The curious case of C-88: impacts of a potato variety on farmers in Yunnan, China

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Abstract

Background: Limited analysis has been conducted of the role of agricultural research in promoting Chinese agricultural growth in less-favored areas. This paper analyzes how a particular potato variety generates benefits to producers and discusses how these benefits may have contributed to poverty reduction in Yunnan province. Cooperation 88 (C88) is a high-yielding, late blight-resistant variety that was developed through a partnership between the International Potato Center and Yunnan Normal University in Kunming, China.

Methods: Qualitative and quantitative methods are used to analyze determinants of adoption of C88, and to estimate impacts of adoption on producer well-being. A unique farm-household database is used to document the determinants of C88 adoption and disadoption. The quantitative assessment is supplemented with a qualitative analysis of the potato value chain to understand how seed availability and concern for processing attributes contributed to and eventually constrained diffusion. Market-level information was used in an economic surplus model to quantify the substantial economic impact of C88 over 20 years since its release.

Results: C88 spread rapidly in Yunnan following its release and was widely adopted by commercially oriented farmers. Disadoption began after 2010 with limited seed availability driving the shift toward newer varieties. Farmers, however, appreciate the ease of marketing, the 15% higher yields, and late-blight resistance associated with C88 suggesting that seed constraints are countervailing the economic benefits of the variety. Total impact on Yunnan potato farmers of the variety was estimated to be around $2.5 billion for the 1996–2015 period.

Conclusions: On per-person terms among C88 growing farm households, the economic advantage of the variety is likely to have contributed to poverty reduction. The aggregate impact of C88 diffusion occurred during a period of rapid poverty reduction in Yunnan and yield and disease-resistance benefits of C88 likely contributed to this reduction.

Introduction

Poverty in China fell dramatically from 53 to 8% between 1980 and 2000, but wide geographic disparities existed into the early 2000s with mountainous interior regions lagging behind coastal areas (Chen et al. 2006). An important source of persistent poverty in areas such as

Yunnan Province, historically one of China's poorest provinces, was slow farm productivity growth (Ahmad and Goh 2007).

Chinese policy for rural poverty reduction mainly concentrated on the non-farm sector. An initial burst of farm income growth followed the introduction of the Household Responsibility System (HRS) in 1978 as the government allowed access to markets and supported producer prices. This income growth contributed to rapid poverty reduction in many agricultural-dominated rural areas. The impact, however, of the HRS on rural

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poverty reduction dwindled by the mid-1980s and government turned to specific actions via its National Targeted Poverty Reduction Programs (NTPR) (1986–1993). These programs, and follow-ups such as the 8–7 Poverty Reduction Plan introduced in 1994, set up regional councils to identify impoverished counties, set standards for poverty reduction and dedicated special funds for poverty alleviation (Qu 2017).

Subsequent analysis of the rural poverty experience showed that growth in agricultural productivity in lagging areas was closely related to poverty reduction (Wang et al. 2004). Limited analysis has been conducted on the role of agricultural research in promoting Chinese agricultural growth. The HRS stimulated a growth spurt by opening markets to small-scale producers, but little is known about how technical change in agriculture has continued to contribute to sustained economic growth and poverty reduction.

The Chinese national agricultural research system is among the world's largest. The country has benefited from technology spill-ins associated with partnerships with international researchers such as the Consultative Group on International Agricultural Research (CGIAR). Documentation of benefits from technology spill-ins has focused on CGIAR-related improved rice varieties, as 15–25% of China's rice areas is sown to varieties containing CGIAR germplasm (Nyberg 2002).

In many less-favored areas, however, rice is not the major crop and it is of interest to understand relationships between CGIAR-Chinese research collaborations and agricultural growth in these areas. In Yunnan Province, for example, potato is widely grown for food security and commercial purposes, and southwest China accounts for about 40% of national production (Jansky et al. 2009). Little documentation exists of research partnerships for potato between Chinese and international institutions, but Chinese potato productivity is among the world's highest, possibly a result of access to improved germplasm. Cooperation 88, is an improved variety resulting from a partnership between the International Potato Center (CIP) and Yunnan Normal University (YNU) (Li et al. 2010; Robinson and Srinivasan 2013). For many years, C88 was the most widely planted variety in China and it is especially popular among processed potato producers due to its size and chemical composition (Robinson and Srinivasan 2013).

Objectives

The overarching goal of this paper is to document the role of agricultural technical change in benefitting small-scale producers in Yunnan province, with a focus on C88. The focus on C88 is appropriate because it is the earliest successful result of a long-term partnership between the CGIAR and Chinese Universities, and it was among the most widely adopted potato varieties in China. It is also favored by the processing industry which needs a steady supply throughout the year, a challenge in the wet season when late blight is especially prevalent.

Specific objectives are to: (i) understand the extent and determinants of adoption and disadoption of C88 and how conditions in potato seed markets contribute to spread of the variety; (ii) estimate the economic impacts of C88 diffusion on producers and consumers; and (iii) analyze the role of the CIP/YNU partnership in stimulating growth in Yunnan Province.

The paper is organized as follows. First, background is provided on the development of C88 as a CGIAR-Chinese collaboration. Second, methods for assessing the determinants of adoption and its impacts are discussed. The farm-household dataset and its collection are described third. Results and conclusions follow.

Background

Since 1993, China has led the world in potato production and area planted (FAOSTAT n.d.). Potato production in China has been increased due to growth in demand resulting from rapid income increases in industrial areas and increased consumption of Western foods (Jansky et al. 2009). Potato cultivar research in China began in the 1940s with selection and introduction of foreign varieties. Since the 1980s research has primarily focused on development of high-yielding late blight-resistant germplasm (Jansky et al. 2009). Late blight spreads quickly in cool, wet environments, and is especially detrimental to winter-season potato production in Yunnan Province (Li et al. 2010; Jansky et al. 2009). Yunnan is a major producing area for winter-season potatoes.

In 1986, a CIP-supported graduate student identified late blight resistant CIP clones in collaboration with two YNU professors. A CIP scientist bred the advanced clones and maintained the germplasm at the CIP genebank (Robinson and Srinivasan 2013). During experimental trials, the variety C88[1] out-yielded Mira, the most widely planted variety in Yunnan at the time, by between 35 and 76% in trials from 1994 to 2000 (Li et al. 2010).[2] C88 also had the lowest late blight infection rate of 13 varieties tested in Yunnan Province (Crook et al. 2013) and is highly resistant to common viruses (Li et al. 2010).

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[1] The name Cooperation 88 was chosen to reflect the collaboration between CIP and YNU in its development.

