size Quartile x Share Not Hybrid Compatible, Post 1985</td>
<td>0.0571</td>
<td>2.547**</td>
<td>1.468</td>
<td>0.0713</td>
<td>(1,107)</td>
</tr>
<tr>
<td>(0.0713)</td>
<td>(1.107)</td>
<td>(1.545)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3rd Size Quartile x Share Not Hybrid Compatible, Post 1985</td>
<td>0.0516</td>
<td>3.917***</td>
<td>3.838***</td>
<td>0.0462</td>
<td>(1.030)</td>
</tr>
<tr>
<td>(0.0462)</td>
<td>(1.332)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4th Size Quartile x Share Not Hybrid Compatible, Post 1985</td>
<td>0.0379</td>
<td>4.340***</td>
<td>6.816***</td>
<td>0.0457</td>
<td>(1.435)</td>
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<td>(0.0457)</td>
<td>(1.850)</td>
<td></td>
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</tr>
</tbody>
</table>

County Fixed Effects: Yes | Yes | Yes | Yes | Yes | Yes |
Census Round x State Fixed Effects: Yes | Yes | Yes | Yes | Yes | Yes |
Additional Controls: Yes | Yes | Yes | Yes | Yes | Yes |
Observations: 18,115 | 18,122 | 18,122 | 18,142 | 18,142 |
R-squared: 0.923 | 0.849 | 0.754 | 0.949 | 0.964 |

Notes: The unit of observation is a county-year. All specifications include county and state-by-year fixed effects. The additional controls include pre-period log of farmland area interacted with a full set of year fixed effects and pre-period log of total farm revenue interacted with a full set of year fixed effects. The outcome variable is listed at the top of each column. Size quartiles refer to the county-level position in the farm size distribution, where farm size is measured as county-level agricultural revenue per farm. Standard errors, clustered by county, are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

with endogenous changes to the farm size distribution. In particular, exposure to the change in patent law might shift the farm size distribution rightward since large farms are disproportionately productive in the new patent regime. This would dampen the impact of the initial county farm size on long-run profits. Columns 4-5 of Table 8 document this pattern. Exposure to the change in patent law led to a significant increase in the number of large farms and a decline in the number of small farms. Thus, the farm size distribution was itself directly affected by the introduction of patenting. Table A2 documents this pattern using a series of more disaggregated farm size bins. The number of farms in the largest size bin significantly increases, while the number of farms in smaller size bins either are unaffected or decline. Therefore, the fact that I find heterogeneous effects on profits but not land values could be driven by the fact that land prices also incorporate longer-run changes in the structure of production, including the growth of large farms in regions affected by the introduction of patent protection.

Second, what about the introduction of patenting could cause profits for counties with small farms on average to decline? Intuitively, farmers for whom new seeds were a bad investment might have been able to continue to farm as they were before 1985 and see no change in profits. There are several reasons, however, why this might not be the case. First, anecdotally many farmers were
caught off guard by the fact that they were unable to save patented inputs. Homan McFarling for example, in 1998 purchased soybean seeds and he claimed not to know that they were patented by Monsanto – Monsanto sued him for saving his seeds and was awarded $780,000 in damages. Moreover, McFarling had lost his stock of saved seeds. Second, and perhaps more plausibly, the results could be driven by a decline in producer prices following the introduction of more productive inputs. If small farmers experience more muted productivity increases from improved inputs or choose not to adopt new seeds, but large farms become more productive after the change in patent regime, price effects could lead to a decline in small farm profits.

While during the sample period, producer price data were collected systematically only for a small set of crops (22-25 depending on the year), comparing the evolution of hybrid compatible and hybrid incompatible crops over time yields a striking pattern; this is displayed in Figure 7. While producer prices for the hybrid-compatible and hybrid-incompatible crops in the USDA producer price data are on similar trends prior to 1985, they diverge around 1988 and remain on different trends thereafter. This is consistent with a decline in producer prices as a result of the introduction of variety patenting; this plausibly led to a decline in profits for small farms, if they experienced a smaller productivity increase than large farms and were paid a lower price for their output. However, these results should be taken as suggestive since, due to the small sample size, statistical precision is low; the differences-in-differences estimate with (log of) producer prices as the outcome is $-0.26$ with a standard error of 0.31.

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6 Discussion and Extensions

This paper documents that the ability to protect intellectual property increased innovative output in US agriculture. While patent protection could in theory come with significant costs to consumers, US farmers were on average made better off by the introduction of patent protection: agricultural land values and profits increased. In this context, the costs of patent protection were outweighed on average by large productivity benefits.

In order to identify the causal effect of the availability of patent protection, this paper focused on a particular industry and context. What lessons might there be for other settings? I would hypothesize that the estimated impact of the introduction of patent protection on innovative output is close to an upper bound. Absent intellectual property protection, new non-hybrid seeds can be easily used, replicated, and re-sold. Once a breeder sells a seed, without formal patent protection there is no way to stop others from producing and selling that same seed, using it as an input in future research, and stealing the original innovator’s rents. Therefore, the impact of patent protection on ex ante research incentives in this context is likely large. In other industries, innovators may be able to recoup some of their profits by maintaining trade secrets; indeed, in many sectors the ability to protect trade secrets has a meaningful impact on R&D (Png 2017). Thus, in some sense non-hybrid plant varieties are the context where patents are most useful and where one would expect the most dramatic impact of the introduction of patenting on innovation.

