New Rice Biotechnology in China: Approval, Adoption, and Stakeholders' Views Yan Jin 2021

New Rice Biotechnology In China

Approval, Adoption, and Stakeholders' Views

Yan Jin

Propositions

1. Postponing the adoption of a superior technology is costly.

   (this thesis)

2. Decision making can be optimal only with assumptions.

   (this thesis)

3. Trade-offs between expected economic returns and exposure to risk are inevitable.

4. Chinese data should be made more accessible to junior researchers.

5. Knowing your limits and knowing your potential are equally important.

6. You do not need to be perfect to start your first trial.

Propositions belonging to the thesis, entitled

New Rice Biotechnology in China: Approval, Adoption, and Stakeholders' Views

Yan Jin

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New Rice Biotechnology in China: Approval, Adoption, and Stakeholders' Views

Yan Jin

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Yan Jin

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CONTENTS

Chapter 1

General Introduction

1. GENERAL INTRODUCTION

1.1 Background and Problem Statement

With only 6% of the world's fresh water and 7% of its arable land, China has to nurture nearly a fifth of the world's population (Wong & Chan, 2016). People working in agriculture accounted for 26% of the total working population in China in 2018 (National Bureau of Statistics of China [NBSC], 2019), a twenty percent decrease over the 2000s. Meanwhile, the population in China has been growing, reaching 1.39 billion in 2019 (NBSC, 2019). This large, growing population needs enough food, but while the importance of food security is well-known, achieving it is still a challenge (Li et al., 2014) despite advances in the development of food-related technologies, such as improved plant varieties that are resistant to pests, diseases, and drought stress. Apart from a potential technology-skill mismatch (Acemoglu & Dell, 2010; Acemoglu & Zilibotti, 2001), a chief reason for food security remaining an issue in China has been smallholder farmers lacking resources to access new biotechnologies and crop-management techniques to improve crop productivity and hence increase income (Paarlberg, 2009). Plant breeding using modern biotechnology, particularly classic genetic engineering, can accelerate crop improvement, which either increases yield or decreases yield loss (Huang et al., 2005) because it is faster and more accurate than conventional breeding to transfer desirable traits into crops, especially in cases where conventional breeding may be difficult.

The total farmland planted with genetically modified (GM) crops reached 191.7 million hectares globally in 2018. By then, 70 countries had adopted GM crops, 26 of which planted them and 44 of which imported them as feed or processing materials (International Service for the Acquisition of Agri-biotech Applications [ISAAA], 2018). The five leading countries in terms of GM crop cultivation are Argentina, India, the United States, Brazil, and Canada, accounting for 91% of GM crop acreage worldwide (ISAAA, 2018).

In China, more than 50 varieties of GM crops have been approved for import as feed and processing material since 2002 (Jin et al., 2019); however, domestic cultivation has not been approved except for GM cotton and papayas (Wong & Chan, 2016; Zhao et al., 2019). In 2016, the China's Ministry of Agriculture and Rural Affairs (MARA) revealed a roadmap for commercializing and cultivating domestic GM crops, starting with cash crops "not for food use" (e.g., cotton), followed by crops used as input for feed and industrial use (e.g., maize), and finally staple food crops (e.g., rice).

Insect-resistant GM rice is the pioneer staple food crop developed with modern biotechnology in China. It can reduce lepidopteran pest damage and the necessity of using insecticides (Huang et al., 2005) and thus increase yield and reduce input costs (Wang et al., 2010). The trait of insect resistance also applies to many other GM crops, such as maize and cotton (Abbas, 2018). GM crops have many other traits, such as the herbicide tolerance of GM canola, maize, and soybeans (Nandula, 2019); the drought and heat tolerance of GM maize (Tesfaye et al., 2018); the virus resistance of GM papayas (Gonsalves et al., 2004); and the longer shelf life of GM apples. With these direct effects, GM crops are expected to reduce the use of pesticides, increase production, lower food prices, improve food and feed safety, and reduce food waste (Federici, 2010; Uzogara, 2000).

Despite their potential to contribute to food security and sustainability, the adoption of GM crops is still affected by public opinion worldwide. In the European Union, the approval of the cultivation of GM maize is still pending (except for Spain and Portugal), not because GM products are unsafe, but because of socio-economic reasons (Hundleby & Harwood, 2019). The major public concerns include the potential long-term uncertainties about human health (Herring, 2008; Herring & Paarlberg, 2016) and the environment (Perry et al., 2016; Qaim, 2009).

Although scientists have spent 20 years investigating the thermal stability, digestibility, toxicity, and nutrient composition of GM rice and the allergenicity of the Cry proteins it produces (Li et al., 2014, 2015), Chinese consumers have continued to oppose its commercialization over the past ten years (Cui & Shoemaker, 2018). Coalitions of supporters and opponents of genetically modified organisms (GMOs) have tried to influence the public through online debate in Europe (Tosun & Schaub, 2017). A similar phenomenon also appears in China, which applies pressure on decision-makers. Deng et al. (2020) has studied agricultural biotech companies' inside-lobbying of the government, but an analysis of the Chinese public online debate regarding GMOs is missing in the literature.

The regulatory processes and policies of GM crops vary among countries and regions, such as in the United States (Food and Agriculture Organization of the United Nations [FDA], 2020), the European Union (Zetterberg & Björnberg, 2017), Japan (Ebata et al., 2013), and Africa (Paarlberg, 2010). The approaches of the European Union and the United States are the two most commonly discussed. The European approach leans more toward a process approach, while the United States adopts a product-based one (Eriksson et al., 2018). The European Union also requires labeling for feed and food products (Castellari et al., 2018), and the United States applies a mandatory labeling with a five percent threshold level for what is called " bioengineered products" and refers "*to a food (A) that contains genetic material that has been modified through in vitro recombinant deoxyribonucleic acid (DNA) techniques; and (B) for which the modification could not otherwise be obtained through conventional breeding or found in nature*" (United States Department of Agriculture [USDA], 2018b). The United States does not mandate the labeling of highly refined ingredients from GM crops if no modified genetic material is detectable; however, it allows manufacturers to make voluntary disclosures on such products in the interests of transparency (USDA, 2018b).