[2] Mira, a German variety, was introduced into China in the early 1950s and has not been improved since. By the mid-1990s, Mira's resistance to late blight and virus diseases was diminished and producers were searching for new replacement varieties (Robinson and Srinivasan 2013).
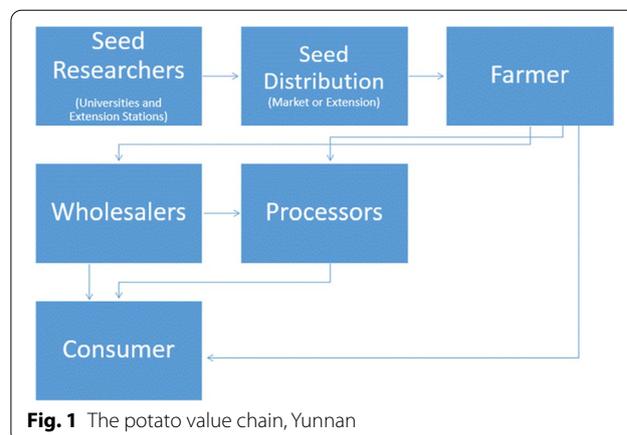
By 2001, C88 was sown to about 70,000 hectares (ha) in Yunnan (Li, personal communication, September 1, 2015), and area under C88 increased until it was the most widely grown variety in Yunnan in 2009 (Li et al. 2010). The variety's appeal is attributed to its late blight resistance, high yield, high quality, good taste, and suitability for the chip processing industry. In 2010, C88 covered 400,000 ha throughout China, with a large share of the national area found in Yunnan (Robinson and Srinivasan 2013).

An important reason for widespread adoption of C88 is its role in the potato chip processing industry. C88 is preferred by this industry due to its low water content, size, gravity, and yellow flesh color. As household income has increased, demand for processed potatoes has grown, stimulating demand for processable potatoes. The processing industry is relatively new to China as the first French-fry processor opened in Beijing in 1992. The growing chip-processing industry requires a reliable year-round supply of raw materials. From January to July (the winter growing season), C88 is one of few appropriate varieties, because it can mature earlier in low altitude, sub-tropical regions during the winter months (Li et al. 2010).

Diffusion of C88 took place when poverty in Yunnan Province, one of the country's poorest, was falling. Poverty was initially concentrated among rural households, and fell dramatically from 1985 through 2005.[3] As of 2003, townships in Southwest and Northeast Yunnan Province had the highest rates of poverty, often exceeding 30% (Ahmad and Goh 2007). In other poor areas, the Chinese government based its poverty reduction strategy on potato processing by small and medium enterprises (Yu et al. 2007),[4] but the major agricultural intervention for economic development in Yunnan was release of C88.

Methods

This study is a multi-dimensional assessment of C88, its diffusion and its role in delivering economic benefits to producers in Yunnan. It focuses on three major components of variety impact: (i) diffusion and factors affecting it; (ii) factors influencing farmer decisions to adopt and to continue planting the variety; and (iii) how adoption affects market supply and leads to broad economic impacts. Methods include expert workshops to estimate the area planted by variety, qualitative and quantitative structured interviews with value chain actors,

Fig. 1 The potato value chain, Yunnan

community and household quantitative surveys and their analysis, and economic surplus analysis to measure the total impacts of the variety from 1996 to 2015.

Since information on area covered by specific varieties can be difficult to obtain (Walker and Alwang 2015) we began by conducting regional workshops in China with potato-sector experts to estimate areas covered by different potato varieties by season using best practices for such data collection (SIAC 2018). These workshops contained the implicit assumption that expert judgment is a good means of estimating adoption at the regional level. For further insights into the determinants of diffusion and impacts in Yunnan, structured interviews were conducted with value-chain actors, including input suppliers and post-harvest marketing agents (Fig. 1). Qualitative methods were complemented by quantitative analysis of community and household surveys with a focus on determinants of adoption, intensity of adoption and variety turnover. Survey data are also used to calibrate the economic surplus model used to measure impacts of variety diffusion and decompose the impacts over time and among producers and consumers. The value chain assessment provides insight into where C88 creates value at different stages.

Data sources

The household survey, conducted by students and faculty from YNU in July–September 2015, collected information on household and farm characteristics, variety adoption, potato production, and market participation. A three-stage sampling design was employed with sample size determined to make the resulting estimates to be representative of potato-growing areas in Yunnan. In the first stage, counties were selected at random with the probability of selection proportional to area planted to potatoes from official statistics. Forty-three villages within these counties were randomly selected with

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[3] Lu (2012; p. 46) cites various sources and states that the incidence of poverty in Yunnan fell from 35.1 to 5.5% between 1985 and 2005.

[4] The Potato Industrialization Strategy in Xiji county, Ningxia Province, beginning in 2003 sought (successfully) to promote small and medium-sized processors in an effort to alleviate poverty (Yu et al. 2007).

probability of selection proportional to area planted to potato, obtained from extension agents. In each village, 15 households were selected at random based on a list of potato-producing households obtained from the local government. The total sample contained 616 households. Small groups (3–5 people) of village officials were convened in a focus group discussion (FGD) to collect information for the village (community) survey.

The household questionnaire had six modules and included information on household composition and characteristics, housing conditions and asset ownership, potato production activities from planting to selling during the 2015 late spring season, questions about the decision to adopt C88, and perceptions of potato traits. The community survey obtained information on village characteristics, validated data about available varieties from the household survey, gathered information on local dynamics of adoption and dis-adoption of different potato varieties, and obtained comparative production costs between C88 and the variety it replaced. The FGD encouraged discussion in order to reach consensus.[5]

For information on potato value chains, interviewees were selected based on their expertise and role in the value chain. The potato seed value-chain informants included county- and province-level extension officers and a representative of a potato seed company. Jansky et al. (2009) highlight the lack of coordination between seed-supply entities and the commercial potato processing industry in China, and separate interviews were conducted with a chip processing company CEO, a chip processing plant manager, and a starch company CEO. Fifteen interviews were conducted during August–September 2015. Additional interviews were conducted in February 2017, including a workshop with all actors of the value chain where preliminary results of the study were presented to stimulate discussion.

Empirical models

Extension agents, potato seed providers, breeders and others responsible for potato production in Yunnan indicate that seed distribution is centrally coordinated with heavy involvement of the state through state-related research institutes and the public agricultural extension system. Seeds are distributed by the public extension system to farmers through local governments and few new varieties are disseminated through private or informal channels. As a result, estimation of determinants of

potato diffusion and spread begins by examining village-level determinants of adoption.

Village-level adoption econometric model

Interviews with value-chain actors indicated that village-level factors play a major role in variety diffusion. Seed-producing entities coordinate seed deliveries with extension agents, local government partners and farmer groups. Most villages receive only one variety at a time. Factors reported to affect seed dissemination include suitability of the variety to village agro-ecological conditions, degree of integration of the village into the regional economy, and ability to obtain production scale and ship production to outside markets. Demands from the chip processing industry are not generally considered during these decisions.

Village-level determinants of adoption are examined using a fractional multinomial logit model (FML) (Mullahy 2010; Papke and Wooldridge 1996). The dependent variable is the share of village potato land allocated to each potato variety and the FML is appropriate when shares are modeled. With M varieties (seven in this study), by definition, for each village $\sum_{m=1}^{M} s_m = 1$, where s_m is the share of the mth variety. Mullahy (2010) proceeds under the assumption that the conditional means have a parametric structure $E[s_m|x] = \xi_m(x; \alpha)$ where the α is a vector of common parameters shared across the M conditional mean parameters. The FML is appropriate when a set of dependent variables take values between 0 and 1 and add to 1. The dependent variables are the shares of potato area planted to C88 and other varieties at the village level. This model then estimates how the different independent variables affect each variety's share of potato area. Using the FML, the M conditional means are assumed to have a multinomial logit functional form:

$$E[s_{mk}|x] = \xi_k(x; \beta) = \frac{\exp(x\beta_k)}{\sum_{m=1}^{M} (x\beta_m)}, \quad k = 1, \ldots, M$$

where x is a vector of characteristics and β is a vector of estimated parameters. Applications of the FML in agriculture include Allen (2014) who examines determinates of crop shares for households in Mali; Paudel et al. (2016), who model irrigation measures used by US nursery producers; and Mu and McCarl (2011) who analyze shares of land allocated to different management systems in the US.

Information from the value-chain interviews guided selection of explanatory variables included in the village-level adoption/diffusion model (the village share of potato land allocated to each variety is the dependent variable). These variables include the number of households and total potato area in the village to reflect the

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[5] To confirm genetic identity of C88, we conducted DNA fingerprinting of a subsample of 144 tubers taken randomly from the household surveys. Identity was confirmed on 141 cases (98%). Together with observations in the field, we concluded that the likelihood of varietal misidentification was very low.

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degree to which commercial production can be brought to scale. These variables are expected to have a positive impact on the variety share of commercially sought potatoes such as C88. Labor market conditions affect ability to achieve production at scale, so dependency ratios, experience in potato cultivation and education levels of farmers averaged at the village-level are also included.

Household-level adoption

The household's decision to adopt C-88 (a binary outcome) is assumed to result from a process of choosing among alternative varieties and adopting the variety best meeting household objectives.[6] A binary dependent variable model (e.g. logit, probit) can be motivated using a latent variable approach. Assume y_j^* is the (unobserved) net return from adopting variety j compared to the next best variety. If $y_j^* - y_k^* > 0$ for all $k \neq j$ then $y_j = 1$ (that is, the variety is adopted, an outcome we observe). Otherwise $y_j = 0$. By modeling the latent outcome in a linear fashion $(y_j^* = x'\beta + \varepsilon)$ and using a probit or logit link function, we obtain an estimable model. Since we are interested in the decision among multiple alternative varieties, we model this decision as a Seemingly Unrelated Regression (SUR) probit (there is no SUR analog for the logit link).

The adoption decision is assumed to be determined by farmer and household characteristics, physical characteristics of the farm, and village characteristics. Information is crucial to the adoption of new technologies and factors such as number of working age members, and their age and education affect access to information. Access to information is also captured through membership in farmer organizations and access to extension services. Better educated farmers, those with more access to information, and those farming at a larger scale tend to adopt earlier, because they can process information better and experiment with new practices (Feder et al. 1985; Huque et al. 1996). Of course, seed availability can constrain farmer choices, but each still has some choice.

Village characteristics used in the household model are similar to those in the village model, and include average farm size, village population, potato area and degree of isolation. In addition, we included two dummy variables reflecting whether the village experienced a serious potato disease/pest problem in the past five years to reflect potential for varietal replacement.

Valuation of variety characteristics helps gain an understanding about adoption decisions. Farmers were asked how important (from 1—not important to 3—very

important) different characteristics were to them when considering new potato varieties. Two characteristics were included in the analysis– the importance of price and the importance of market demand. Farmers who consider price to be important are assumed to be more likely to sell in the market, and thus adopt C88 (Li et al. 2010). C88 was targeted towards commercial farmers, who are more likely to be market-oriented, so the subjective importance of market demand was also included as a regressor.

Physical capital, in the form of land, agricultural equipment, and livestock ownership, can influence adoption. During the C88 roll-out, extension agents targeted wealthier and commercial farmers (Myrick 2016). Wealth, measured using a livestock index,[7] the value of agricultural equipment, and farmland is expected to have a positive impact on adoption.

Adoption of C88 slowed since its peak around 2010 and we are also interested in the determinants of disadoption. The disadoption decision is only observed for farmers who adopted the variety at one point in time (the household survey asks this question) and we use a Heckman probit to adjust for this sample selection problem. In this case, the probit equation for disadoption is specified as a latent variable $(y_i^* = x_i\beta + u_{1i})$ and the binary outcome, y_i, takes a value of 1 if $y_i^* > 0$ and equals 0 otherwise. The outcome is only observed if a selection criterion is met, if $y_i^{select} = (z_i\gamma + u_{2i} > 0)$ which indicates whether C88 was adopted at some time in the past. Non-zero correlation between the two equation errors (corr(u_1, u_2) = ρ) means that estimation of the first equation without correcting for the correlation will lead to biased results. We use the Heckman probit correction to overcome this problem.

The Heckman model is well-identified only if the selection equation has at least one variable that is not present in the selection equation. We exclude the following variables from the second stage: number of potato plots, household wealth quintile, and village elevation. The number of plots and household wealth should make the household more willing to experiment with new varieties (Feder et al. 1985) but should not affect the rate of disadoption, which is determined by yield, growing experience, and other factors. Households at higher elevations should also be more willing to experiment, since yield can vary dramatically by elevation. Summary statistics for the household variables are shown in Table 1.

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[6] While the seed system limits the ability to choose among all possible varieties (due to lack of access in some villages), individual farmers still can choose among some varieties. No village was found where all farmers plant a single variety, so choice is possible.

[7] The livestock index is calculated using livestock units from Chilonda and Otte (2006).

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Table 1 Summary statistics by C88 cultivation status, household survey

	Ever grown			Never grown	Sample
	Grow now	Stopped	All		
# HHs	143	132	275	341	616
% of all households	23.2	21.4	44.6	55.4	
% of ever grown	52.0	48.0			
HH size	4.30	4.28	4.29	4.24	4.26
Dependency ratio	0.20	0.23	0.22	0.29	0.25
HH head education (%)					
Primary&-	52.5	60.6	56.4	73.0	65.6
Junior secondary	38.5	36.4	37.5	23.8	29.9
Senior secondary&+	9.1	3.0	6.2	3.2	4.6
Visited by extension agent in the last year (%)	63.6	50.8	57.5	16.4	34.7
HH is a member of farmer organization (%)	26.6	22.0	24.4	1.8	11.9
Farm size (ha)	1.6	0.9	1.2	0.3	0.7
Potato area (ha)	0.7	0.5	0.6	0.1	0.3
Potato intensity (%)	60.2	49.4	55.0	39.9	46.7

Economic surplus model

The contribution of C88 to the Yunnan economy over time is estimated using an economic surplus model. We use a small open economy model as Yunnan potatoes are shipped to the coastal provinces in the east for processing (Li et al. 2010) and part of the reason for economic growth since the late 1980s is improved connectivity by rail and highway. This reality means that local prices are determined in a national market with very little response to local supply/demand conditions. The open economy model assumes that trade is relatively costless and, as a result, farmers in Yunnan are price takers; in addition, prices of other goods and factors are assumed to be fixed.[8] According to Alston et al. (1995), in most cases it is appropriate to assume a small open economy since it is unlikely that a province such as Yunnan has enough market power over the long run to influence the national potato price.

The surplus model is set up to look backwards from 2015 and estimate the market supply that would have existed in the absence of C88. Beginning in 1996, market supply shifted outward as increasing numbers of farmers adopted C88; the supply shift was due to higher yields of C88 and associated lower per-unit cost of production. With a small open economy, the shift is against a perfectly elastic demand curve which causes quantity to increase to Q_1 and does not affect price (Fig. 2). In the open economy case, all surplus accrues to producers and the change in surplus is the area $W_0 X_0 X_1 W_1$.

To measure the relationship between the inward supply shift (moving backwards) and C88 adoption, the shift is expressed as a proportion of price, known as the K-shift:

$$K = \left(\frac{Y}{\varepsilon}\right) - \left(\frac{C}{1+Y}\right)A \tag{1}$$

where Y is the proportionate yield increase per hectare after adopting C88, C is the proportionate change in variable input cost per hectare, and A is the proportion of total Yunnan potato land under C88 (Alston et al. 1995). The K-shift reflects production costs savings per unit of
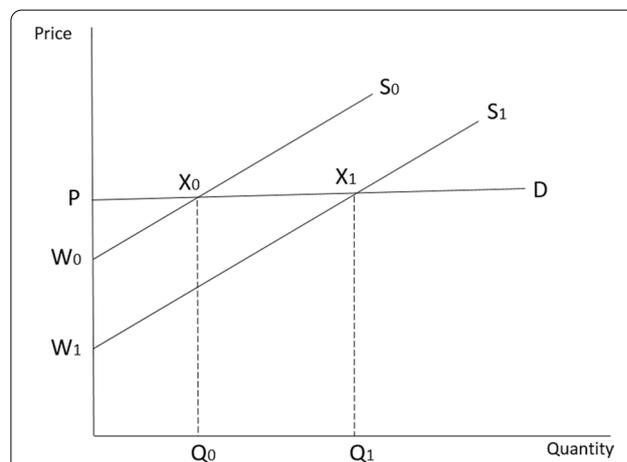

Fig. 2 Graphical representation of a rightward supply curve shift due to C88 adoption in a small open economy in a single year

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[8] We discuss the sensitivity of the results to assumptions about market trade using a closed-economy model as a comparison.

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output, a function of input costs and yields which vary by variety.

The main difference between a small open economy and a closed economy is the measurement of benefits since the demand curve is perfectly elastic and there are no gains to consumers. The K-shift (Eq. 1) is the same in the closed and open economy models. Change in total surplus can be obtained:

$$\Delta TS = \Delta PS = P_C Q_0 K (1 + 0.5 K \varepsilon)$$

where P_C is the price for potatoes in Yunnan and Q_0 is the initial quantity of potatoes in the market in Yunnan in 2015.

Results

Expert workshops showed that about 22% of 587,000 ha of potatoes in Yunnan were planted to C88 in all seasons in 2014. In the winter season, when few potatoes are available for the processing industry in China,[9] 56% of Yunnan's roughly 60,000 ha of potatoes is covered by C88. C88 has an advantage in the winter season due to its resistance to late blight, which flourishes under the cool, wet conditions of Yunnan's winter.

The potato value chain

Heavy involvement of the state on the input side is a defining characteristic of the Chinese potato value chain. Potato variety research in China is conducted by some 30 national and regional research organizations, and universities develop varieties to increase yields and address production constraints, particularly late blight. As a result, before C88 most cultivars were slow in maturing and did not have acceptable processing characteristics (Jansky et al. 2009). Variety testing takes many years as potential germplasms are tested under different agroecological conditions for multiple years. Once a variety is approved for release, research centers provide germplasm to groups capable of seed multiplication.

Interviews with YNU faculty and experts in the Yunnan potato industry revealed that most potato seeds in Yunnan are provided through the formal sector led by potato research institutes and universities and coordinated by the Chinese agricultural extension system.[10] These groups include seed companies and extension/experiment stations. Government extension agents and other officials build relationships with seed multipliers to determine if the variety is appropriate for their farmers.

This determination may include running regional trials to evaluate the agronomic properties of the variety in their targeted areas. Seed companies will sell the seed either in the private market or to government (local, county-level, or provincial).

County officials and extension agents identify broadly suitable areas for the variety (basing this decision on agroecological conditions, farm sizes, access to markets and other factors) and work with village leaders to determine if a variety is appropriate for a village. Many villages do not have regular access to clean seed, and extension agents and officials are the primary sources of new and replacement seed. Households located in villages targeted for diffusion of C88 have the option to adopt C88; our data indicate that many villages have no access to the variety. Households residing in villages without access to C88 seed are less likely to be aware of the new variety and thus, to adopt.

Market channels vary by season of production. In the spring and summer seasons, potatoes are produced throughout Yunnan and sold locally. In the winter months, potatoes are produced mainly in the counties near the southern Myanmar border and processing potatoes are produced and are shipped to processors in Kunming and coastal areas. During winter months, C88 accounts for more than 50% of the potato area and C88 area expansion is constrained by the availability of seed. Our interviewees concurred that seed producers do not cater to industry needs and only in the past couple of years has certified C88 rebounded in response to demands from processors.

The enabling institutional environment for C88 might be described as a "perfect storm" of success factors. While the country was experiencing strong macroeconomic growth leading to growing demands for processed potatoes, potato technology-specific factors were present in Yunnan. A durable inter-institutional collaboration during the research phase (1990–1998) helped develop and validate the new technology. Domestic research institutions (mainly YNU) took a leading role to influence government policy and promote adoption of the variety. C88 was particularly attractive to a rapidly growing chipping industry lacking winter season supplies of potatoes and a set of private–public linkages within the potato chip value chain helped coordinate government policy. These policies supported dissemination and adoption of clean seed for the variety.

Diffusion was also promoted by engagement of the extension systems (with presence of Experiment Stations relatively near the potato growing areas) and farmers' participation during the adoption phase through involvement of local communities. The presence of champions (the Chinese and CIP breeders) promoting the

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[9] In the winter season, only four provinces produce potatoes (SIAC 2018), yet processors need a year-round supply.

[10] Jansky et al. (2009) also note the role of potato seed (public and private) companies, but few of these are found in Yunnan Province.

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Table 2 Fractional probit average marginal effect estimates of village-level intensity of adoption of potato varieties, Yunnan Province, 2015 (Marginal effects and standard errors shown)

	C-88 AME	Hui-2 AME	Weiyu-3 AME	Mira AME	Xuanshu-2 AME	Qingshu9 AME	Lishu-7 AME
Number of HHs in village	0.0005** (0.000)	− 0.0008* (0.000)	− 0.0001 (0.000)	0.0014*** (0.000)	0.0002** (0.000)	− 0.0001 (0.000)	− 0.0007*** (0.000)
Village total potato area (mu)	0.0003*** (0.000)	0.0005*** (0.000)	0.0003 (0.000)	− 0.0013** (0.001)	0.0002*** (0.000)	− 0.0003*** (0.000)	0.0001*** (0.000)
Distance to county town (km)	0.0037*** (0.001)	0.0013*** (0.000)	− 0.0019 (0.001)	0.0010 (0.001)	− 0.0002 (0.000)	0.0007*** (0.000)	− 0.0032** (0.001)
Average HH dependency ratio	0.1271 (0.457)	1.4382*** (0.198)	− 0.0130 (0.313)	− 1.2023*** (0.381)	0.4917** (0.246)	− 0.5185*** (0.116)	0.1033 (0.196)
HH average years of experience in potato cultivation	− 0.0182*** (0.005)	0.0048 (0.004)	0.0120*** (0.004)	0.0178** (0.008)	− 0.0021 (0.003)	− 0.0135*** (0.003)	− 0.0003 (0.004)
Average HH livestock wealth index	0.0490*** (0.015)	0.0385*** (0.010)	− 0.0883*** (0.021)	− 0.1416*** (0.037)	0.0264*** (0.009)	0.0342*** (0.009)	0.0206 (0.013)
Average HH head years of education	0.0806*** (0.027)	− 0.1009*** (0.015)	− 0.0029 (0.023)	0.0171 (0.026)	− 0.0006 (0.008)	− 0.0027 (0.006)	0.0162 (0.013)
% of self-kept seeds in total quantity of seeds	0.0766 (0.070)	− 0.0210 (0.056)	− 0.2031*** (0.055)	0.2832*** (0.072)	− 0.0305 (0.037)	0.0157 (0.027)	− 0.1013** (0.048)

1. AME: average marginal effects on village adoption rates

2. Level of significance: "***" 1%; "**" 5%; "*" 10%

technology across all phases of the institutional environment is consistent with the literature describing similar cases (e.g. Jansky et al. 2009).

Intensity of adoption: Village-level model

Adoption of potato varieties at the village level is modeled using a FML; dependent variables are the adoption intensity[11] for seven varieties (see Table 2); for each village, these intensities sum up to one. Although the formal seed system constrains seed availability, all villages have access, through seed saving and informal transfer to many varieties. Conditions in the seed system do not eliminate village or household choices. As expected, C88 is more intensively adopted in areas with more commercial potential (due to the presence of larger farms and more people). The C88 adoption rate increases by 4.5 percentage points for each additional 10 ha of potato area and is marginally higher for larger (in terms of population) villages. Paradoxically, however, adoption intensity is also higher for more distant villages. As the distance between the village and the county town (where the county government is located, generally the most populous and developed area of the county) increases by 10 km, the C88 adoption intensity increases

by 3.7 percentage points. Better average village education is associated with higher intensity of adoption (an additional year of education is associated with about an 8-percentage point increase in adoption), but experience growing potato, another indicator of human capital is associated with lower village adoption rates.

An advantage of the FML is that additional information about the relationship between C88 adoption intensity and potato-growing characteristics of the village can be gleaned from regression coefficients for the intensity of adoption of alternative varieties. For example, the adoption intensity of Mira is higher if a village has more households, and is lower if the village has a larger potato area, suggesting that intensive adoption of C88 displaces Mira in more commercialized areas. Mira is also more intensively planted in areas where farmers have more potato-growing experience, suggesting that C88 substitutes for Mira in villages with younger farmers. Hui-2, a relatively new variety, is frequently planted when farmers abandon C88 and it substitutes for C88 under certain conditions. For example, higher average education is associated with higher adoption intensity of C88, and lower adoption intensity of Hui-2.

The results show a tradeoff between village-level production of C88 and Mira. Except for the number of households in the village, all the variables that significantly affect C-88 adoption have marginal effects of opposite signs to those for adoption of Mira. C88 is also preferred in villages with better-educated farmers, and this variable has a significant and positive marginal effect

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[11] Village adoption intensity is defined as the fraction of village potato area allocated to each variety. It is computed by dividing total area allocated to the variety of surveyed households in a village by their total potato area. Only varieties with more than 5% of the village potato land are included in the numerator and denominator.

Table 3 SUR Probit estimation results of household-level determinants of adoption of major potato varieties (marginal effects and standard errors)

	C88	Hui-2	Weiyu-3	Mira	Xuanshu-2	Qingshu-9	Lishu-7	Others
# of working age farmers	0.0643*** (0.018)	− 0.0112 (0.020)	0.0099 (0.014)	− 0.0200 (0.016)	− 0.0006 (0.017)	− 0.0218 (0.016)	− 0.0037 (0.013)	− 0.0110 (0.022)
Avg. age of working age farmers	0.0028* (0.002)	− 0.0021 (0.002)	0.0007 (0.001)	0.0006 (0.001)	0.0008 (0.001)	0.0028** (0.001)	0.0008 (0.001)	0.0017 (0.002)
Avg. yrs of education of working age farmers	0.0101** (0.005)	− 0.0231*** (0.006)	0.0099** (0.005)	− 0.0017 (0.005)	− 0.0048 (0.005)	0.0036 (0.004)	0.0065** (0.003)	0.0061 (0.006)
Dummy: 1 if a household is a member of a farmer organization	0.1323*** (0.044)	− 0.2031*** (0.038)	− 0.0783 (0.050)	− 0.0981 (0.070)		0.1665*** (0.057)	0.0354 (0.026)	0.2893*** (0.070)
Dummy: 1 if a household is visited by extension agents in the last year	0.1117*** (0.033)	− 0.1191*** (0.035)	0.0134 (0.031)	− 0.0392 (0.033)	0.0000 (0.000)	0.0560* (0.029)	− 0.0254 (0.020)	− 0.0286 (0.037)
Share of household farmland allocated to potato	0.0449 (0.051)	0.1785*** (0.063)	− 0.1239* (0.069)	− 0.1366** (0.061)	0.0802 (0.057)	0.1380*** (0.048)	0.0569 (0.036)	− 0.0247 (0.064)
Household farm size (mu)	0.0018* (0.001)	0.0000 (0.000)	− 0.0037 (0.003)	0.0005* (0.000)	0.0023 (0.002)	0.0005** (0.000)	0.0008** (0.000)	0.0007 (0.000)
Share of self-kept seed in the total quantity of potato seed	0.0379 (0.034)	0.0751** (0.034)	− 0.0796*** (0.027)	0.1378*** (0.025)	− 0.0682** (0.030)	0.0169 (0.026)	− 0.0439* (0.025)	0.0012 (0.039)
# of households in village	− 0.0001 (0.000)	− 0.0015*** (0.000)	− 0.0003 (0.000)	0.0010*** (0.000)	0.0005*** (0.000)	0.0005*** (0.000)	− 0.0012 (0.001)	− 0.0001 (0.000)
Village average farm size per HH (mu)	0.0037* (0.002)	− 0.0038 (0.003)	− 0.0329*** (0.010)	0.0188*** (0.004)	− 0.0042 (0.004)	0.0051* (0.003)	0.0153*** (0.004)	0.0002 (0.002)
Village total potato area (mu)	0.0002*** (0.000)	0.0000 (0.000)	− 0.0002 (0.000)	− 0.0010*** (0.000)	0.0000 (0.000)	− 0.0004*** (0.000)	− 0.0004*** (0.000)	0.0000 (0.000)
Dummy: 1 if village experienced serious disease problem in past 5 years	− 0.0843** (0.033)	0.0281 (0.040)	− 0.1030*** (0.036)	0.1194*** (0.040)	0.0000 (0.000)	0.0047 (0.035)	− 0.1555*** (0.025)	0.0259 (0.041)
Dummy: 1 if village experienced serious pest problem in past five years	− 0.2890*** (0.018)	− 0.1070*** (0.033)	0.2739*** (0.038)	0.0134 (0.030)	0.0000 (0.000)	− 0.0811*** (0.024)	− 0.1294*** (0.017)	− 0.0429 (0.038)
Distance from village to city town (km)	− 0.0010*** (0.000)	− 0.0014*** (0.000)	0.0002 (0.000)	0.0020*** (0.000)	0.0002 (0.000)	0.0007*** (0.000)	− 0.0017** (0.001)	0.0000 (0.000)
Distance from village to county town (km)	0.0028*** (0.001)	0.0023*** (0.000)	− 0.0026*** (0.001)	− 0.0013*** (0.000)	0.0001 (0.000)	0.0013*** (0.000)	− 0.0046** (0.002)	− 0.0005 (0.001)

1. Since the farm organization dummy perfectly predicts the adoption of Xuanshu-2, the variable is omitted for Xuanshu-2

2. AME: average marginal effects on the probability for a household to adopt a variety

3. Level of significance: "***" 1%; "**" 5%; "*" 10%

only in the regression for C88 adoption. To gain more insight into adoption dynamics, we turn to household-level determinants.

Determinants of adoption: Household-level model

At the household-level, determinants of adoption include household, farm and village characteristics (Table 3). Results are intuitive and consistent with the village-level findings and with expectations. In particular, a household is more likely to adopt C88 if it has more working-age farmers and education of working members is greater. While experience is negatively associated with village-level intensity of adoption (Table 1), age is positively associated with adoption at the household level. With an additional working-age farmer, a household is 6.4 percentage points more likely to adopt C88. The probability of adopting C88 increases by about 1% as the average age of working-age farmers increases by four years and

average years of education increases by one year. Comparing these findings to the village-level results, we see that better-educated farmers have higher adoption intensities and higher adoption, but older farmers are more likely to adopt, but less likely to adopt intensively.

Farmers with more access to technical assistance are also more likely to adopt C88. A household with a member in a farmer organization or who has been visited by extension agents in the previous year is 13.2 and 11.2 percentage points more likely, respectively, to adopt C88. So, access to extension and information services has a positive effect on C88 adoption.

Village characteristics also affect household decisions. For example, if the village had not experienced serious diseases or pest problems with potato in the past five years, the household is 8.4 and 28.9 percentage points more likely to adopt C88. These results might appear to be counter-intuitive, but may reflect two factors. First,

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since C88 has more resistance to late blight than other varieties, higher adoption may be associated with lower disease prevalence, particularly when the village-wide adoption intensity is high. In this case, the causality is reversed and higher areas of C88 reflect lower disease prevalence. Second, because C88 is targeted toward areas where commercial production is higher, seed vendors (mainly extension agents) may avoid areas with more pest and disease problems.

C88 has also been more widely disseminated in villages where farm sizes and potato areas are greater, providing evidence that the variety may have bypassed some of the poorer areas of Yunnan. Households in villages that are nearest to the metropolitan areas (city towns) are more likely to adopt C88, providing further evidence that the variety's spread was more concentrated in favored areas where access to processors is highest.[12] Consistent with the village-level estimates, distance to county towns (in contrast to city towns, which tend to be larger) is positively associated with C88 adoption, and the combined (city, county town) results show that C88 diffusion efforts were focused on commercial areas nearest the larger cities. These efforts bypassed smaller villages, likely because of market access in the larger cities.

In general, results from village and household models are consistent. With better education, larger village potato area, and longer distance between villages and county towns, both village adoption rate and the likelihood that a household adopt C88 rise. Glauben et al. (2012) show larger holding sizes to be associated with higher persistent poverty in China, but villages with a higher population density and those located closer to cities have a lower probability of being long-term poor. Reliance on cropping as a single household business increases poverty persistence—agricultural activities yield only modest returns. In Yunnan, commercial production of C88 substituted for proximity to urban suggesting an alternate escape route from poverty.

Determinants of ever planting and disadoption of C88

The first two columns in Table 4 show the determinants of whether a farm household ever planted C88 and last two show the determinants of disadoption, conditional on having grown C88. We include additional covariates in this regression because factors such as commercial orientation and the importance of prices received are likely to be related with experimentation with new varieties. The study of ever adopting and disadoption decisions explores the determinants of this experimentation.

The determinants of ever adopting C88 are similar in sign and significance to the determinants of current planting of the variety (shown in Table 3). Larger farm sizes with less fragmented land holdings (reflected by the number of potato plots, conditional on total area planted) are more likely to have ever planted C88. Larger farms are also significantly less likely to disadopt, with a one hectare increase in landholding associated with an eight-percentage point lower probability of abandoning the variety, conditional on its adoption.

Commercial orientation, captured by the dummy variable reflecting the importance of price, is a strong determinant of adoption. Households who said price is important (very important) are 14 (17) percentage points more likely to have planted C88 compared to households that say price is unimportant. The importance of price is, however, not significantly associated with disadoption.

Further evidence of the commercial importance of C88 is reflected in the significant marginal effect of the importance of market demand. For adopters who state that market demand is very important, the likelihood of disadopting is 18-percentage points lower than farmers who say market demand is unimportant.

As in the case for current adoption, the presence of diseases and pests in the village are negatively associated with ever adopting C88, but, conditional on adopting, experiencing a disease problem in the village is negatively associated with disadoption. The negative sign on the marginal effect for disadoption is consistent with expectations, but the estimate is not significant. In contrast to disease problems, the presence of pest problems is positively and strongly associated with disadoption. Conditional on adoption, the presence of pest problems leads to more disadoption, which is to be expected because purchasers of C88 have high expectations for tuber quality and are unlikely to purchase commercial potatoes in areas with large disease infestations.

While location of a farm with respect to cities and market towns has similar effects on ever adopted and currently growing C88 (compare Tables 3 and 4), once a farmer adopts, location has only very small effects on disadoption. Proximity to a city is not significantly associated with disadoption, while being farther from a county town is negatively associated with disadoption. Villages that are distant from county towns have limited access to new potato seeds as discussed above, so variety turnover in such areas tends to be lower.