A related question about the external relevance of this paper’s findings is whether one would expect similar results in other countries. Whether countries – particularly low-income countries – should adopt intellectual property protection for plant varieties has been and remains the subject of intense debate (e.g. Cullet 2001; Srinivasan 2005; Jordens 2005; Correa et al. 2015). Since 1960, 74 countries have adopted intellectual property protection for plant varieties, and several countries are currently debating whether to introduce it; unsurprisingly, it has often been a politically contentious process. Here too, it seems likely that this paper’s estimates offer an upper bound; pre-existing infrastructure for both private and public R&D in agriculture was larger than all other countries, and the United States has a large and comparatively wealthy farm sector making potential profits from novel varieties large.

A final question about the interpretation of the paper’s estimates is whether the differential impact of patent protection on hybrid compatible and hybrid incompatible crops was driven by an absolute increase in research activity and investment in hybrid incompatible crops or, in part, a shift in research activity across crops or technologies. In order to make progress on econometric identification, this study relied on differences-in-differences estimates and comparisons across crops; a shortcoming of this approach, as is the case in virtually all differences-in-differences es-

29 See here, for example, on potatoes in India: https://finance.yahoo.com/news/potato-pepsi-co-obsessing-over-india-080435284.html.
30 For example, US inventors own three times as many agricultural patents as the second highest patenting country (Japan) and two times as many agriculture-related publications as the second highest publishing country (China). Both statistics are more extreme when patents and articles are citation weighted. For more information, see here: https://www.ers.usda.gov/amber-waves/2016/november/us-agricultural-rd-in-an-era-of-falling-public-funding/
timates, is that the treatment effect is the differential change in innovative activity between the treatment and control group and it is not possible to convincingly estimate the direct effect of the introduction of patenting on the treatment and control groups separately.

Some evidence, however, lends support to the interpretation that the results are driven (at least in part) by an absolute increase in treated technologies and not a commensurate decline in untreated technologies. For example, I find no evidence of a decline in patenting activity for non-variety technologies following the introduction of patent protection for varieties; if anything, the opposite (Table 4). It does not seem like innovative output shifted out of non-variety innovation following the introduction of patents for varieties. The same is true for research investment; figure A1 shows no evidence of an absolute decline in private research investment in chemicals following the introduction of patent protection for varieties. Investment in both chemicals and breeding increased but investment in breeding increased at a faster pace after 1985. Relatedly, across crops I find no evidence of an absolute decline in total private research investment or in the share of research investment from the private sector for crops in the control group. However, it is of course not possible to know the counterfactual trends in the absence of the change in patent law and this evidence is only suggestive.

While, on average, I find that the introduction of patent protection had a positive effect on the consumers of newly patentable technologies – i.e. farmers – the last part of the paper shows that its impacts were highly heterogeneous. Patent law made counties with smaller farms on average worse off in the short run. This raises a set of questions about the impact of patenting and research incentives on the structure of downstream production that, to my knowledge, have not been explored in prior empirical work. Patent law might disproportionately benefit downstream producers who, for whatever reason, are better positioned to make use of improved technologies. As a result, those producers may increase their market share, as indeed seems to have been the case for large farms following the introduction of patent protection for seeds (Tables 8 and A2). These changes in the structure of production changes might then amplify or dampen the overall effect of intellectual property protection on downstream productivity. Moreover, if producers that benefit from patent protection produce different products from producers that do not, this logic implies that that patent protection might affect not only the direction of innovation (e.g. Moser 2005) but also the “direction” of production. The absence of farm-level data or more detailed output information makes it difficult to investigate these questions in the context of the present study; however, this seems like an exciting area for future work.

Changes in the patent regime may affect not only the market structure of downstream production but also the market structure of the innovative activity itself. These changes in the market structure of the innovative sector may also shape the long run consequences of the introduction of patent protection. Qualitative work suggests that patent protection played a major role in the recent drastic consolidation of the seed industry (e.g. Bonny 2017); the five firm concentration ratio in the global seed sector increased from 10% in 1985 to nearly 55% in 2016. There is substantial theoretical justification for the hypothesis that the introduction of patenting contributed to this
significant increase in concentration \cite{gilbert1982fudenberg1983}. While this paper was able to study the impact of the introduction of patenting on the concentration of production by linking crops to counties using counties’ crop composition, measuring the concentration of crop-level innovation over time is more challenging. However, using data compiled by Fernandez-Cornejo \citeyear{fernandez2004} from a range of sources, it is possible to track the four firm concentration ratio (CR4) of seed sales for corn – a control crop – and cotton – a treatment crop – over time. These trends are presented in Figure 8 and the time series pattern is striking. The CR4 for corn and cotton seeds were on similar trends prior to 1985; after 1985, they diverge and the CR4 for cotton seeds increases substantially relative to the CR4 for corn seeds. This is merely a case study; however, it suggests that changes in the market structure of the innovative sector might be an important factor mediating the long run impact of the introduction of patenting. While the direct effect of the introduction of patenting on the concentration of innovation is not possible to study systematically using this paper’s identification strategy, it seems like an interesting area for future exploration.