China follows an approach similar to the European one. After the assessment of food safety, gene flow, nontarget organism effects, and other potential risk factors, a three-phase process then starts to acquire a biosafety certificate: field trials (equivalent to small contained trials in the United States), environmental release trials (known as "farmer field trials" in the United States), and preproduction trials (Huang et al., 2008). Another three documents are needed to domestically cultivate GM crops in China: a seed variety certificate showing successful new crop variety registration, a production license for a new crop variety, and a marketing license for the commercialization of a new crop variety. In general, the regulatory process in China is complex and time-consuming, and a biosafety certificate does not necessarily guarantee domestic cultivation due to socio-economic reasons, such as strong resistance from the public.

The biosafety regulatory process, however, has economic consequences because biosafety regulations are not costless endeavors. A rich literature assesses the foregone benefits of the delayed approval of GM crops worldwide, such as GM eggplants in India (Krishna & Qaim, 2008), GM bananas, cowpeas, and maize in Africa (Wesseler et al., 2017), GM rice, eggplants, papayas, and tomatoes in the Philippines (Bayer et al., 2010), and GM maize in China (Xie et al., 2017). As a major producer, consumer, and trader of rice, China also suffers from the foregone benefits of delayed approval, but a quantification of the postponement cost of GM rice in China is still lacking. The requirements of biosafety tests can also consume significant amounts of time, as shown in the European Union and the United States (Smart et al., 2015, 2017). How long it takes for China and whether trends are changing is unknown to the public. Although the regulatory process can create additional information about new biotechnology and improve selection and regulation, decision-makers should also consider the foregone benefits of delaying approval, especially for a large country like China.

While regulatory processes lag, biotechnology advances rapidly. Recent developments in new plant-breeding technologies, such as genome editing, enable the development of new crop varieties that are indistinguishable from those developed through traditional plant-breeding methods but more quickly and precisely (Gao, 2018; Hundleby & Harwood, 2019). In 2018, the USDA stated that some new varieties developed through genome editing do not need more regulation than conventional varieties (USDA, 2018a). Many countries such as Argentina and Brazil made the same decision and exempted varieties from regulation when there is no insertion of transgenes (Custers, 2017). In 2018, the Court of Justice of the European Union (ECJ) decided that gene-edited crops should be subject to the same stringent regulations as GMOs and would need to undergo the lengthy approval process (ECJ, 2018; Wesseler & Purnhagen, 2020; Eriksson et al., 2018). So far, it is unclear how China will regulate genome editing. Despite the considerable potential of helping farmers address the challenges of global food security and sustainability (Huang et al., 2017), the uptake of genome editing by plant breeders has been slow due to the uncertainty associated with regulation (Hundleby & Harwood, 2019). If China follows the European approach, the decision may hinder investment in crop research by limiting commercial applications like GMOs (Callaway, 2018). Ex ante economic analyses for crops derived by genome editing, such as clustered regularly interspaced short palindromic repeats (CRISPR) rice, are lacking in the literature, possibly because of the novelty of the biotechnology. However, these analyses are crucial for stakeholders before making final regulatory decisions. Another issue that must be considered is the impact of asynchronous approvals of different leading world players in the rice market.

1.2 The Relevance of New Rice Biotechnology to China

Rice is one of the most widely consumed grains in the world, and China consumes more rice than any other country (143.8 million metric tons in 2018 [USDA, 2019]). The total annual acreage of rice has hovered around 30 million hectares since 2015, which in 2018 corresponded to 18% of the world's total rice acreage (Food and Agriculture Organization of the United Nations [FAO], 2020). Although rice production in China has tripled in the past three decades due to increased grain yield and improved crop-management practice, there has also been yield stagnation in the past ten years (Peng et al., 2009). The share of people working in agriculture dropped from 68% to 26% in the past three decades due to urbanization and industrialization (NBSC, 2019). Together with an increasing population, which will further reduce the arable land per capita, and an increase in the demand for rice, China will need to produce around 20% more rice by 2030 to meet its domestic consumption (Peng et al., 2009).

However, rice yields in China are severely reduced by pest damage. Rice in China suffers from many insect pests, such as rice planthoppers, stem borers, and leaf folders (Lou et al., 2013), which cause losses of billions of dollars and the extensive use of environmentally damaging insecticides for their control (Fahad et al., 2015; Lu et al., 2018). Chinese farmers are claimed to overuse insecticides by more than 40% (Huang et al., 2003; Peng et al., 2009). Insecticides harm humans and the environment (Aktar et al., 2009). Bacillus thuringiensis (Bt) rice—an insect-resistant, GM rice variety developed in 1989 by scientists from the Chinese Academy of Agricultural Sciences—aims to address these constraints.

Bt rice is transgenic rice in which genes from the soil bacterium *Bacillus thuringiensis* have been transferred into the rice genome to reduce lepidopteran pest damage and the necessity of using insecticides (Huang et al., 2005). Bt rice requires less pesticide than conventional rice, reduces labor input (Rozelle et al., 2016), and improves farmers' health (Huang et al., 2015). The yield of Bt rice can be up to 60% higher than conventional rice when no pesticides are used (Wang et al., 2010). On October 22, 2009, the MARA issued biosafety certificates for two GM rice hybrids (Cry1Ab/Ac Huahui No. 1 and Cry1Ab/Ac Bt Shanyou 63) (Chen et al., 2011). The issuance of these certificates indicates that the two hybrids are considered as safe as conventional rice, both for humans and the environment, and thus ready for commercialization.

China is pursuing an active bioeconomy strategy. In 2010, research funding for GMOs amounted to 20 billion Chinese Renminbi (RMB) (2.5 billion US dollars), having increased at a rate of 22.2% per year since 2005 (Cai et al., 2016). In 2008, the Chinese government announced a GMO project to support research and development for new GM crop varieties through 2020, with a total budget of RMB 240 billion (35 billion US dollars) (Cai et al., 2016). Published in 2016, the *13th Five-Year Plan for Science and Technology Innovation* officially promoted the development of domestic GM crops and their step-by-step release into the environment (State Council, 2016). So far, however, no GM crops have been approved for cultivation in China except for GM cotton and papayas (Wong & Chan, 2016; Zhao et al., 2019). With the rapid development of genome editing in the past decade, its precision, ease of use, and low cost make it another alternative to traditional plant breeding (Bartkowski et al., 2018). However, how China will regulate genome editing has been debated since 2016 (Gao et al., 2018), which might dramatically influence its path of research and development and its market application.

Recent advances in CRISPR technology for rice (Lu et al., 2018) based on genome editing present an alternative to insect-resistant GM rice, which is similar to rice developed by traditional breeding techniques, because no foreign genes are inserted. In fact, a mutation producing a gene structure similar to that of CRISPR rice can also occur in nature. Therefore, segregation and labeling might not be required depending on the regulations. However, at this stage, there is a trade-off between lower yield and pest resistance (Lu et al., 2018). Scientists are improving the yield performance of insect-resistant CRISPR rice to better match the yield expectation of the market. Other CRISPR rice with enhanced blast resistance and herbicide tolerance are available in the lab (Sun et al., 2016; Wang et al., 2016) and will be in field trials in coming years.

This thesis presents Bt rice as a case study to explore the cost-benefit trade-offs of its introduction and welfare changes for different stakeholders. Understanding how public debate influences policy decisions in China is crucial to explain the lengthy regulatory process and trends of approving GM crops, which foregoes the benefits of approval. Realizing the great potential of CRISPR rice to substitute for Bt rice in the future, I explore the most influential factors for CRISPR rice adoption and potential ex ante benefits. Understanding these issues may improve government policy around genome editing, which in turn could increase consumer trust and confidence in products developed by genome editing.

1.3 Objectives, Research Questions, and Methods

Based on Sections 1.1 and 1.2, ongoing discussions and policymaking on GM crops in China need more science-based input, particularly with respect to food crops, such as rice. The general objective of this study is thus to examine the approval process and stakeholders' views on GM crops and the economic impacts of adopting new rice biotechnology in China. This study has four chapters that respectively address four research questions to achieve its general objective.

Research question 1: What are the main characteristics and trends of the public debate on GMOs in China?

Research question 1 examines the public debate on the cultivation and use of GM crops and the main characteristics of the public debate on GMOs in China. I examined stakeholder participation in the online public debate on GMOs in China and how the debate influences the reactions of stakeholders over time. I used discourse network analysis to trace the online debate of GM crops in China, visualize competing coalitions, scrutinize their composition and structure, and analyze the time dynamics. I also performed social network cluster analysis to identify communities within each coalition and analyze the public debate over time to determine whether various stakeholders had changed their positions. This study therefore sheds light on how public debate influences policy decisions in a developing country.

Research question 2: What is the approval process of commercializing GM crops in China, and what are the factors affecting the approval length for imported GM crops in China?

Research question 2 aims to understand the regulatory system of GMOs in China better by investigating the approval process of commercializing domestic and imported GM crops and analyzing the approval time for imported GM crops in China between 2002 and 2017. I used regression analysis to examine the factors affecting the approval process and approval trends. To achieve a globally comparative view of the GM crop–approval statute in China, I further investigated and compared the differences in approval dates for the same GM varieties in China, the United States, Canada, and the European Union, and I finally investigated and compared the differences in approval lengths for the same GM varieties in China and the European Union.

Research question 3: What are the foregone benefits of lower pesticide use associated with Bt rice and its technology spill-overs on the price of international rice?

Research question 3 assesses the opportunity cost of postponing Bt rice commercialization in China between 2009 and 2019 considering the external costs of pesticide use. I used the economic surplus model to calculate the welfare change between the counterfactual state of affairs had China commercialized Bt rice and the actual state of affairs due to postponing its commercialization. The pesticide environmental accounting tool estimating the annual total external costs due to pesticide usage was included in the economic surplus model for a better estimate of the welfare change considering environmental costs. Finally, I analyzed the effect of potential technology spill-overs, the maximum adoption rate, and the rate of diffusion on the cost of postponing Bt rice commercialization in China.

Research question 4: What is the annual benefit of CRISPR rice adoption under the uncertainty of pest severity, and which factors are the most influential on the optimal planting share of CRISPR rice?

Research question 4 explores the market potential of CRISPR rice based on genome editing to enter the Chinese market. The potential commercialization of CRISPR rice faces a dilemma regardless of the regulatory environment: the trade-off between lower yield and pest resistance under the uncertainty of pest severity. Based on the current technical performance of CRISPR rice, I investigated the ex ante value of adoption in China as well as the optimal planting share and its most influential factors. To do so, I theoretically derived and calculated the optimal planting share of CRISPR rice with the uncertainty of pest severity for a representative farmer in China. Considering the uncertainty of key parameters influencing the baseline results in the microeconomic model, I determined the most influential factors of the optimal share based on Monte Carlo simulations and then decomposed the total and unit profit of the farmer in different scenarios. Finally, I calculated the annual benefit of adopting CRISPR rice.

This thesis consists of six chapters, including the general introductory chapter. The main part of the study (Chapters 2–5) addresses the research questions. Chapter 6 synthesizes the main findings of the study and discusses policy implications that transcend the discussions in each chapter and explores limitations and recommendations for future research.

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Chapter 2

Does China Have a Public Debate on Genetically Modified Organisms? A Discourse Network Analysis of Public Debate on Weibo

2. DOES CHINA HAVE A PUBLIC DEBATE ON GENETICALLY MODIFIED ORGANISMS? A DISCOURSE NETWORK ANALYSIS OF PUBLIC DEBATE ON WEIBO[1]

ABSTRACT: In the European Union and the United States, food policies are shaped by a well-documented public debate on modern biotechnology. Less is known about whether this is the case in China. We examine stakeholder participation in the online public debate on genetically modified organisms (GMOs) in China and how the debate influences the reactions of different stakeholders over time. We analyze posts on Weibo, a Chinese microblog website, using discourse network analysis to identify coalitions and communities within each coalition. Our findings reveal strong opposition to genetically modified (GM) crops, along with the existence of two competing coalitions of supporters and opponents. We further observe an increasing number of supporting posts by anonymous individuals in recent years, with the positions of stakeholders changing over time. We present several policy implications for countries with strong public resistance in general, and for China in particular.

KEYWORDS: Policy debate, discourse network analysis, genetically modified organisms (GMOs), Weibo, China

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2.1 Introduction

China is pursuing an active bioeconomy strategy. In 2010, research funding for genetically modified organisms (GMOs) amounted to 20 billion Chinese Renminbi (RMB) (2.5 billion US dollars), having increased at a rate of 22.2% per year since 2005 (Cai et al., 2016). In 2008, the Chinese government announced a GMO project to support research and development for new genetically modified (GM) crop varieties through 2020, with a total budget of RMB 240 billion (35 billion US dollars) (Cai et al., 2016). Published in 2016, the *13th Five-Year Plan for Science and Technology Innovation* officially promotes the development of domestic GM crops and their release into the environment (State Council, 2016). The program starts with cash crops designated as “not for food use” (e.g., cotton), to be followed by crops intended for use as input for feed and industrial use (e.g., maize) and, finally, by staple food crops (e.g., rice) (State Council, 2016).

Despite strong support, the cultivation of GM crops is actually prohibited in China, with the exception of GM cotton and papayas (Wong & Chan, 2016; Zhao et al., 2019). At first glance, the government’s response to GM crops thus seems contradictory. Meanwhile, a lack of public confidence in GM crops due to historical events (see Section 2.2.2) has sparked a heated online debate as GM crops approach commercialization. This debate exhibits similarities to those observed in the European Union and the United States (Bovay & Alston, 2018; Castellari et al., 2018; Tosun & Schaub, 2017). At first glance, it might not seem likely that the Chinese government would consider public opinion when making policy decisions, as governmental actors in China do not depend on competitive public elections to remain in office (Acemoglu & Robinson, 2012; Easterly, 2013). In this regard, the government’s current policy of prohibiting the cultivation of GM crops might appear surprising, possibly implying that the government does indeed take public opinion into account, at least to some extent. Furthermore, previous research has demonstrated that the use of mass media can influence public opinion and steer the public debate (Rim et al., 2020), which subsequently affects the level of GM food policy in a country (Shao et al., 2020, Herring

& Paarlberg, 2020).

In this paper, we examine the existence of a public debate on the cultivation and use of GM crops and what the main characteristics of the public debate on GMOs are in China. To this end, we investigate underlying lines of conflict related to the authorization of GM crops in China. Although negative public response has been reported (see Section 2.2.2), we are particularly interested in identifying two or more distinct coalitions of actors holding opposing views on GM in the policy debate, as well as the composition of such coalitions and possible changes in their membership in the past seven years.

In the European Union, two actor coalitions composed of different organizations (e.g., biotechnology companies and environmental nongovernmental organizations) either supporting or opposing GMOs have been observed (Tosun & Schaub, 2017). It has been argued that these coalitions play a role in public debates in many other countries as well (Herring & Paarlberg, 2016). We analyze the public debate based on a network analysis of posts placed on Weibo, the most popular social media platform in China. More specifically, we analyze the dynamics of the Weibo debate on GM crops over time (between March 2013 and April 2020). To the best of our knowledge, this is the first study to focuses on the online debate concerning GMOs in China. Based on Weibo posts, our results reveal strong opposition to the cultivation of GM crops in China. The Weibo debate was characterized by two competing advocacy coalitions, as well as by regional differences and changes in coalition membership over time. In general, the debate was dominated by opponents of GM crops, most of whom were anonymous individuals.

Our empirical investigation has several important policy implications. First, we provide information about the current online debate on GM crops, thereby revealing the concerns of the general public and various stakeholders, including decision-makers and companies with lobbying intentions. Second, the regional distribution and time dynamics of the debate should be of great interest to prominent players in the public debate, as they could help them to adjust their strategies in time to have a greater influence on specific target groups in the future. Third, the results of this study indicate how governments might lose trust and the will to regain trust. This is important with regard to food policies relating to controversial topics (e.g., GMOs, food labelling) and, more generally, other societal issues.

2.2 Background Information

Before addressing the Chinese case, we provide background information to set the stage for the subsequent analysis.

2.2.1 Background: GMOs in China

The contribution of biotechnology to crop productivity has been debated among scientists, as well as in other societal groups. Studies have noted the advantages of adopting GM crops, including increased crop productivity, associated environmental benefits, poverty reduction, and improved nutrition (Barrows et al., 2014; Bennett et al., 2013). Others emphasize the unknown risks and negative impact on the environment through the potential increase in monoculture and reliance on glyphosate-based chemicals (Myers et al., 2016; Nicolopoulou-Stamati et al., 2016). Yet others argue that other strategies based on agro-ecological concepts could also achieve the intended objectives of GM crops without exposing society to the potential risks (Maghari & Ardekani, 2011).

Despite existing controversy, GM crops accounted for 191.7 million hectares in 2018. The five leading countries in terms of GM crop cultivation are Argentina, India, the United States, Brazil, and Canada. These countries account for 91% of GM crop acreage worldwide (ISAAA, 2018). By 2018, 70 countries had adopted GM crops, with 26 countries planting and 44 countries importing such crops (ISAAA, 2018). China approved the commercialization and cultivation of GM cotton in 1997, and GM papayas in 2006 (Wong & Chan, 2016; Zhao et al., 2019). In 2017, GM cotton accounted for 2.78 million hectares, with GM papayas covering 2.8 million hectares in China (ISAAA, 2017). Since 2006, no additional GM crops have been approved for cultivation in China.

Although several varieties of GM crops have undergone strict risk assessment and a complex regulatory process with regard to cultivation, final approval is pending (Jin et al., 2019b).

Since 2000, China has pursued an active bioeconomic strategy, with substantial investment in R&D for GMOs. Despite a cut in funding for research on GMOs due to public resistance in the early 2010s, the government resumed its support for research and commercialization with regard to GMOs in 2016. One milestone was the July 2016 announcement of the *13th Five-Year Plan for Science and Technology Innovation*, which promotes the development and application of domestic GM crops. Another milestone was in July 2018, when the Ministry of Agriculture and Rural Affairs (MARA) released a report on increasing public biotechnology literacy to advance the commercialization of GM crops. The strategy includes closer cooperation between local governments and the media (MARA, 2018), including Weibo.

Given the high demand for feed and processing materials, the Chinese government has approved the import of more than 50 GM crop varieties since 2002, including GM soybeans, maize, canola, cotton, and sugar beets (Jin et al., 2019b). China is the world's largest grain consumer. Further, it consumes one third of the world's soybean production, which amounts to 1.1 billion tons per year (Han, 2019). China imports 95% of its soybeans from three main countries: Brazil, the United States, and Argentina. Over 90% of these soybeans are GM (Wong & Chan, 2016).

2.2.2 How did the Debate on GM Crops Start in China?

In China, GM crops were introduced to the public in a "negative" way, with three critical events that had a corresponding impact on public opinion.

The first event involved the issuance of biosafety certificates for an insect-resistant GM rice on October 22, 2009. Given that rice is the main staple food for more than half of the population in China, it is of special importance to Chinese people. The biosafety certificates for the GM rice indicated that the it was considered as safe as conventional rice, for both humans and the environment, and that it was thus ready for commercialization (Jin et al., 2019a). At first, the MARA did not disclose any information on the results of the health and environmental studies, even though the GM rice had successfully passed laboratory testing for thermal stability, digestibility, toxicity, and nutrient composition, in addition to three phases of field trials testing potential environmental risks. It would not be until five years later, when the certificates were set to expire and renewal was requested, that the MARA would disclose the results (Cao, 2018). In addition, the public did not know the identity of the members of the biosafety committee, who had decided to issue the biosafety certificates for the GM rice, nor were the biosafety criteria generally known. As a result, people became increasingly critical of the transparency of the process on social media (Cao, 2018).

The GM rice had already been cultivated illegally before its official approval (Zi, 2005). In February 2005, Greenpeace collected samples of rice from various sectors in the supply chain in the province of Hubei, where the GM rice had initially been developed. Greenpeace sent the samples to GeneScan (a GMO laboratory in Germany) for testing. Of the 25 samples, 19 were found to include GM rice, which should have still been in the experimental stage (BBC, 2005; Cao, 2018). Greenpeace revealed similar information on the illegal cultivation of GM rice again in May 2014, after having tested rice bought at random in supermarkets in the province of Hubei. Two months later, on a television program, the Chinese state broadcaster, China Central Television (CCTV), broadcast that GM rice had been found on sale in the provinces of Hubei, Hunan, Anhui, and Fujian after having bought rice at random in supermarkets and sending it for testing (Cao, 2018). Subsequently, the MARA and the Chinese government were blamed online for the weak implementation of laws and regulations on GMOs.

The third event alludes to "*golden rice*", a type of GM rice that developers genetically enriched with beta-carotene, with the objective of producing a fortified food to be grown and consumed in areas with a shortage of dietary vitamin A (Black et al., 2008). In 2012, a nutrition test on *golden rice* was performed in the province of Hunan. The study was funded by the U.S. National Institute of Diabetes and Digestive and Kidney Diseases and the U.S. Department of Agriculture (Hvistendahl & Enserink, 2012). The research team included four US-based and three China-based researchers.

The implementation and publication of the research resulted in disputes among the scientists involved and authorities supervising and allocating grants for research. The three China-based researchers were ultimately removed from their positions, and financial compensation was granted to those subjects involved in the nutritional study (Hvistendahl & Enserink, 2012). The incident nevertheless caused substantial damage to public trust in science, causing further deterioration in the Chinese GMO research environment as a whole (Qiu, 2012).

The events and reactions of the government, which had been perceived as not taking the public interest into consideration, decreased public confidence in GM crops, as well as trust in the MARA and the government (Chow, 2019; Cui & Shoemaker, 2018; Pray et al., 2018). In both 2016 and 2018, government documents established official support for GMOs (MARA, 2018; State Council, 2016). The loss of confidence and trust, together with government support for GMOs, generated a tense atmosphere for GM crops in China, as well as a heated debate on social media (Cao, 2018).

2.3 Theoretical Considerations on the Chinese Policy Response to GMOs

In democratic political systems, governmental actors are dependent on competitive elections to remain in office. They consequently tend to be responsive to public opinion when making policy decisions (Soroka & Wlezien, 2009; Wlezien, 2017). In autocracies (e.g., China), this mechanism does not operate directly, due to the lack of competitive elections. At first glance, therefore, it might not seem likely for the Chinese government to consider public opinion when making policy decisions. According to recent literature, however, some authoritarian regimes are also responsive to societal actors, albeit for different reasons (Chen et al., 2016; Kornreich, 2019; Popović, 2020; Tang et al., 2018). The responsiveness of the Chinese government has largely been due to concerns about political stability, loss of regime legitimacy, and the threat of rebellion (Chen et al., 2016; Popović, 2020). Central and local governments have increasingly used public consultation to gather information on public opinion, in order to prevent potentially threatening collective actions that could destabilize the regime (Jiang et al., 2019; Kornreich, 2019; Su & Meng, 2016). A second mechanism applies especially to the responsiveness of lower-level (e.g. local) government officials. Because public dissatisfaction poses a threat to the career prospects of these lower-level officials, they are especially motivated to prevent any unfavorable public opinion (Chen et al., 2016). For this reason, there exists a multilevel dynamic that might produce inconsistency in the behavior of governments at different levels. Controlling the public debate is one way in which the Chinese government has tried to influence public opinion. Traditionally, the regime has applied various censorship methods to suppress online criticism of the regime (Chang & Lin, 2020; Keremoğlu & Weidmann, 2020; King et al., 2013). In addition, the government has participated in the public debate, albeit somewhat indirectly, by hiring internet commentators to take part in online discussions anonymously, spreading government-friendly views (Han, 2015; King et al., 2017).

Plans by the Chinese government to establish large-scale cultivation of GM crops have faced increasing public opposition (Cui & Shoemaker, 2018). Based on a nationwide Chinese consumer study, the main reason for opposition is that "GM food may have unknown risk to human beings, such as some genetic defects, which may affect human beings for many generations. It will take a long time to validate the safety of GM food using scientific experiments" (Cui & Shoemaker, 2018). Negative public opinion on the commercialization of GM crops and associated fears of diminishing regime stability could potentially explain why the government has been hesitant to lift the ban on GM crop cultivation. Instead of revoking its overall plan on GMO commercialization, however, the government has cemented its intentions to foster GM crop cultivation in the *13th Five-Year Plan for Science and Technology Innovation*, which was released in July 2016. The Chinese government is thus likely try to influence public opinion in ways that will allow the implementation of its biotechnology plans without the risk of losing public support. As explained above, one way in which the government could try to change public opinion would be to intervene into the public debate. This could be done by censoring media outlets and social media on the internet or by participating in the public debate either directly or indirectly through paid anonymous internet commentators.

We expect to observe a controversial debate divided by a single main line of conflict that separates participating actors into supporters and opponents of GMO commercialization. We further expect greater activity among the opponents, given their ability to use media platforms to express contradictory views and influence supporters. With regard to the Chinese government, we expect to observe efforts to influence the public debate. The government could participate either directly, in support of GMOs, or indirectly, by changing the behavior of other participants in the debate (e.g., media outlets or businesses). Finally, we expect to observe changes in the debate and the behavior of various types of actors in response to crucial policy events, like the release of the current *Five-Year Plan* in 2016 (State Council, 2016).

2.4 Methodology

Discourse network analysis is a versatile methodological approach that is widely used to describe the structure of policy debates, the presence of coalitions, and the dynamics of policy debates over time (Leifeld, 2017, 2020). It has been applied in a variety of policy sectors (Breindl, 2013; Fisher et al., 2013; Rinscheid, 2015; Tosun & Schaub, 2017). Discourse networks are defined as verbal interactions between actors making public statements about a given debate, conditional on each other (Leifeld, 2016, 2017).

A discourse network consists of a set of dates, actors, concepts, agreement/disagreement on concepts. In this study, discourse network analysis is used to trace the online debate on GM crops in China, as well as to visualize competing advocacy coalitions, scrutinize their formation, and analyze regional differences and time dynamics to investigate the formation of actor coalitions among various types of stakeholders and how such coalitions contribute to the policy debate. We also include locations in the discourse network to indicate the regional distribution of the GMO debate. The information is coded using Discourse Network Analyzer software, based on statements posted by actors (Leifeld et al., 2019).

To study the formation of the coalitions, we adopt a one-mode actor congruence network, in which actors are connected according to their attitudes toward specific concepts. In this case, concepts are references made by actors with differing opinions when discussing GM crops. The resulting network matrix contains actors in rows and columns, with cell values indicating the similarity of actors (i.e., how often two actors co-support or co-oppose the concepts). We use the *Jaccard similarity measure* to normalize the network matrix, thereby correcting potential biases produced by highly active nodes (Leifeld et al., 2019). We use the *ggnet2* function within the *R* software (R Core Team, 2020) to visualize network graphs, with actors as nodes that are linked by ties if they co-reference at least one concept. In the graph, actors with higher degrees of similarity (i.e., more co-referenced concepts) are positioned closer to each other.

We use social network cluster analysis to identify different communities in competing coalitions. In social networks, clustering involves grouping nodes into clusters based on similarity, with "communities" of nodes sharing common properties and characteristics. Identifying communities within the competing coalitions helps to explain different patterns of supporting or opposing arguments. The analysis we use is based on the *Walktrap algorithm*, which is suitable for graph patterns with a strong community structure. The *Walktrap algorithm* searches for densely connected subgraphs through random walks, in addition to identifying the optimal number of clusters (Charrad, 2016).

2.5 Data

The social media platform Weibo is the data source from which we collected statements from various actors. This Chinese microblogging website (similar to Twitter in the western countries) has been one of the most popular and widely-used platforms in China since 2009. Among the more than 203 million Weibo daily users, the most frequently used feature is the ability to follow hot topics and news (Business Statistics, 2020). Weibo can thus be regarded as a public sphere in which public debate on societal and political developments takes place through mass media (Peters, 2013; Stockmann et al., 2020). Given the influence of mass media on public opinion (Delshad & Raymond, 2013; Rim et al., 2020; Soroka & McAdams, 2015; Tosun & Schaub, 2017), we assume that Weibo discussions about GM crops simultaneously influence perceptions and opinions on the topic.

According to a 2016 survey, most people in China obtain their information on GMOs through the internet (Cui & Shoemaker, 2018). We can therefore assume that actors interested in influencing the public engage in strategic participation in Weibo discussions to influence public opinion (Hestres, 2014; Tosun & Schaub, 2017).

Weibo contains a massive amount of information about GM crops. Most statements are descriptive (e.g., news about the development of GM crops), however, and have already been analyzed in a previous study focusing on semantic networks and the frequency of keywords about GMOs (Li et al., 2019). As concluded by Li et al. (2019), keywords about GMOs have changed from clustering around "harmful" to clustering around "scientific" in recent years. To analyze how different stakeholders try to influence the public over time, we focus on statements from various actors with a clear attitude either supporting or opposing GM crops. To this end, we select a special function (i.e., Weibo topics) to draw a sample from the debate in which Weibo users express themselves according to the topics. Topic selection was based on popularity of participation, relevance to the historical events (see Section 2.2.2), and availability. Based on this selection criteria, 14 debate topics were selected for this study (see Appendix 1). Due to the settings of Weibo, only the latest posts on the topics were available, as older posts are automatically replaced by newer posts. Topics are updated as long as new posts are generated. The database is thus dynamic, and the earliest statement we could trace for the topics covered in our study was from March 2013.

Based on the selected Weibo topics, we coded 778 statements in which Weibo users expressed a clear attitude toward GM crops between March 2013 and April 2020. If available, we also included the user's organizational affiliation and location. There are two kinds of Weibo accounts: individual and business. We coded the actor's organization only if Weibo had verified the account as an official account of the relevant organization (e.g., large companies may verify official Weibo accounts to promote products and inform consumers). For individual and unverified business accounts, we coded the actors as individuals without organizational affiliation. Of all coded users, 70% had provided location information, which indicates the provinces of origin (e.g., Beijing, Hubei, and Heilongjiang), based on registration information. The regional distributions of posts are illustrated in Table 1, differentiated by individuals and organizations.

Table 1. Regional distribution of posts, differentiated by individuals and organizations

Province	Anhui	Beijing	Chongqing	Fujian	Gansu	Guangdong	Guangxi
Individual	4	110	5	5	5	40	6
Organization	1	37	0	0	0	1	1
Province	Guizhou	Hainan	Hebei	Heilongjiang	Henan	Hubei	Hunan
Individual	2	10	24	7	15	40	13
Organization	0	2	0	9	2	7	0
Province	Jiangsu	Jiangxi	Jilin	Liaoning	Macao	Neimenggu	Ningxia
Individual	30	1	9	14	1	1	3
Organization	7	0	2	1	0	0	0
Province	Qinghai	Shaanxi	Shandong	Shanghai	Shanxi	Sichuan	Taiwan
Individual	0	6	17	24	11	25	2
Organization	1	0	5	4	0	0	2
Province	Tianjin	Xinjiang	Yunnan	Zhejiang	Abroad	Not mentioned	
Individual	8	3	5	12	53	144	
Organization	0	0	0	1	24	16	

Source: Authors, based on Weibo (2013-2020)

Given that anyone can post on Weibo about anything, the Weibo administrator sometimes deletes posts according to the *Weibo Service Agreement* (Weibo, 2020). Deleted posts might include fake information, erroneous citations and interpretations, or other issues. We have included deleted posts in our study. Actors are independent, as they either influence or learn from each other. If commenters have clearly expressed attitudes toward GM crops based on the deleted posts, such information is relevant to this study. Re-posts are not considered unless they contribute statements indicating clear attitudes toward GM crops, as the act of re-posting does not necessarily mean that the re-poster agrees with the original post. Our study considers only the plain text contained in discussions and comments. Images, videos, and external links are not included.

Within the collected posts, we coded statements on relevant concepts, as derived from a previous study on GMOs in the European Union (Tosun & Schaub, 2017) and adjusted to reflect the situation in China. All concepts used in the data-collection process are listed in Table 2. Concept 1 indicates whether actors agreed that transparency concerning GM crops was already existent in China, and Concept 2 concerns their agreement that the current approval process included strict risk assessment and regulations. Concept 3 identifies actors rejecting GMO crops due to long-term uncertainties associated with them. Concept 4 indicates whether actors attributed negative effects on public health, the environment, or traditional agriculture to GMOs. Concept 5 indicates whether actors supported the promotion and cultivation of GM crops, and Concept 6 concerns support for placing GMOs on the market as either food or feed. Concept 7 refers to whether actors pointing to a lack of knowledge on biotechnology in general as a reason for opposing GM crops. Concept 8 concerns trust in the government with regard to the approval process and the implementation of laws and regulations in general. Table 2 further identifies the positions corresponding to supporting or opposing views on GM crops (1 = agreement, and 0 = disagreement).

Table 2. Specification of concepts

No	Concepts	Supporters	Opponents
1	Existing transparency (yes)	1	0
	Existing transparency (no)	0	1
2	Existing strict risk assessment and regulations (yes)	1	0
	Existing strict risk assessment and regulations (no)	0	1
3	Scientific uncertainty and no to GMOs (yes)	0	1
	Scientific uncertainty and no to GMOs (no)	1	0
4	Negative effects on public health, the environment, or traditional agriculture (yes)	0	1
	Negative effects on public health, the environment, or traditional agriculture (no)	1	0
5	GMO promotion and cultivation (yes)	1	0
	GMO promotion and cultivation (no)	0	1
6	Market placement as food or feed (yes)	1	0

	Market placement as food or feed (no)	0	1
7	Lacking knowledge on biotechnology (yes)	1	0
	Lacking knowledge on biotechnology (no)	0	1
8	Distrust of the government (yes)	0	1
	Distrust of the government (no)	1	0

Source: Authors, based on Tosun and Schaub (2017).

2.6 Results and Discussion

2.6.1 Supporters and opponents of GM crops

An overview of the frequency with which supporters and opponents of GM crops referred to the various concepts on Weibo is provided in Table 3, based on all observations. Frequencies for supporters are presented in the third column, with frequencies for opponents in the fourth column. For all concepts but one (distrust of the government), both supporters and opponents of GM crops invoked the same concepts, with opponents posting more often than supporters for all concepts.

Table 3. Overview of concepts

No	Concepts	Supporters	Opponents
1	Existing transparency	2	46
2	Existing strict risk assessment and regulations	15	17
3	Scientific uncertainty and no to GMOs	24	203
4	Negative effects on public health, the environment, or traditional agriculture	55	164
5	GMO promotion and cultivation	20	43
6	Market placement as food or feed	8	66
7	Lacking knowledge on biotechnology	22	25
8	Distrust of the government	0	68
	Sum	146	632

Source: Data collection from Weibo (2013-2020).

To evaluate whether both supporters and opponents of GM crops strive to influence the public through Weibo debates, we summarize the number of statements made by each group annually between 2013 and 2020 in Figure 1. In 2014 and 2017, statements by opponents dramatically exceeded those of supporters (12 times as many), possibly because of two influential events. First, Greenpeace revealed the illegal cultivation of GM rice in May 2014. Second, the province of Heilongjiang officially issued the first provincial legislation ban on GMOs in December 2016, taking effect in May 2017. As shown in Figure 1, the number of statements from opponents exceeded the number of statements from supporters in all years. Results from an independent sample *t*-test assuming unequal variances confirm that the observed differences between the mean numbers of statements were significant at the 10% level (see Appendix 2).