Economic surplus and impacts of diffusion on market-level outcomes

Several parameters are needed to estimate surplus changes using the model described above: adoption rates by year, equilibrium quantity and price of potatoes in the

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[12] In China, a prefecture (city) includes several counties, and each county has its county town.

Table 4 Household-level Heckman probit estimates of ever-adopting and disadoption C88

	Ever grown C88		Disadopted C88	
	Coef	AME	Coef	AME
# of working age farmers	0.0656 (0.097)	0.0094 (0.014)	− 0.3530*** (0.129)	− 0.0559** (0.026)
Avg. age of working age farmers	0.0195*** (0.006)	0.0028*** (0.001)	− 0.0121 (0.008)	− 0.0029* (0.002)
Avg. yrs of education of working age farmers	0.0872** (0.034)	0.0125** (0.005)	0.0002 (0.030)	− 0.0048 (0.005)
Dummy: 1 if a household is a member of farmer organizations	0.2765 (0.437)	0.0407 (0.066)	− 0.5513 (0.434)	− 0.1112 (0.094)
Dummy: 1 if a household is visited by extension agents in prior year	0.5122** (0.230)	0.0794** (0.038)	− 0.2241 (0.275)	− 0.0688 (0.045)
Share of household farmland allocated to potato	0.5358 (0.407)	0.0770 (0.056)	− 0.0613 (0.489)	− 0.0387 (0.066)
Farm size (mu)	0.0921*** (0.023)	0.0132*** (0.003)	− 0.0022 (0.002)	− 0.0054*** (0.002)
# of potato plots	− 0.2645*** (0.070)	− 0.0380*** (0.012)		
Share of self-kept seed in total potato seed	0.0068 (0.236)	0.0010 (0.034)	− 0.5058** (0.225)	− 0.0753* (0.041)
Dummy: 1 if a household receives information from cooperatives/extension agents	0.4440** (0.191)	0.0682** (0.032)	0.2964* (0.170)	0.0187 (0.020)
Importance of potato price in choosing potato varieties				
1 if important	0.9246*** (0.170)	0.1438*** (0.034)	0.4732 (0.291)	0.0102 (0.046)
1 if very important	1.0843*** (0.305)	0.1703*** (0.057)	0.5028 (0.341)	0.0057 (0.056)
Importance of market demand in choosing potato varieties				
1 if important	− 0.0951 (0.212)	− 0.0132 (0.029)	− 0.3370 (0.356)	− 0.0483 (0.055)
1 if very important	− 0.2902 (0.317)	− 0.0400 (0.042)	− 1.1534*** (0.403)	− 0.1804** (0.085)
HH wealth quintile dummies				
1 if quintile 2	− 0.1452 (0.232)	− 0.0210 (0.033)		
1 if quintile 3	− 0.4745* (0.287)	− 0.0682 (0.042)		
1 if quintile 4	0.3448 (0.243)	0.0506 (0.037)		
1 if quintile 5	− 0.4964* (0.263)	− 0.0713* (0.040)		
# of households in village	0.0012 (0.001)	0.0002 (0.000)	− 0.0017 (0.003)	− 0.0003 (0.000)
Village average farm size per HH (mu)	0.0751 (0.054)	0.0108 (0.008)	− 0.0315 (0.024)	− 0.0088* (0.005)
Village total potato area (mu)	− 0.0001 (0.000)	0.0000 (0.000)	− 0.0004 (0.000)	0.0000 (0.000)
Dummy: 1 if a village experienced serious disease problem during the past five years	− 1.1259*** (0.417)	− 0.1730** (0.071)	− 1.0595* (0.546)	− 0.0866 (0.069)
Dummy: 1 if a village experienced serious pest problem during past five years	− 1.1126** (0.499)	− 0.1732** (0.073)	3.0170*** (1.073)	0.3310*** (0.043)
Distance to city town (km)	− 0.0105*** (0.003)	− 0.0015*** (0.000)	− 0.0093 (0.006)	− 0.0008 (0.001)
Distance to county town (km)	0.0155*** (0.006)	0.0022*** (0.001)	− 0.0160 (0.010)	− 0.0032* (0.002)
Village elevation (m)	0.0006 (0.000)	0.0001 (0.000)		

Table 4 (continued)

1. AME for "ever grown": average marginal effect on the probability that a household had ever grown C88

2. AME for "stopped": average marginal effect on the probability of disadopting given a household had ever grown C88

3. Level of significance: "***" 1%; "**" 5%; "*" 10%

market, size of the shift in supply caused by C88 adoption (the K-shift in Eq. 1), supply and demand elasticities and exogenous changes in income and population which would lead to shifts in demand over time. These exogenous shifts in demand must be accounted for to isolate the market-level effects of C88 diffusion.

The C88 adoption rate in Yunnan from 1996 to 2015 is based on the land area adoption rates and area estimates for specific years. Adoption started with informal release of the variety in 1996 and was assumed to grow linearly from that time forward until a peak was achieved in 2007. In 2007, about 30% of total area under potato in Yunnan was planted to C88. Lacking further data on annual area adoption, we assume the variety declined in the province linearly since 2007 to 2015, for which the expert panel has specific estimates (SIAC 2.1 2018). With evidence of disadoption from the household-level data and the SIAC 2.1 database, a linear interpolation of the adoption profile begins with zero percent in 1995, peaks at 30% in 2007, and falls to 22% in 2014 (Fig. 3).

Prices

The price of potatoes was obtained by the community survey. Community prices, base year 2015, were weighted by quantity produced by variety by village and quantity weighted at the provincial level. The per-ton prices are divided by the Purchasing Power Parity (PPP) exchange rate of 3.56 Yuan to the US Dollar (OECD 2016). The weighted average price for all potato varieties in Yunnan in 2015 was $375 per ton.

In a small open economy, prices have to be adjusted to reflect the variation in the exogenously determined price from year to year while maintaining 2015 values. To do so, the nominal price for potatoes in Yuan per ton and GDP deflator for China from 1995 to 2015 were obtained from FAOSTAT and the World Bank, respectively. FAOSTAT only had prices for potatoes in China for 1996 to 2013. The proportionate changes for 2013 to 2015 were assumed to be the same as those from 2012 to 2013.

In an open economy model, demand is infinitely elastic. An elasticity of supply of one is assumed. Estimates of the potato supply elasticity for China are not available in the literature, and Alston et al. (1995) suggest using an elasticity of one when in doubt for annual crops.

Quantity produced, land area and K-shift

The land area under potato in Yunnan in 2014 is estimated to be 587,000 ha (Gatto et al. 2016). To infer land area under potato from 1996 to 2013 and in 2015, the percentage change in potato area from 1996 to 2015 in Yunnan is assumed to be the same as the percentage change for all China. The latter was computed using data on area under potato production in China between 1996 and 2015 obtained from FAOSTAT. Using the area estimates from Gatto et al. 2016, an annual growth rate of 2% was applied to project the area under potato in Yunnan backwards from 1996 to 2013 and forwards to 2015.