7 Conclusion

This paper investigates the impact of the introduction of patent protection on innovative output and downstream production. I identify the causal effect of the introduction of patenting for novel plant varieties by comparing innovative activity between crops with perfect and imperfect flowers, before and after the introduction of patent protection in 1985. The presence of imperfect flowers facilitates the development of hybrid crop varieties, which have \textit{de facto} intellectual
property protection even in the absence of formal patents; hence, crops with imperfect flowers serve as a control group to estimate the impact of the introduction of patent protection. In order to measure innovation both before and after the introduction of patenting at the crop-level, I construct a data set of crop-specific variety releases – the exact technology that became patentable in 1985. I supplement this new data set with measures of crop-specific research investment, patenting in non-variety technologies, and crop yields.

I find that the ability to protect intellectual property led to a substantial increase in innovative output. I also document that the introduction of patenting led to an increase in private research investment and overall shift in research investment toward the private sector, as well as an increase in innovation in complementary non-variety technologies. To investigate the impact of patenting on downstream production, I measure county-level exposure to the introduction of patenting using counties’ crop composition. Counties that were more exposed to the change in patent law experienced an increase in land values and profits; in this context, even though patent protection implies a trade off between ex ante incentives and deadweight loss, I find that the productivity benefits of patent incentives outweighed the additional costs paid by consumers. Not all rents from innovation were accrued by the inventors; substantial profits flow downstream.

The idea that the ability to patent new technologies could lead to an increase in productivity has been challenged by recent work. For example, Boldrin and Levine (2013) 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” (p. 3). This study documents that, in its particular context, the ability to patent new technologies did lead to an increase in productivity and that patent protection had major consequences not only for innovative output, but also for the productive sector of the economy. Patent incentives drove innovation and productivity growth.

References


Correa, Carlos M et al., “Plant variety protection in developing countries: A tool for designing a sui generis plant variety protection system: An alternative to UPOV 1991,” By: Association for Plant Breeding for the benefit of society (APBREBES) and its member organizations: Berne declaration, the development fund, SEARICE and third world network, 2015.


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Figure A1: Private Sector Investment in Agricultural Breeding and Chemicals. This figure plots total private sector research investment in (i) crop breeding and (ii) agricultural chemicals, relative to investment in 1984. The data were compiled from Klotz et al. (1995) and Fernandez-Cornejo (2004).
Figure A2: **Patent Protection and Complementary Technologies Over Time.** Coefficient estimates from Equation (2). 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 A3: **Patent Protection and Crop Yields Over Time.** Coefficient estimates from Equation (2). 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 A4: **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.

Table A1: County-Level Results: IV Estimates Using Actual Crop Shares

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<th>Dependent Variable:</th>
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<td>Total County Profits</td>
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<td>County Profits Per Farm</td>
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Estimator: 2SLS

Share Not Hybrid Compatible i x $s^*_t$ Post 1985

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<td>0.127**</td>
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<td>20,105**</td>
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<td>(0.330)</td>
<td>(0.0606)</td>
<td>(0.632)</td>
<td>(0.0196)</td>
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County Fixed Effects: Yes
Census Round x State Fixed Effects: Yes
Additional Controls: Yes
K-P F-Statistic: 77.277

Observations: 17,806

Notes: The unit of observation is a county-year. All specifications include county and year fixed effects. The additional controls include pre-period log of farmland area interacted with a full set of year fixed effects and pre-period log of total farm revenue interacted with a full set of year fixed effects. The outcome variable is listed at the top of each column and all columns report IV-2SLS estimated where the GAEZ-derived predicted non-hybrid compatible share is used as an instrument for the actual share of non-hybrid compatible crop production computed from the US Census of Agriculture. Standard errors, clustered by county, are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels.
Table A2: Patents and the Farm Size Distribution

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Share Not Hybrid Compatible, $x_{it}^{Post1985}$

-0.0411*  -0.0167  -0.0354  -0.0171  -0.0307  0.00923  0.0952***
(0.0212)  (0.0225)  (0.0226)  (0.0229)  (0.0234)  (0.0243)  (0.0293)

County Fixed Effects
Yes      Yes      Yes      Yes      Yes      Yes      Yes

Census Round x State Fixed Effects
Yes      Yes      Yes      Yes      Yes      Yes      Yes

Additional Controls
Yes      Yes      Yes      Yes      Yes      Yes      Yes

Observations

R-squared
0.949    0.936    0.933    0.976    0.974    0.973    0.952

Notes: The unit of observation is a county-year. All specifications include county and state-by-year fixed effects. The additional controls include pre-period log of farmland area interacted with a full set of year fixed effects and pre-period log of total farm revenue interacted with a full set of year fixed effects. The outcome variables are the number of farms in a series of size bins, listed at the top of each column. Standard errors, clustered by county, are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels.