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Modeling Agricultural Innovation in a Rapidly Developing Country: The Case of Chinese Pesticide Industry

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Paper prepared for presentation as a Selected Paper at the
AAEA Annual Meetings in Pittsburg, PA, July 2011

Abstract: Technology and innovation play an increasingly important role in the economic development of both developed and developing countries. We investigate how policy and market factors influence firms' (or other potential innovators') decisions on innovation or imitation by developing a conceptual model and then empirically testing it using pesticide innovation data from a rapidly developing country, China. We find that the government encouraged local innovation by opening regions to more international trade, more investment in public research and education, strengthening intellectual property right (IPR) enforcement, and limiting the role of foreign inventors. However, the role of the extension of patent life in the early 1990s has little impact. Theory and some of our measures of market size suggest that this factor also is important, but the empirical evidence is mixed. The results suggest that the government policies for openness, public research and education and IPR enforcement can encourage innovation. Limiting foreign invention could encourage more local patenting but might limit Chinese farmers' access to new technology.

Key Words: Innovation; Pesticide; China; Patent

JEL Code: O31, O34, O38

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1. Introduction

While there is considerable disagreement about the effectiveness of various innovation policies, there is much less debate on the increasingly important role of technology and innovation in the economic development. Policy makers promote government investments and policies to expand their nation's innovative capacity in order to either maintain the leading position in the global competition (e.g. the developed countries)[1], or in expectation of catching up and/or leapfrog the competition (e.g. the developing countries).[2]

In recent years a substantial body of research has focused on to understand the determinants of innovation capacity and often found that the developed and developing countries follow different innovation models (e.g. Ginarte and Park 1997; Lai 1998; Yang and Maskus 2001; Sakakibara and Branstetter 2001; Varsakelis 2001; Grossman and Lai 2004; Chen and Puttitanun 2005; Schneider 2005; and Eicher and Garcia-Penalosa 2008). For example Park (2008) surveyed the relevant literature and found that the effects of policies such as intellectual property rights (IPRs) on innovation varies by the existing level of IPRs and level of economic development of that country. Chen and Puttitanun (2005) found a U-shaped relationship between the economic growth and optimal IPR protection, while others find either a positive relationship between research and development (R&D) and IPRs (e.g. Varsakelis 2001), or a U-shaped relationship between the two (Allred and Park 2007). Eicher and Garcia-Penalosa (2008) recognized the role of market size on the functioning of IPR both in stimulating innovation and in stimulating imitation. In addition, researches have also found that patent reforms have had insignificant impact on R&D and patenting (e.g. Sakakibara and Branstetter 2001; Lerner 2002).

[1] President Obama's 2011 State of the Union Address "We need to out-innovate, out-educate and out-build the rest of the world" http://www.whitehouse.gov/the-press-office/2011/01/25/remarks-president-state-union-address
[2] The President of China, Jintao Hu, announced in 2005 that one of China's development goals is to foster innovative capacity and become an "innovative country" by 2020.

Given limited data availability on innovation and its determinants, most empirical studies rely on cross-sectional analysis with pooled data across industries from various countries. This may limit the usefulness of their estimation results, as determinants of innovation may differ substantially across industries (Levin et al. 1987). Moreover, there are very few studies on innovation in developing countries and almost none on agricultural innovation. Qian (2007) examined the effects of patent protection on pharmaceutical innovations using data from 26 countries; however, she measures the innovation using US patent awarded to the innovators in those countries, thus may not capture the effects of national policies on domestic patenting.

In this study, we use data on Chinese pesticide patent applications filed by Chinese firms, individuals, and research institutes from 1986 to 2005 to examine the effects of government policies and other related determinants of innovation. China provides an excellent case study for such research because it has experienced dramatic changes in government research and innovation policies over the last 25 years. A major goal of the Chinese government and industry is to move away from labor intensive industries to science intensive industries. To encourage this type of development the government has put a number of policies in place and made substantial investments in public sector research and human capital. This allows us to assess empirically whether these policies and public investments have had much impact.

The policies that the Chinese government has put in place to stimulate innovation include the following:

1. The strengthening of intellectual property rights (IPRs) including strengthening the patent system through changes in the laws and better enforcement of the laws.
2. Policies to privatize government owned firms to make them more responsive to the needs of foreign and Chinese markets.

3. Government policies to open the economy to foreign technology and investment, as research and innovation by foreign firms could also stimulate local innovation by providing local firms with new ideas, competition from new technology, and more technology to copy or improve upon.
4. Changes in the public sector pesticide R&D system to try to make it a source of new innovations and a stimulus to private R&D. The public research establishment was reorganized into North and South Centers with additional funding for pesticide research and these centers were encouraged to work more closely with the private sector.
5. Other major government investment program that could impact innovation. Programs that increase the size and quality of undergraduate and graduate programs in the sciences would increase the supply of human capital, which is one of the major inputs into the research process.

In this paper we first develop a model of innovative behavior by profit maximizing firms in section 2,which suggests what firms will do when IPRs are strengthened, how they will react to new technological opportunities for innovation, and larger expected markets for innovations. Then in section 3 we present an econometric model that allows us to examine how Chinese pesticide firms actually responded to the changes in IPRs, technical opportunities, and market size. In sections 4 and 5 we discuss data and empirical results . In the final section we draw out some policy implications from the research. We find that government can encourage local innovation by strengthening IPR enforcement, encouraging more international trade and more investment in public research and education, and by limiting the role of foreign inventors. However, this set of policies may not be optimal for the country as a whole because it may mean that farmers will have to wait longer to get access to the best technology which still seems to be coming from foreign firms.

2. Conceptual model

Following most innovation research in the literature, our model focuses on the decision of a representative firm on R&D inputs, and the stochastic innovation outcome of such inputs (e.g. Green and Scotchmer, 1995). We assume that at time 0, a firm decides whether to (1) invest C_1 in R&D for innovation; (2) infringe with cost C_2 and bear the risk of being caught and paying a penalty, or (3) use an outdated technology with cost C_3. In general, option 1 is the most costly, while staying with the current technology is the least costly: $C_1 > C_2 > C_3$.

If the firm invests C_1 in R&D, it may generate an innovation successfully with probability $\rho = f(C_1, \mathbb{Z}) + \varepsilon$, where $\rho \in (0,1)$, $\partial f(\cdot)/\partial C_1 \geq 0$, $\partial^2 f(\cdot)/\partial C_1^2 < 0$, and ε is a stochastic component. The vector $\mathbb{Z}$ contains covariates that may be correlated with the probability of success in discovery, such as the stock of knowledge, human capital, etc.

Let $v(\mathbb{k})$ be the net value of the innovation per period, where $\mathbb{k}$ is a vector of covariates that may affect the size of *v*. If the innovation is incremental, $\mathbb{k}$ may include the degree of product improvement and market demand factors such as size and elasticity of demand for that product. We assume that the technologies in options 1 and 2 are of same quality, and that both are superior to the existing technology in option 3: $v_1(\mathbb{k}) = v_2(\mathbb{k}) = v(\mathbb{k}) > v_3(\mathbb{k})$. For simplicity, we assume that the market for the existing (inferior) technology is competitive; thus the expected net return $v_3(\mathbb{k})$ is normalized to zero. We also assume that the marginal cost of production is constant and is normalized to zero.

The firm can appropriate *v* via certain mechanisms: monopoly position granted by IP protection, first mover advantage, investment in complementary assets (including marketing, sales efforts, and services), or a combination of these. However, several empirical researches on firms' patenting behavior (e.g. Mansfield 1986; Levin et al. 1987; Cohen, Nelson and Walsh 2000) have shown that chemical industries including pesticide producers rely heavily on IP protection as a means of appropriation. In this model, we assume that the firm uses IP protection.

Let *T* denote the time length of IP protection, and let $\theta \in (\underline{\theta},1)$, a measure of the strength of local intellectual property protection system and the enforcement, denote the proportion of $v(\mathbb{k})$ that can be appropriated by the firm per period during the life of protection. The parameter $\underline{\theta}$ is a positive lower bound of θ such that $\underline{\theta} \cdot v(\mathbb{k}) = v_3(\mathbb{k})$. For a given *T*,[3] a high value of θ suggests that IP enforcement is effective so that the patent-holder can appropriate more net value of the innovation per period.

If the firm chooses option (2), it will not invest in R&D, and will instead illegally copy (i.e. infringe) other firms' protected technology. If the firm infringes, it may be caught with probability $\eta \in [0,1]$, and has to pay a penalty *F* to the rights holder.[4] The probability of being caught depends on θ, the above-mentioned measure of the strength of the local intellectual property protection system and enforcement.[5] We assume that $\eta(\theta)$ is quasi-concave in θ: $\partial\eta/\partial\theta > 0$, $\partial^2\eta/\partial\theta^2 > 0$ initially and $\partial\eta/\partial\theta > 0$, $\partial^2\eta/\partial\theta^2 < 0$ eventually. Therefore, the initial

[3] According to TRIPS, member countries of WTO need to harmonize the IPR legal system to provide some minimum level of protection. As a result *T* may be the same across countries.

[4] The penalty *F* may be set equal to the lost profits of the right holder, or the unjust earned profits by the infringing firm, or higher as to "punish" or "deter" the infringing behavior such as the treble damage in the US laws.

[5] In reality, the characteristics of firms and technology itself may also affect η. For example, a big firm may be more likely to be caught infringing because it is more visible in the marketplace. On the other hand, the big firm may have more resources available to forestall or defend against legal action for infringement.

strengthening of the IP system has increasing marginal effectiveness. We further assume that $\eta(\theta)=0$ when $\theta \to \underline{\theta}$, and $\eta(\theta)>\theta$ when $\theta \to 1$.

We can write the expected net return for the three options as follows:

Option 1 (innovator):

$$\Delta_1 = \rho(C_1,\mathbb{Z})\cdot\int_0^T \theta\cdot v(\mathbb{k})\cdot e^{-r\cdot\tau}d\tau - C_1 = (1-e^{-rT})\cdot\rho(C_1,\mathbb{Z})\cdot\theta\cdot v(\mathbb{k})/r - C_1$$

Option 2 (infringer):

$$\Delta_2 = \int_0^T (\theta\cdot v(\mathbb{k})\cdot(1-\eta(\theta)) - F\cdot\eta(\theta))\cdot e^{-r\cdot\tau}d\tau - C_2 = (1-e^{-rT})\cdot(v(\mathbb{k})\cdot(\theta-\theta\eta(\theta)) - F\cdot\eta(\theta))/r - C_2$$

Option 3 (status quo):

$$\Delta_3 = \int_0^T v_3(\mathbb{k})e^{-r\tau}d\tau - C_3 = 0\ .$$[6]

A firm invests in R&D (option 1) if and only if the individual rationality (*IR*) condition and the incentive compatibility (*IC*) condition both hold. These are: (IR) $\Delta_1 > 0$; (IC) $\Delta_1 > \max(\Delta_2,\ \Delta_3)$. Note that Δ_3 is normalized to be 0. Thus the (IC) condition reduces to $\Delta_1 > \Delta_2$ if $\Delta_2 > 0$. We further assume that when θ is high enough, the IR condition is not binding for option 1; otherwise there will be no innovation at all.

We then obtain the following lemmas (all proofs are in the appendix):

Lemma 1: *Ceteris paribus,*

a) If θ is *sufficiently high, option 1 dominates options 2 and 3;*

b) If θ is *sufficiently low, option 3 dominates options 1 and 2;*

c) If θ is *in the intermediate range, option 2 dominates options 1 and 3.*

[6] The lifetime of the existing technology is assumed to be *T*, as it may be replaced by a more advanced technology upon the expiration of IP protection.

According to lemma 1, no IPRs or lack of enforcement could destroy the incentive to innovate and/or to copy if the copying also involves certain additional costs. In the early stages of IPR establishment, firms are inclined to copy illegally because the probability of getting caught (η) lags behind the general strengthening of patents (θ). When patent protection gets sufficiently strong, there is more incentive for firms to innovate.

Lemma 2: *Ceteris paribus, if the size of the potential market goes up (increase in v), then*

a) option 1 and option 2 tend to dominate option 3; and

b) the firm tends to choose option 1 over option 2 if the probability of success in R&D is greater than the probability of not being caught infringing, and vice versa.

Lemma 2 suggests that policies that target on increasing *v* (the expected market for innovation) through adjusting $\Bbbk$ will speed up the replacement of current technology with the more advanced new technology, either through innovation or copying. However, such policies may actually induce a reduction in innovation activities in the domestic market and a proliferation of infringements, if IP enforcement system is weak.

Lemma 3: *Ceteris paribus, if ρ increases, then option 1 tends to dominate the other options; however, it is not always optimal for firm to increase ρ by spending more on C_1.*

According to Lemma 3, policies that stimulate R&D investments may lead to more innovation. However, it is also possible that government may over-invest in such policies, as the marginal effectiveness of R&D inputs is decreasing once it reaches certain level. Policies that increase the chance of success in innovation through other factors, such as increased human capital and better flow of information, tend to induce more innovation with less ambiguous effects.

Finally, we examine the impact of extension of patent life *T*:

Lemma 4: *Ceteris paribus, if T increases, no switching will be induced among option 1 firms; some option 2 firms will be switched to option 1, while other option 2 firms will find the switch to option 1 even less desirable.*

Lemma 4 suggests that an extended patent life benefits innovators. Potential infringers that were deterred before the increase in patent life will be further deterred after the change. If the IP system failed to deter an infringer prior to the change, then some infringers will find it more lucrative to infringe afterwards, while some other infringers will switch from infringing to innovation. However, a potential cost to society of this policy change is the loss incurred by consumers of the option 3 firms. While the profit change does not affect option 3 firms in terms of profitability (they still earn zero economic profits), an extended patent life implies that their customers need to wait longer before accessing to the new technology upon the patent expiration.

These four lemmas taken together suggest that economists' standard model of innovation which emphasizes larger expected market size leads to more the innovation; greater appropriability through stronger intellectual property rights increases innovation; and technological opportunity - increasing the probability of successful innovation through more R&D increases innovation - is generally consistent with profit maximizing behavior. But these lemmas also suggest that relationship may be more complicated that the "naïve" model suggests. Lemma 1 suggests that at the early stages of IPR development many firms will chose copying rather than developing their own innovations through research. Lemma 2 suggests that when IPRs are weak, policies to increase expected market size could increase copying rather than inducing R&D investments. Lemma 3 implies that there are circumstances in which increasing the probability of successful research will lead to less R&D investment rather than more. And lemma 4 suggests that while an extension in patent life may induce some infringers to switch to innovation, it also reinforces the original standing of the other infringers (and innovators). Such a policy may come at a social cost due to delayed technology upgrading upon patent expiration.

3. Empirical model

In this section, we present an empirical study of innovation, measured by the number of invention patent applications, in the agricultural pesticide industry in China. We test whether the commercial firms in China respond to expected markets, appropriability, and technological opportunity in ways as suggested by the economic theory in section 2. We also examine whether potential innovators other than the commercial firms (i.e., individual innovators and research institutes) follow the similar model or not.

The empirical model used here is specified as:

$$\begin{aligned} AP_{it} = {} & \beta_{0i} + \beta_1 GA_{it} + \beta_2 VA_{it} + \beta_3 OA_{it} + \beta_4 DO_{it} + \beta_5 Y_{it} + \beta_6 Y_{it}^{2} + \beta_7 LAW + \beta_8 WTO \\ & + \beta_9 BS_{it} + \beta_{10} YR + \beta_{11} LAW * YR + \beta_{12} WTO * YR + \beta_{13} NC_{it} + \beta_{14} SC_{it} \\ & + \beta_{15} f\_AP_t^{A01N} + \beta_{16} f\_AP_t^{Other} + \varepsilon_{it}, \end{aligned} \tag{1}$$

where AP_{it} is the number of pesticide-related Chinese invention patent applications by applicants from the *i*-th province in year *t*, and ε is an error term with mean zero and constant variance. For the explanatory variables, the first set of variables is related to potential market size. We use the total grain acreage (*GA*), the total vegetable acreage (*VA*), and the total other crop acreage (*OA*) for each province as proxies for potential market size as many domestic pesticide producers sell their products locally. The foreign export dependency ratio (*DO*) is a proxy for the degree of openness which could increase foreign competition. The growth level, measured by deflated provincial GDP (*Y*), can reflect the potential market size for new innovation, and can also be associated with the level of R&D investment that local firms and local government are able to carry. The square term for GDP allows for the possible curvature of the relationship between innovation activity and growth levels as implied by Lemmas 2 and 3.

A second set of variables are related to appropriability, which affects the innovation activities according to Lemmas 1 and 4. We use a dummy for the amendment of the Patent Law in 1993 (*LAW*) that included chemicals under the patent protection and increased the length of patent protection from 15 years since granted to 20 years since filing for all patent applications filed in 1993 and later, and a dummy variable for China's entry to WTO in 2001 (*WTO*). The WTO entry has many institutional impacts. In accordance with the TRIPs agreement, China extended the patent life of those applied prior to the 1993 amendment to 20 years upon the entry. China also committed to free market and national treatment upon the entry, and adjusted the regulations on pesticide production and registrations accordingly.

The technological opportunity variables include the number of college graduates with bachelor's degree graduated in the i-th province in year t (BS_{it}) as a proxy for human capital in that province, and several variables for public sector R&D. The North Center of Pesticide Research was established from existing government programs in 1995 with two regional institutes in northern China and the South Center was established in 2000 with four regional institutes in southern China. The government allocated R&D funding specifically designated to pesticide innovations to those research institutes upon the establishment of the two centers. Patent applications behavior by research institutes and related stakeholders may be influenced specifically by such public R&D support. So, we include dummy variables *NC* (North Center) and *SC* (South Center) to capture such impact.,

We also include the time trend (*YR*) to capture the national or global structural changes over time, or any other time specific factor effect. In order to examine whether the time effect may change after the patent law amendment and WTO entry, we allow for interaction terms of the relevant factors. Besides we also hypothesize that foreign applicants' patenting behavior may have potential effects on domestic innovators, and the impact may differ by what they are patenting: those in the "A01N" group, most of which are formulation or process type innovations; and those in the "Other" group, most of which are likely product innovation.

Equation 1 is for the aggregate number of patent applications. It is possible that innovation behavior differ by innovations types. Thus, we also run the regression of patent applications by categories: those "A01N" type or "Other" type. We hypothesize that the lagged patent applications by government research institutions may have a spillover effect on the current patent applications by non-government agents. We would expect in the Chinese system that patents of products (the "Other" type) might induce patenting of new processes to produce the product or new formulations of the product, while the opposite flow of impact may be unlikely. We will test for both hypotheses. Therefore, the group-specific models are specified as:

$$AP_{it}^{A01N} = \beta_{0i} + \mathbf{\beta X} + \gamma_1 r\_AP_{i,t-1}^{Other} + \varepsilon_{it}, \quad (2)$$

$$AP_{it}^{Other} = \beta_{0i} + \mathbf{\beta X} + \gamma_2 r\_AP_{i,t-1}^{A01N} + \varepsilon_{it}, \quad (3)$$

where $r\_AP_{i,t-1}^{Other}$ and $r\_AP_{i,t-1}^{A01N}$ are the lagged number of "Other" and "A01N" applications by government research institute, respectively. In general, we expect γ_1 to be positive and significant, and γ_2 to be insignificant. The vector **X** in equations 2 and 3 includes covariates with coefficient β_1 to β_{16} in equation 1.

We also distinguish between three types of domestic applicants for patents: individuals[7], firms, and government research institutes, because factors affecting the decision to apply for a

[7] According to Chinese patent law, if filed by individuals, the application fee and maintenance fee are only 15% of the standard level that a corporate applicant pays. As a result, a unique phenomenon in Chinese patent application

patent may differ across applicant types. We test this hypothesis by jointly estimating the following three equations, each for one type of applicants.

For the individuals (*I*):

$$I\_AP_{it} = \beta_{0i} + \boldsymbol{\beta}\mathbf{X} + \gamma_3 r\_AP_{i,t-1} + \varepsilon_{it}; \qquad 4(a)$$

For commercial firms (*C*) :

$$C\_AP_{it} = \beta_{0i} + \tilde{\boldsymbol{\beta}}\tilde{\mathbf{X}} + \gamma_3 r\_AP_{i,t-1} + \varepsilon_{it}; \qquad 4(b)$$

For government research institutes (*R*):

$$R\_AP_{it} = \beta_{0i} + \boldsymbol{\beta}\mathbf{X} + \varepsilon_{it}. \qquad 4(c)$$

The vector **X**'s in equations 4(a) and 4(c) are the same as in equations 2 and 3. The vector $\tilde{\mathbf{X}}$ in equation 4(b) differs from **X** by omitting the North and South center dummies. The North and South centers were designed to support government research institutes only, and may not have direct impact on commercial firms' R&D decisions. Since many of the individual applicants are researchers affiliated with the research institutes, we expect that the North and South Center factor would affect these applicants in the relevant provinces as well. For the same reason, the lagged research institute patent application could have a spillover effect on the individual applicants.

4. Data

Data used in this study are taken from the official Chinese statistical publications, including *China Statistical Yearbook* (1987 – 2006), and from the online database of the State Intellectual Property Office of China (SIPO). We focus on invention patent only, as its application, similar to the U.S. utility patent, is subject to the examination for utility, novelty and

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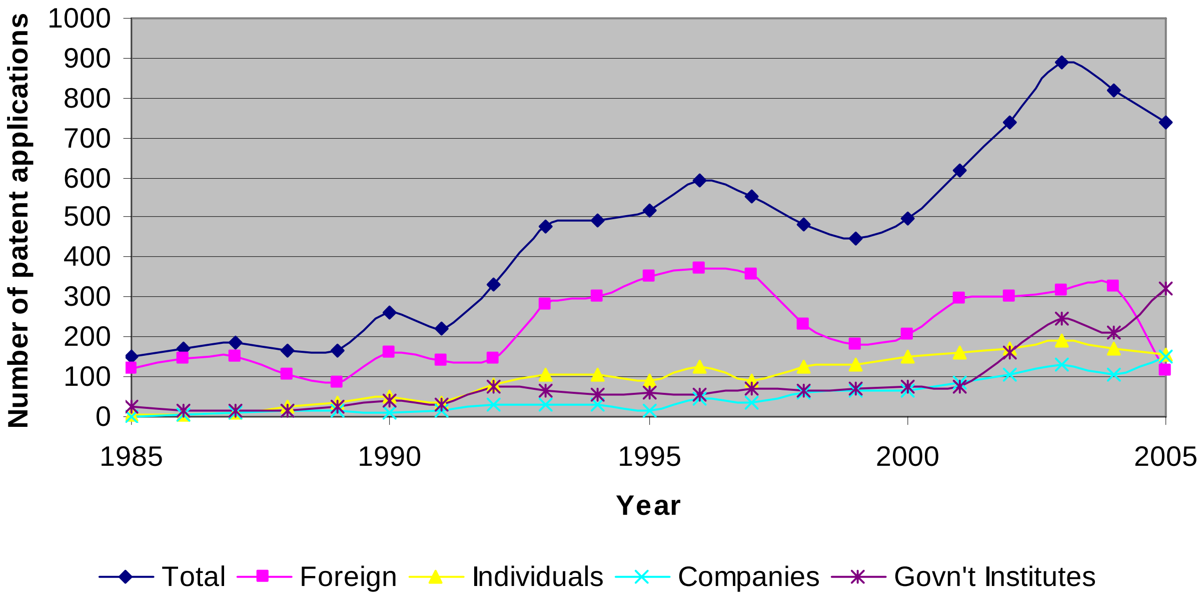
pool is that most of the domestic applicants are individual filers. These individual filer can be merely a transfer from corporate filers due to the cost consideration, non-obviousness, while the other patent types (the utility model patent and the design patent) do not need to demonstrate novelty and non-obviousness. Our patent application data were compiled till July 2007. However, in this study we will only analyze those applications filed by the end of 2005. This is to avoid the potential downward bias in the number of patent applications filed in 2006 and 2007 because many of these applications had not been publicly disclosed yet by July 2007.[8] China institutionalized its first patent law in 1985. We use observations since 1986 to avoid the potential initial year bias due to ignorance. In fact, observations in 1985 are very limited.

We identified a total of 4749 pesticide related Chinese invention patent applications, filed by domestic applicants from 1986 to 2005, of which 797 applications are of product innovation type (often in the SIPO category C07C and C07D), and 3952 applications are of formulation type (in the SIPO category A01N). The domestic applicants include individuals, private firms, and research institutes, filing 42%, 22%, and 36% of the total applications, respectively. The foreign applicants, almost all private companies, filed 4678 pesticide related patent applications during the same time period, of which 2546 applications are of product innovation type, and 2132 applications are of formulation type. The multinational firms dominate the application pool: four companies (BASF, Bayer, Syngenta and Dow) account for 55% of the total.

. Figure 1 illustrates the trend in pesticide related patents applied and issued from 1985 to 2005 for total and by applicant types. Overall the number of patent application is rising throughout the time period, with obvious spurts in growth in the early 1990s and around 2001.

[8] According to SIPO, the public disclosure of a patent application could take up to 18 months from the date of application.

Figure 1. Trend in pesticide related patent applications in China, 1985 – 2005



The study uses province level panel data from 1986 to 2005 for 29 regions in mainland China.[9] The dataset contains 565 observations.[10] Table 1 gives selective descriptive statistics of the data used in this study. Individual applicants apply the most number of patents (on average), followed by the research institute applicants, and firm applicants apply for the least. However, research institute apply the most number of product type patents, although on average the product type application account for only 17% of the total application. In contrast, foreign applicants, almost all being firm applicants, applied for more product type applications than the process type of application (54% vs. 46%). The grain production is the major market for pesticide consumption because of the dominant share of rice production. Other major markets

[9] We do not include Chongqing in the study due to the short history of Chongqing as a direct administrative district since 1997. Xizang (Tibet) is not included because no pesticide patent application record is found.
[10] In total we could have a maximum 29 x 20 = 580 observations. However, 15 provinces did not have any patenting activities in 1986. We treat them as missing values (while in later years treat as value zero if no patent application) because of the concern of ignorance during the initial years of the patent law.

Table 1. Summary statistics of selective variables, 1986-2005

		Mean	Standard deviation	Minimum	Maximum	Count
Total number of patent applications by domestic applicants/province/year	**Individuals**	3.55	4.90	0	37	565
	Commercial firms	1.80	3.77	0	52	565
	Research institutes	3.06	5.70	0	43	565
	Subtotal	8.41	12.01	0	99	565
Number of A01N patent applications by domestic applicants/province/year	**Individuals**	3.38	4.64	0	37	565
	Commercial firms	1.47	2.95	0	41	565
	Research institutes	2.14	3.80	0	29	565
	Subtotal	6.99	9.35	0	73	565
Number of "Other" patent applications by domestic applicants/province/year	**Individuals**	0.16	0.57	0	8	565
	Commercial firms	0.33	1.27	0	14	565
	Research institutes	0.92	2.88	0	32	565
	Subtotal	1.41	3.99	0	42	565
Total number of patent applications by foreign applicants per year		233.9	97.41	85	369	20
Number of A01N patent applications by foreign applicants per year		106.6	54.96	24	196	20
Number of "Other" patent applications by foreign applicants per year		127.3	62.11	38	232	20
GDP in 1990 RMB (100 million RMB)		1422.08	1592.93	58.25	12799.63	565
Total grain acreage (million ha)		3.73	2.53	0.14	10.03	564
Total vegetable acreage (million ha)		0.38	0.35	0.005	2.03	564
Total other crop acreage (million ha)		1.05	0.78	0.02	3.23	564
Number of bachelors granted annually		32020	27395	1540	197423	564
Foreign trade dependency ratio		0.235	0.313	0.02	1.84	565

include the vegetable production, and other minor crop production (e.g. cotton, oildseeds, and the fruit orchards). This is consistent with the relative size of the grain land (with provincial mean at 3.73 million hectares), other crop land (with mean at 1.05 million hectares), and the vegetable land (with mean at 0.38 million hectares). For the foreign trade dependency ratio, big variation exists across provinces and over time. In general, the ratio has been increasing over time.

5. Econometrics results

The results of our econometric modeling on innovation measured by the different types of patents are shown in table 2. We estimate the fixed effect panel regression with a disturbance following a first-order autoregressive process (AR(1)) for the "Other" group (equation 3), but not for the total application (equation 1) and the “A01N” application (equation 2). We conduct the Wooldridge test for autocorrelation in panel data for equations 1-3, which reject the null hypothesis of no autocorrelation for the “Other” group, but failed to reject the null for the total application equation and the total “A01N” application equation. This provide indirect evidence that patenting behavior differ by innovation types. Product innovation often takes longer time than the formulation innovation, thus may contribute to the autocorrelation in error terms.

For the market size variables, none has a significant impact on the total number patent applications. For the process innovation, the other crop production is negatively associated with the number of patent applications (significant at 10% level), while the other two size variable are insignificant. For the product innovation, the only significant variable is the vegetable land (negative and significant at 5% level). These results suggest that the innovation activities in the Chinese pesticide industry do not seem to respond to changes in market size of the major crops, but may be discouraged by expanding vegetable production or other minor crop production. According to Lemma 2, increased market size may induce a reduction in innovation activities in the domestic market and a proliferation of infringing if the IP system is not effective. Our results seem to provide indirect evidence of the lack of strength and enforcement in IPRs in China.

The growth level variable GDP has positive and statistically significant coefficient in all three regression models: higher GDP is associated with more patent applications. The positive sign is consistent with the conceptual model that higher growth level may increase innovation by providing more resources available for pesticide R&D (Lemma 3), either in the form of local government support, or firm’s own revenue. The coefficient of the quadratic term of GDP is not statistically significant, suggesting lack of evidence on curvature in the R&D input-output relation in our data.

The amendment of the patent law in 1993 does not seem to have had a significant impact on the number of applications, although the coefficients are positive in all three cases. This is likely due to the fact that the amendment in which chemical compound is patentable may not have direct impact on Chinese pesticide industry as most of the patenting activities by Chinese firms are process innovations , which were protected before the amendment anyway.

The coefficient of WTO entry is positive for all three models and significant in the cases of all pesticide patent application and the formulation type of application. The institutional changes associated with WTO entry, including the expected strengthening in IPR enforcement harmonization in accordance to TRIPs and a free market production and distribution system, seem to stimulate the number of pesticide patent applications in general, especially in the formulation innovations.

The degree of openness has positive and significant coefficient for all three regression models, suggesting that the more international exposure the regions have, the more innovations are conducted regionally. This may reflect the learning aspect of domestic innovators' perception and utilization of IPRs through increased world market exposure. It is also consistent with the anecdotal evidence that firms that targeting domestic markets find IP less useful while firms that interact with foreign markets rely on IP protection more. In addition, openness may allow firms to take ideas from outside China and turn them into innovations in China, – international spillover has been found to stimulate innovation in India (Basant and Fikkert 1996)

The number of college graduates with bachelor's degree has positive and significant coefficient in all cases except for the case of the product innovation type of application (positive but insignificant). As a proxy for human capital, a high number of college graduates with a bachelor's degree not only means there are more educated people available for research and technical jobs associated with innovation but also may be associated with a high volume of related faculty and researcher human capital in the universities. The positive sign is consistent with Lemma 3, in which more human capital may increase the probability of innovation output, thus leads to more patent applications.

The time effect is positive, suggesting increasing trend in patent application over time (but is again insignificant in the case of product innovation type of applications). This may reflect Chinese researcher's learning process in perceiving and utilization of IP mechanism, and the accumulation of expertise in conducting R&D and innovation activity. The lack of significance for both the time effect and human capital effect in the case of the production innovation seem to suggest that most of the efforts by Chinese researchers are devoted to formulation/process type of innovation activities, which is consistent with the anecdotal observations.

While WTO entry has an upward shifter effect on the number of patent application in general, the slope effect on time trend is negative post-entry. This may reflect a fishing-out effect: after an increased effort in finding and patenting innovation after WTO entry, it becomes more and more difficult to generate new innovation over time, *ceteris paribus*. The slope effect of the amendment of the IP law is again insignificant for all three models, suggesting lack of impact of such an institutional change.

The establishment of the government sponsored North research center shows no impact on patent applications. However, the South research center's inception has a positive and significant effect on patent applications in all three cases. This may be due to the fact that the North center was established before the administrative reform in the government research institutes in the late 1990s. Thus the research output may be transferred to the industry directly by government discretion, thus the formal change in structure did not make much difference in patenting behavior. In contrast, the South center was established around 2000 as an amalgamation of smaller regional centers which may have had more impact on its output and impact in the rest of the industry. In addition, China's transition to the market economy has fully implemented by that time. Thus higher research inputs may lead to increased innovation output, therefore more patent applications, which is consistent with Lemma 3 in the conceptual model.

For the spillover effects from the research institute, the lagged research institute's application of product type innovation is not found associated with the current number of application of formulation patent: the coefficient is positive but not statistically significant. Moreover, we fail to reject the null hypothesis that the spillover effects do not go from formulation/process innovation to product innovation. Instead, the lagged research institute's application of formulation patent is negatively associated with the current number of application of product type innovations (significant at 5% level). Note that the product innovation often precedes the formulation type of innovation. In China, government policy, especially prior to the transition to the market economy, was that the research institutes conduct more product innovation type of R&D while the firms tend to conduct the formulation type of R&D, if any. If the research institutes switch to conduct more formulation type of innovation instead of transferring their product innovation output to the firms, this may crowd out product innovation output in the following years. Our results suggest that there may be a problem of too much applied research by government institutes which crowds out basic researches. A recent study of private R&D by Hu et al. (2010) found that in other parts of the agricultural sector – livestock, fisheries, plants and food industries – there was a similar crowding out phenomena.

Table 2. Fixed effects panel analysis of pesticide related Chinese patent applications by Chinese organizations.[a]

Variable		Total applications		A01N applications (process and formulation)		Other applications (product)	
		Coeff.	t-Stat.	Coeff.	t-Stat.	Coeff.	t-Stat.
Total grain acreage		0.36	0.50	-0.06	-0.11	-0.02	-0.03
Total vegetable acreage		-2.36	-1.07	1.16	0.61	-4.27**	-2.36
Total other crop acreage		-2.30	-1.45	-2.28*	-1.72	-0.28	-0.24
GDP		4.63***	3.90	3.12***	3.19	2.24***	2.62
GDP_sqr		-0.07	-0.92	-1.64E-03	-0.03	-0.05	-1.00
Law		0.80	0.20	0.87	0.25	2.44	0.76
WTO		51.56***	3.47	49.85***	4.07	1.55	0.22
Openness		15.09***	5.39	6.87***	2.95	9.22***	5.14
Bachelor graduates		1.15***	4.11	0.69***	3.05	0.13	0.94
Time		0.85***	3.83	0.73***	3.75	0.33	1.11
Law*time		-0.19	-0.52	-0.27	-0.83	-0.27	-0.78
WTO*time		-2.88***	-3.47	-2.76***	-4.04	-0.05	-0.13
North center		0.65	0.31	-0.84	-0.51	0.30	0.20
South center		7.40***	1.91	2.71*	1.75	1.98*	1.71
Lagged A01N application by research institute		-	-	-	-	-0.12**	-2.47
Lagged other application by research institute		-	-	0.19	1.37	-	-
Foreign “A01N” application		-0.06***	-3.56	-0.03*	-1.88	-0.02***	-3.41
Foreign “Other” application		6.10E-03	0.84	0.003	0.53	3.36E-04	0.12
Constant		-5.48	-1.59	-2.66	-0.94	-2.90**	-2.19
R^2	Between	0.51		0.49		0.33	
	Within	0.66		0.60		0.32	
	Overall	0.56		0.54		0.32	
Number of observations		564		545		516	

[a] Statistical significance: * at the 10 percent level, ** at the 5 percent level, *** at the 1 percent level.

The effect of foreign applicants’ patent activities on domestic applicant’s patenting behavior differs by application types. The number of formulation application by foreigners has negative and significant impact on number of domestic applications in all three cases, while foreign applicants' product innovation application has no significant impact on domestic patenting behavior. This is consistent with the observation that the product innovations by foreign applicants (mostly the multinationals) are distinctive from and often superior to those by the domestic innovators. Thus the domestic innovators are unable to compete with the foreign innovators in that market. In the formulation market, domestic innovators may be competing with the foreign applicants. As the restrictions on foreign firms are released and there are more foreign applications, domestic applications are declining, suggesting that they have difficulty competing even in the process technology where they were thought to have an advantage.

Next, we will examine the patenting behavior of different applicant types: individuals, commercial firms, and government research institutes. Equation 4(a)-(c) are estimated with a fixed effects model with correlated panels corrected standard errors and panel specific auto correlation. We also run the regression model by application groups ("A01N" and "Other"). All results are reported in table 3.

Total Number of Applications

Applicants seem to respond to the size changes in the three markets (grain, vegetable, and other crops) differently: individual researchers respond positively to the increase in vegetable acreage and negatively to the increase in other crop acreage. Commercial firms respond negatively to the increase in the main market, the grain production, which may suggest the lack of effective IP and enforcement according to Lemma 2. Government research institutes respond positively to the grain market size and the other crop market size, but negatively to the vegetable market size. Since the grain production and the other crop production dominate the agricultural land in China, it is likely that the government put priority on research activities targeted on these two markets. Government research institutes are likely following such a priority call, especially

Table 3. Regression on Chinese patents by Chinese individuals, research institutes and firms.[a]

Total applications						
Variable	**Individual**		**Firm**		**Research institute**	
	Coeff.	**z-Stat.**	**Coeff.**	**z-Stat.**	**Coeff.**	**z-Stat.**
Total grain acreage	0.54	1.54	-1.07***	-3.87	0.76*	1.78
Total vegetable acreage	5.67***	4.08	0.50	0.46	-8.39***	-4.75
Total other crop acreage	-2.01**	-2.14	0.40	0.64	2.26**	2.37
GDP	1.75**	2.46	1.67***	3.60	4.93***	5.06
GDP_sqr	-0.09*	-1.84	-0.09***	-2.73	-0.14**	-2.04
WTO	16.47***	2.60	17.41***	4.58	12.39*	1.85
Law	3.69**	1.97	-2.42**	-1.98	0.95	0.43
Openness	0.95	0.63	2.65**	2.00	3.66*	1.82
Bachelor graduates	0.35**	2.03	-0.34**	-2.53	0.25*	1.86
Time	0.41***	3.67	0.08	1.01	0.22	1.42
Law*time	-0.42**	-2.27	0.24**	1.99	-0.11	-0.52
WTO*time	-0.94***	-2.63	-0.97***	-4.46	-0.61	-1.61
North center	-0.09	-0.08	-	-	3.08	1.11
South center	0.55	0.55	-	-	0.60	0.43
Lagged application by research institute	0.03	0.59	0.21***	4.61	-	-
Foreign A01N application	-0.008	-1.04	-0.02***	-3.40	-0.03***	-4.05
Foreign other application	-4.81E-04	-0.16	0.003	1.36	0.004	1.11
Constant	2.23	1.49	2.34***	2.94	4.59	1.37
R^2	0.72					

A01N (process and formulation) Applications						
	Individual		**Firm**		**Research institute**	
Variable	**Coeff.**	**z-Stat.**	**Coeff.**	**z-Stat.**	**Coeff.**	**z-Stat.**
Total grain acreage	0.47	1.51	-1.04***	-3.84	0.20	0.77
Total vegetable acreage	5.40***	3.83	1.79	1.52	-3.48***	-3.12
Total other crop acreage	-1.91**	-2.01	-0.14	-0.24	1.02*	1.67
GDP	1.73**	2.43	0.64	1.27	1.75***	3.60
GDP_sqr	-0.10**	-2.07	-0.01	-0.28	0.02	0.38
WTO	13.49**	2.18	15.04***	3.84	16.33***	3.28
Law	3.78**	2.11	-2.58**	-2.13	0.62	0.41
Openness	0.18	0.13	2.86**	2.16	3.38***	2.79
Bachelor graduates	0.28*	1.71	-0.06	-0.47	0.29***	2.90
Time	0.39***	3.65	0.04	0.54	0.21**	2.27
Law*time	-0.44**	-2.50	0.25**	2.11	-0.11	-0.76
WTO*time	-0.77**	-2.20	-0.87***	-3.90	-0.86***	-3.07

North center	0.18	0.15	-	-	0.48	0.61
South center	0.24	0.28	-	-	0.35	0.48
Lagged A01N application by research institute	0.10	1.29	0.08	1.25	-	-
Lagged "Other" application by research institute	-0.04	-0.40	0.09	1.43	-	-
Foreign A01N application	-0.003	-0.46	-0.01**	-2.47	-0.02***	-2.77
Foreign other application	-0.001	-0.44	0.001	0.74	0.003	1.30
Constant	2.10	1.45	1.60**	2.33	3.32	1.34
$\mathbf{R^2}$	0.73					

Other (product) applications

	Individual		**Firm**		**Research institute**	
Variable	**Coeff.**	**z-Stat.**	**Coeff.**	**z-Stat.**	**Coeff.**	**z-Stat.**
Total grain acreage	0.07	1.55	0.16**	2.35	0.08	0.41
Total vegetable acreage	-1.05	-0.23	-0.43*	-1.71	-3.65***	-4.50
Total other crop acreage	-9.28E-04	-0.01	-0.14	-0.90	0.85*	1.86
GDP	-0.04	-0.31	0.18	1.00	2.22***	3.74
GDP_sqr	0.01	1.33	-0.002	-0.18	-0.10***	-2.64
WTO	2.36**	2.09	7.79**	5.35	-7.33**	-2.42
Law	0.12	0.40	-0.47	-1.13	2.26*	1.92
Openness	0.80***	3.30	1.78**	2.55	0.28	0.20
Bachelor graduates	0.09***	2.63	0.12***	3.20	-0.01	-0.17
Time	0.03	1.58	0.06**	2.05	0.13	1.48
Law*time	0.01	0.18	0.06	1.58	-0.20	-1.63
WTO*time	-0.14**	-2.14	-0.44***	-5.32	0.45**	2.54
North center	-0.09	-0.72	-	-	2.87	0.93
South center	0.76**	2.23	-	-	1.01	0.83
Lagged A01N application by research institute	-0.005	-0.33	0.07***	2.67	-	-
Lagged "Other" application by research institute	0.02	1.42	0.17***	5.44	-	-
Foreign A01N application	-0.005***	-3.28	-0.01***	-6.18	-0.01***	-3.48
Foreign other application	4.94E-04	0.87	0.001	1.51	-3.32E-04	-0.23
Constant	-0.21	-0.95	-0.54	-1.32	1.28	1.45
$\mathbf{R^2}$	0.47					

[a] Statistical significance: * at the 10 percent level, ** at the 5 percent level, *** at the 1 percent level. Total number of observations for each model is 545.

given that part of their R&D funding are still from government sources. Vegetable production, while with smaller scale, is often associated with higher profit margin compared to the grain and other minor crop production. Individual researchers, most of who work for the research institutes, have financial incentive to devote to and apply for vegetable related pesticide innovation patents under their own name. This may also create a “stealing-away” effect on patent application filed by the research institutes where those individual researchers are affiliated with, as suggested by the negative and significant coefficient of the vegetable acreage for research institutes.

Like the whole group, the income variable GDP has a positive and statistically significant coefficient for all three applicant types: higher income is associated with more patent applications. The coefficient of the quadratic term of GDP is now negative and statistically significant for all three applicant types, suggesting that the income effects will reach a peak level and then decrease, consistent with our Lemma 3. Note that the income level at the peak is not the same across types: highest for individuals and lowest for the firms. This may explain why the curvature is not observed when we group all three applicant types together.

The WTO effect is positive and significant for all applicants. They all respond positively to the strengthening of IP and freeing of market and distribution upon WTO entry as it implies higher market reward. The amendment of the patent law (*LAW*) induce more patenting from individuals but less from firms, while no impact on research institutes. According to Lemma 4, an extended patent life may reinforce the firms’ initial standing: more innovations if they were initially innovating, and more infringing if they were initially infringing. Our results seem to suggest different initial standings of different applicants: firms are likely involved in infringing activities in the first place, while individuals (most likely from the research institutes) are likely innovating in the first place. Since many individual innovators are researchers in the government research institutes, the self-interests seeking behavior of these researchers may contribute to the lack of response of the research institutes to the institutional change in law. Note that the time slope effect of the WTO entry is similar to that in the whole group. However, for the interaction term of *LAW* and time, we observe a negative effect for individuals and a positive effect for commercial firms. The individuals may experience a fishing-out of new ideas over the time, while the firms, if infringing, may experience a push to switch to more innovations over the time.

For the degree of openness, the coefficient is positive for all types, while significant for firms and research institutes but not for individuals. The international spillover effects do not seem to pass over to the individual patenting behavior.

The coefficient of the number of college graduates with bachelor's degree is positive and significant in the case of individual applicants and research institutes. This is consistent with Lemma 3 as it is a proxy variable for human capital. However, the coefficient is negative and significant in the case of commercial firm applicants. If firms are indeed infringing in the first place, as suggested by our results above, more human capital can make more "copying" possible, which may result in a reduction in innovation activities.

The time trend variable has positive coefficient for all three applicant types, but is significant only in the case of individual applicants. Individual researchers who are active in searching for IP protection of their research seem to be also active in the learning process.

Since the North and South research centers involve only research institutes and their affiliated individuals, we examine the impact of these two dummy variables on the patenting behavior of these two types of applicants. None of the coefficients are statistically significant. This may be due to the fact that the individual applicants are mainly from the research institutes.

Thus the impact of research centers, if any, is diluted between the two groups (individuals and research institutes).

For the spillover effects from the research institute, the coefficient of the lagged number of research institute's applications is positive and significant for commercial firm applicants. This is consistent with the positive spillover from research institutes to commercial firms.

The pattern of effects of foreign applicants' patent activities on domestic applicant's patenting behavior is similar to what we found in the general model: The number of formulation application by foreigners has negative and significant impact on number of domestic applications by firms and research institutes. We find again lack of impacts of the foreign applicants' product innovation application on domestic patenting behavior across applicant types. This confirms our observation that domestic producers may compete with the foreign producers only in formulation market but not in the product innovations market.

We then run the same regression to the subgroup of formulation type of patent applications and product innovation type of patent applications. Below we will focus on new insights, and may not discuss the details of similar findings we learned earlier.

Formulation Innovation Applications and Product Innovation Applications

The results for individual applicants in terms of formulation type of innovation are similar to those obtained in the case of total number of application. However, for the product type applications, the individual applicants respond positively to WTO entry, degree of openness, number of bachelor graduates, and the establishment of the South Center, and negatively to time after WTO entry and the number of foreign formulation applications. The coefficients of other covariates are insignificant. Compared to the process/formulation innovations, the product innovation applications seem more likely to be affected by foreign market variables. With more open economy and free market, domestic innovators seem to devote more to product innovation activities. The south center effect may reflect higher R&D input, similarly for the human capital.

For commercial firm applicants, the results for the subgroup of formulation type of applications are similar to those for the total number of applications, except that the GDP and GDP squared, and the number of bachelors now have insignificant coefficients. The evidence of spillover effect from domestic research institutes also disappeared, although being positive. For the subgroup of product innovation applications, firms now respond positively to the grain acreage, but negatively to the vegetable acreage. The evidence of direct impact of provincial GDP disappeared. The number of bachelors now has a positive and significant coefficient. Firm applicants respond to time trend positively, and there are strong evidences of spillover effects from domestic research institutes' product type of innovation. Note that we found evidence in the general model that research institutes may conduct too much applied research that crowds out the basic product innovation. Our results here suggest that the impact may be passed to the commercial firms: If the research institutes conduct less product innovation, the commercial firms will also conduct less product innovation activities.

For research institute applicants, the WTO entry effect is positive and significant for formulation type of applications, but is negative and significant for product type of innovations. This seems to suggest that research institutes experience some pressure in the product type innovation since the WTO entry. This pressure may come from firm applicants' increasing patenting activities due to strengthened IP after WTO entry. Or it may be that research institutes switch from product innovation activities to formulation type of activities as the result of institutional transformation happens around the WTO entry period. The IP law amendment effect is positive and significant for product innovation applications. The amendment of law that extends the patent protection to chemical compound and an extension in patent life does seem to stimulate the product type of innovation.

The impact of number of bachelors is positive and significant for formulation applications, but negative and insignificant for product innovation applications. Anecdotal evidence suggest that young professionals in Chinese pesticide market tend to be more market oriented, and they tend to commit more to formulation type of activities, for which they have relative advantages. In contrast, product innovation activities required more time and effort but with less chance of success. Therefore, young professionals may contribute to switch R&D activities in the research institutes from product innovation to formulation innovation.

6. Conclusions and implications

Economic theory shows that if there is no way to protect intellectual property, innovators will not invest in research to develop innovations and will not invest to copy the innovations of others. With stronger protection of innovation, innovators are more likely to invest in research. However, with weak IPRs, copying may be more attractive than investing in R&D to innovate. Our empirical test of this hypothesis suggests that Chinese innovators do respond positively to stronger IPRs. The dummy variable representing the strengthening of patent enforcement which took place with China's entry into WTO in 2001 is consistently positive and statistically significant. This suggests that the government's efforts to strengthen IPRs and enforcement have encouraged Chinese innovation and should continue.

Economic theory also suggests that larger potential markets will stimulate research in the presence of some protection of IP, but may cause a proliferation of infringment if IP protection is weak. In the regression analysis, several of our market size variables (land acreages) have negative and significant coefficients for the commercial firm applicants, but positive for individual or research institute applicants. The economic growth variable, provincial GDP, is another proxy for expected markets for new inventions from R&D, but it also could be interpreted as a measure of governments' and firms' ability to finance research. This variable is consistently positive and usually statistically significant, and the square term is usually negative and significant, suggesting an inverted-U relationship.

The variable for the importance of foreign trade in the province (the Openness variable) stimulates research perhaps because firms in these provinces have access to large foreign markets – particularly for generic pesticides. One could also argue the companies need to innovate more to keep ahead of foreign competition. However, the presence of foreign firms that are patenting there has a negative impact which suggests that Chinese innovators are concerned that new products by foreign firms might reduce the long term prospects for their own new products and processes.

Theory also suggests that policies that strengthen a firm's technical capacity to innovate increase the probability of successful innovation. The empirical study provides evidence that several policies have been important. Public sector pesticide R&D investments, particularly the development of the South Center for research, stimulated Chinese patenting. Patenting by the government centers, which is a much more accurate measurement of their research activities, had a positive impact on firms' patenting (table 3) although this affect gets buried in the aggregate results (table 2). However, if the product innovation activities are deemed as especially desirable, we find evidence of a potential policy failure in that the government centers may devote too much effort to the applied research, which may crowd out product innovation by both research institutes and commercial firms. The other major government investment program that should impact innovation is human capital. The regression analysis does support the hypothesis that it has a positive impact. Finally, patenting by foreign firms particularly patenting of new process and formulation innovations has a negative impact as mentioned above – perhaps out of concern about foreign firms taking away future markets.

The policy implications for patenting are fairly clear. The government can encourage local innovation by supporting stronger IPRs, encouraging more exports, more investment in public research and education, and limiting the role of foreign inventors. However, this set of policies may not be optimal for the country as a whole because if the government limits foreign inventors it may mean that farmers will have to wait longer to get access to technology from foreign firms upon patent expiration. The country would be trading off the social gains of 100s of millions farmers in order to protect the patenting by a relatively small number of local pesticide companies.

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Appendix: Proofs for Lemma 1 – Lemma 4.