Household and community interview respondents indicated that variety-specific difference in inputs applied were minimal. We used expected differences in yield to compute the K-shift. Yields were calculated at the plot-level using household data. The estimated potato yield of non-C88 variety was computed as a weighted average based on land area for each variety. The weighted average yield for all potato varieties in Yunnan, C88, and all varieties excluding C88 were 21, 24, and 19 tons per hectare, respectively. Thus, C88 yields are substantially higher than other potato varieties.
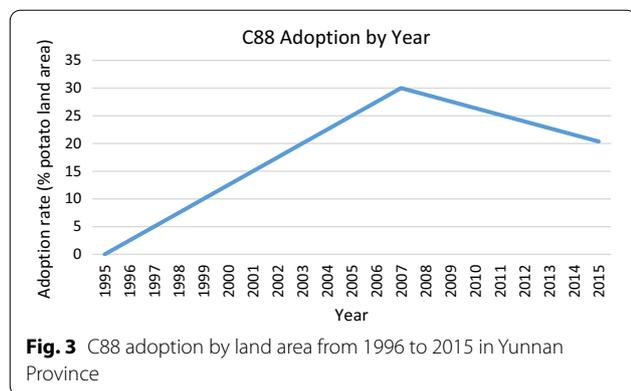
Economic surplus results

C88 adoption has led to significant economic benefits to producers in Yunnan County. Assuming a small open economy model, total benefits, base year 2015, from 1996 to 2015 equal $2.35 billion with a present value of $2.84 billion.[13] In an open-economy model, all benefits are assumed to accrue to Yunnan C88 potato producers. These results were compared to those assuming a closed economy and an elasticity of demand of -0.65 (Ahmadi-Esfahani and Stanmore 1997). Under a closed economy (full details on model inputs and assumptions are available in Myrick 2016), where prices fall, benefiting consumers, the total surplus over the same period was estimated at $3.08 billion with a present value of $3.73 billion. Under model assumptions about demand, consumers captured 61% of the benefits, while 39% of the benefits went to producers.

Discussion

The analysis shows clearly that potato producers in Yunnan place a high value on the attributes of the variety C88. Commercially oriented farmers and those in predominantly commercial areas are more likely to produce the variety. Declining area planted to the C88 variety

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[13] Using a 3 percent discount rate and expressed in 2015 dollars.

Fig. 3 C88 adoption by land area from 1996 to 2015 in Yunnan Province

appears to be mainly attributable to the lack of clean seed; breeders are incentivized to release newer varieties and the close linkage between researchers and seed multiplication and distribution has contributed to the replacement of C88 with newer varieties. Commercial demand for the attributes of C88, however, remains quite strong and Yunnan farmers indicate a continuing desire to plant the variety if clean seeds are made available.

While we do not have sufficient information on how the producer surplus change associated with C88 diffusion was distributed among farmers, we can provide some illustrative comparisons. First, using the information presented above, we know that approximately 130,000 ha were planted to C88 in Yunnan in 2015. The open-economy estimate, assuming that 130,000 hectares were cultivated from 1996 to 2015 (a very conservative assumption), of annual benefits per hectare are about $1100 (in 2015 dollars).

Given average production areas of C88 growers from the household survey (0.7 hectares), the open-economy model predicts an annual gain of $770 per household or about $0.50 per person per day on average. This income gain is substantial and, depending on the average depth of poverty among poor farm households, would have a large effect on poverty reduction. The direct benefits of technology adoption are substantial, and the magnitude of benefits is due to large size of the market and the production cost savings associated with C88 cultivation.

This poverty reduction effect is a conservative estimate as our survey, upon which the estimates of yield gains from C88 production were built, did not include winter-season production. During winter, the yield gains from late blight-resistance are far greater than the yield gains during the late-summer season. As the surplus model is based on averages, the yield benefit due to C88 production under-estimates the winter yield effect.

Conclusion

The research partnership that brought C88 to Yunnan led to substantial increases in incomes among potato producers in the province and is likely to have contributed to poverty reduction among potato-growing farm-households. The large areas planted to C88 in Yunnan are testament to the economic advantages of its production. In a short time period, the variety replaced substantial areas of other varieties. While the economic surplus model relies on assumptions (open/closed market) that determine in part the distribution of benefits among producers and consumers, the qualitative interviews identified significant impacts that were achieved beyond farmer fields. In fact, the variety helped support a growing transformation of the food processing industry in Eastern China (value-chain interviews). This transformation is durable and has economy-wide implications, but the dynamics of potato production in Yunnan clearly contributed to a structural transformation in the rural areas.

Generalization of these findings suggests that strong government policies, including intervention in markets, and inter-institutional collaborations, can be effective in the short to medium run to scale up technologies and drive development. In the longer run, absence of appropriate market forces can delay adaptation of institutions to changing policy environments where their role is no longer central. This in turns delays the creation of new technologies to sustain the contribution of R&D to growth in the long run. In the C88 case, incentives for release and diffusion of new varieties led to relative neglect of production of clean seeds for continued planting of the variety and disadoption followed.

Potato farmers in Yunnan Province have limited access to seed beyond those disseminated by local government and extension, and lack of replacement seeds prevents households from replacing old seed and experimenting with new varieties. A household's decision to plant a variety is constrained (but not eliminated) by government decisions. Thus, more distant farmers and villages are hesitant to disadopt, while those closer to markets have replaced C88 with newly released varieties like Hui-2. Farmers expressed continued interest in planting C88, but noted that clean seeds had not recently been made available. Processing industry representatives voiced demand for increased production of C88 as the variety has advantages as a processed potato over other varieties. These findings highlight a limitation of the institutional structure deemed so important for the growth in C88 area. Without a robust seed market, potato producers depend on officials, who may not heed market signals, to supply the appropriate seeds.

Perfect storms do not last forever and neither did the institutional environment identified in this study. Lack of

clean seed in the last 7–8 years has driven disadoption of C88, despite the interest—and concerns—of the industry, which has to resort to more expensive supply sources for a key input. Demand from research systems to create novel technologies can misalign incentives so that scientists devote too much time and resources to identifying new varieties and show "new" success. Champions of the specific variety (C88) focused much of their efforts on preserving the predominance of that variety, rather than solving generic problems such as failure of seed potato markets. Overreliance on government presence implies that when support begins to decline, institutions are not ready to identify or respond to market signals and lack the basic knowledge and cultural experience to operate independently (immature value chains). Lack of transparent open trade policies impede receipt of clear signals from markets abroad. Changes in government policies also change incentives due to diversion of efforts and resources to new development programs.

Authors' contributions
All contributions have been made by the authors. All authors read and approved the final manuscript.

Availability of data and materials
All materials are available on dataverse (https://cipotato.org/open-access/datasets-status/).

Ethics approval and consent to participate
The fieldwork in this research was approved by the Institutional Review Board of Virginia Tech under protocol IRB-15–635. Interviewees were asked for verbal consent to participate.

Consent for publication
All authors contributed to in drafting the paper and their consent for publication is implied.

Competing interests
None.

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