Lemma 1: *Ceteris paribus, a) If* θ is *sufficiently high, option 1 dominates options 2 and 3;*

b) If θ is *sufficiently low, option 3 dominates options 1 and 2;*

c) If θ is *in the intermediate range, option 2 dominates options 1 and 3.*

Proof: a) When $\theta \to 1$, the unbinding IR condition ensures $\Delta_1 = (1-e^{-rT}) \cdot \rho\theta v / r - C_1 > 0$. It follows that $(1-e^{-rT}) \cdot \rho\theta v / r > C_1$, and $\Delta_1 - \Delta_2 =$ $(1-e^{-rT}) \cdot [\rho\theta v - v \cdot (\theta - \theta \cdot \eta(\theta)) + F \cdot \eta(\theta)] / r$ $-(C_1 - C_2)$. Since $\eta(\theta) > \theta$ when $\theta \to 1$, we can pick up $\tilde{\theta}$ such that $\eta(\theta) = 1 > \theta$ for $\theta \in (\tilde{\theta}, 1)$. Thus $\Delta_1 - \Delta_2 = (1-e^{-rT}) \cdot [\rho\theta v - v \cdot (\theta - \theta) + F] / r - (C_1 - C_2) =$ $(1-e^{-rT}) \cdot \rho\theta v / r - C_1$ $+(1-e^{-rT}) F / r + C_2 > 0$ because $(1-e^{-rT}) \cdot \rho\theta v / r - C_1$. Therefore, we expect that $\Delta_1 > \Delta_2$, and $\Delta_1 > \Delta_3 = 0$, when θ is sufficiently large ($\theta \to 1$).

b) The critical value of θ for $\Delta_1 = (1-e^{-rT}) \cdot \rho\theta v / r - C_1 < 0$ is $\theta < rC_1 \big/ (1-e^{-rT}) \rho v$. If $\underline{\theta} < rC_1 \big/ (1-e^{-rT}) \rho v$, then when $\theta \to \underline{\theta}$, we expect $\Delta_1 < 0 = \Delta_3$. For Δ_2, recall that $\eta(\theta) = 0$ when $\theta \to \underline{\theta}$. Thus $\Delta_2 = (1-e^{-rT}) \cdot v(\mathbb{k}) \cdot \theta / r - C_2 < 0$ when $\theta < rC_2 \big/ (1-e^{-rT}) v$. If $\underline{\theta} < rC_2 \big/ (1-e^{-rT}) v$, then when $\theta \to \underline{\theta}$, we may expect $\Delta_2 < 0 = \Delta_3$. Note that $C_1 > C_2 > C_3$ and $\rho \in (0,1)$, it follows that $rC_2 \big/ (1-e^{-rT}) v <$ $rC_1 \big/ (1-e^{-rT}) \rho v$. Therefore, if $\underline{\theta} < rC_2 \big/ (1-e^{-rT}) v$, then when for a sufficiently low $\theta \to \underline{\theta}$, we expect that $\max(\Delta_1,\ \Delta_2) < \Delta_3 = 0$

c) We need to show that when θ is in the intermediary range, we expect that $\Delta_2 > \Delta_1$, and $\Delta_2 > \Delta_3 = 0$. From the proof of part b), we can infer that when $\theta \in (rC_2 \big/ (1-e^{-rT}) v$, $rC_1 \big/ (1-e^{-rT}) \rho v)$, $\Delta_2 > 0 = \Delta_3$ and $\Delta_1 < 0 = \Delta_3$, thus $\Delta_2 > \Delta_1$.

Lemma 2: *Ceteris paribus, if the size of the potential market goes up (increase in v), then* *a) option 1 and option 2 tend to dominate option 3; and*

b) the firm tends to choose option 1 over option 2 if the probability of success in R&D is greater than the probability of not being caught infringing, vice versa.

Proof: a) Since $\partial\Delta_1/\partial v = (1-e^{-rT})\cdot\rho\cdot\theta/r > 0$ and $\partial\Delta_2/\partial v = (1-e^{-rT})\cdot\theta\cdot(1-\eta(\theta))/r > 0$, it follows that Δ_1 and Δ_2 increase in *v*. When *v* is big enough, Δ_1 and Δ_2 tend to be positive, thus option 1 and option 2 tend to dominate option 3.

b) Since $\partial(\Delta_1-\Delta_2)/\partial v = (1-e^{-rT})\cdot\theta\cdot(\rho-(1-\eta))/r$, it follows that $\partial(\Delta_1-\Delta_2)/\partial v > 0$ if $\rho > (1-\eta)$. Therefore, if the probability of success in R&D (ρ) is greater than the probability of not being caught infringing ($1-\eta$), increasing *v* will make option 1 more desirable than option 2.

Lemma 3: *Ceteris paribus, if ρ increases, then option 1 tends to dominate the other options; however, it is not always optimal for firm to increase ρ by spending more on C_1.*

Proof: Since $\partial\Delta_1/\partial\rho = (1-e^{-rT})\cdot\theta\cdot v/r > 0$, $\partial\Delta_2/\partial\rho = \partial\Delta_3/\partial\rho = 0$, it follows that option 1 may dominate options 2 and 3 if ρ is high enough. However, if the increase in ρ is achieved through spending more on C_1, we have $\partial\Delta_1/\partial C_1 = (1-e^{-rT})\cdot(\partial f(\cdot)/\partial C_1)\cdot\theta\cdot v/r - 1$, which can be negative because $\partial^2\Delta_1/\partial C_1^2 = (1-e^{-rT})\cdot(\partial^2 f(\cdot)/\partial C_1^2)\cdot\theta\cdot v/r < 0$ by the assumption that $\partial^2 f(\cdot)/\partial {C_1}^2 < 0$. The optimal level of C_1 should chosen at when $\partial\Delta_1/\partial C_1 = 0$.

Lemma 4: *Ceteris paribus, if T increases, no switching will be induced among option 1 firms; some option 2 firms will be switched to option 1, while other option 2 firms find switch to option 1 even less desirable.*

Proof: Since $\partial\Delta_1/\partial T = e^{-rT}\rho\theta v > 0$, an increase in patent life T always make option 1 more profitable. For $\partial\Delta_2/\partial T = e^{-rT}(v(\mathbb{k})\cdot(\theta-\theta\eta)-F\eta)$, the sign depends on whether the unjust enriched gross profits if not caught, $v(\mathbb{k})\cdot\theta\cdot(1-\eta)$, is more than the penalty payment if caught, $F\eta$, or not. If $\partial\Delta_2/\partial T < 0$, then $\partial(\Delta_1-\Delta_2)/\partial T > 0$, i.e., firms tends to choose option 1 over option 2 when patent life increases. If $\partial\Delta_2/\partial T > 0$, then the sign of $\partial(\Delta_1-\Delta_2)/\partial T$ depends on whether the expected per period gross profits of innovation, $\rho\theta v$, is more than the expected per period gross profits of infringing, $v(\mathbb{k})\cdot\theta(1-\eta)-F\eta$, or not. Given that $C_1 > C_2$, firms choose option 1 must earn more than if they choose option 2, $\rho\theta v > v(\mathbb{k})\cdot\theta(1-\eta)-F\eta$, thus $\partial(\Delta_1-\Delta_2)/\partial T > 0$, an extended patent life makes option 1 more attractive relative to option 2. For those firms choosing option 2, some firms have $\rho\theta v < v(\mathbb{k})\cdot\theta(1-\eta)-F\eta$, then $\partial(\Delta_1-\Delta_2)/\partial T < 0$, such a policy change will make option 2 more profitable. However, there also exist some firms with higher per period gross return from option 1 than the per period gross return from option 2, but choose option 2 over option 1 due to $C_1 > C_2$. For these firms, $\partial(\Delta_1-\Delta_2)/\partial T > 0$, it is possible that an extension in the patent life will induce them to switch from infringing to innovation.