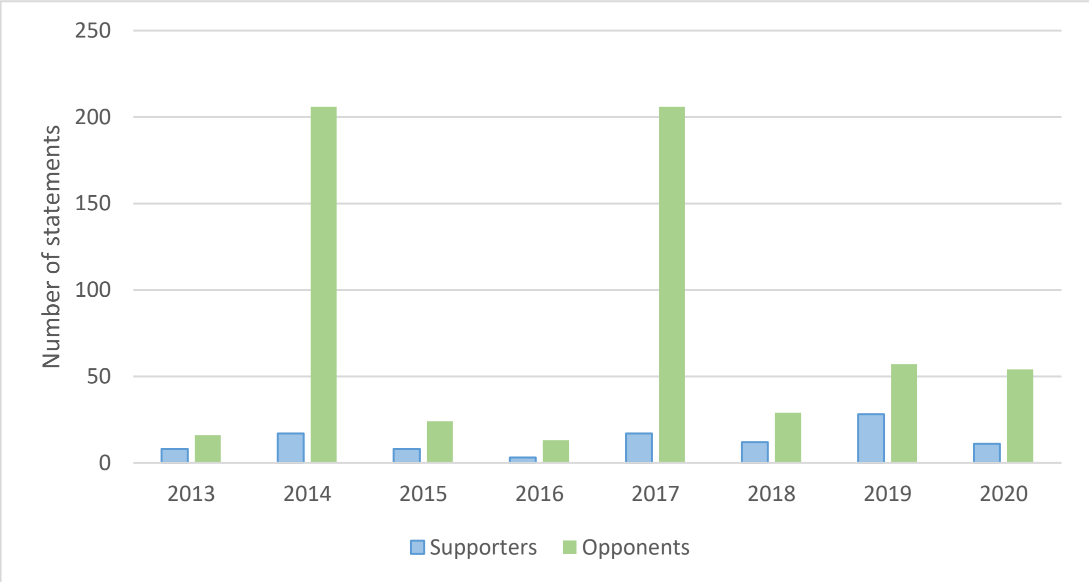

Figure 1. Number of statements between May 2013 and April 2020

Note: The data represent the period between March 2013 and April 2020, due to the availability of data on Weibo. Data for 2013 and 2020 are therefore incomplete.

Source: Data collection from Weibo (2013–2020)

2.6.2 Actor type

In Table 4, we provide an overview of 10 types into which we assigned actors and their organizations. Most of the statements (84.2%) were from anonymous individuals, followed by members of the scientific community (e.g., universities and research institutes), governmental entities (e.g., MARA, local and central governments), the business community (e.g., biotechnology and agricultural technology companies), the media (e.g., CCTV and newspapers), foreign governments and legislatures (e.g., the Russian government), international organizations (e.g., the UN Food and Agriculture Organization), international environmental groups (Greenpeace), and a court (the Henan Court). One statement stemmed from the US Consulate in Shenyang; it was categorized as "Other." Although the absolute number of statements from the government may seem small, it is important to note that Chinese government officials seldom engage in online debate, in contrast to government officials in some other countries (e.g., the United States; see Team, 2020). The last two columns of Table 4 indicate the absolute number of supporters (fourth column) and opponents (fifth column) in each actor type.

Table 4. Number of statements per actor group

Actor type	Total	Share in %	Supporter	Opponent
Anonymous	655	84.2	65	590
Science	33	4.2	33	0
Government	32	4.1	21	11
Business	22	2.8	10	12
Media	13	1.7	8	5
Foreign government and legislature	11	1.4	2	9
International organization	8	1	6	2
Environmental group	2	0.3	0	2
Court	1	0.1	0	1
Other	1	0.1	1	0
Sum	778	100	146	632

Source: Data collection from Weibo (2013–2020)

2.6.3 Regional distribution

In Figure 2, we summarize the regional distribution of actors for all observations. In general, people from the eastern part of China participated more actively in Weibo debates on GM crops than did those from the western part and remote inland regions. People from Beijing were the most active participants (27% of total participation), followed by Hubei (8.7%), Guangdong (7.6%), Jiangsu (6.8%), and Shanghai (5.2%). Beijing, Shanghai, and Guangdong are regarded as the three most developed regions in China. Consciousness concerning GM crops might therefore be relatively high in these regions, and inhabitants might therefore be eager to express their opinions online to influence policy-makers. In both 2005 and 2014, illegally-planted GM rice was found on sale in Hubei (see Section 2.2.2), possibly explaining the active participation of actors in that province.

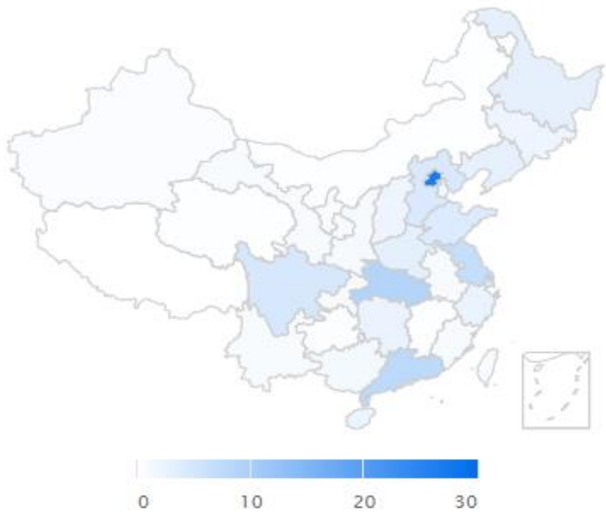

Figure 2. Regional distribution of Weibo participation density
Source: Data collection from Weibo (2013–2020)

2.6.4 Coalition formation in the public debate

The actor congruence networks are depicted in Figure 3.[2] Separate groups of actors in the graph can be interpreted as competing advocacy coalitions with higher degrees of similarity in concepts. Neither the absolute spatial distance between actors nor their absolute positions can be interpreted in any meaningful way (Leifeld, 2013). Based on

[2] Given that the absolute spatial distance between two coalitions in Figure 3 is meaningless, the empty space between the two coalitions has been removed for a clearer view.

the congruence network, there are two separate coalitions, each consisting of actors with similar positions toward the concepts. Opponents to GM crops are depicted by the coalition on the left, with the coalition on the right representing supporters.

The opponent coalition comprises six times more actors than the supporter coalition. Anonymous individuals are dominant in both competing coalitions. Different actor types are indicated by different colors. Both similarities and differences in actor types can be observed between the two coalitions. The supporter coalition includes members from the government, international organizations, the business community, media, science, foreign governments, and the legislature, while the opponent coalition includes members from the government, foreign governments, business, media, environmental groups, international organizations, and courts. Within each coalition, higher tie weights indicate a higher degree of similarity in concepts. Stronger ties among actors in the opponent coalition indicate a higher degree of congruence in their positions on different concepts.

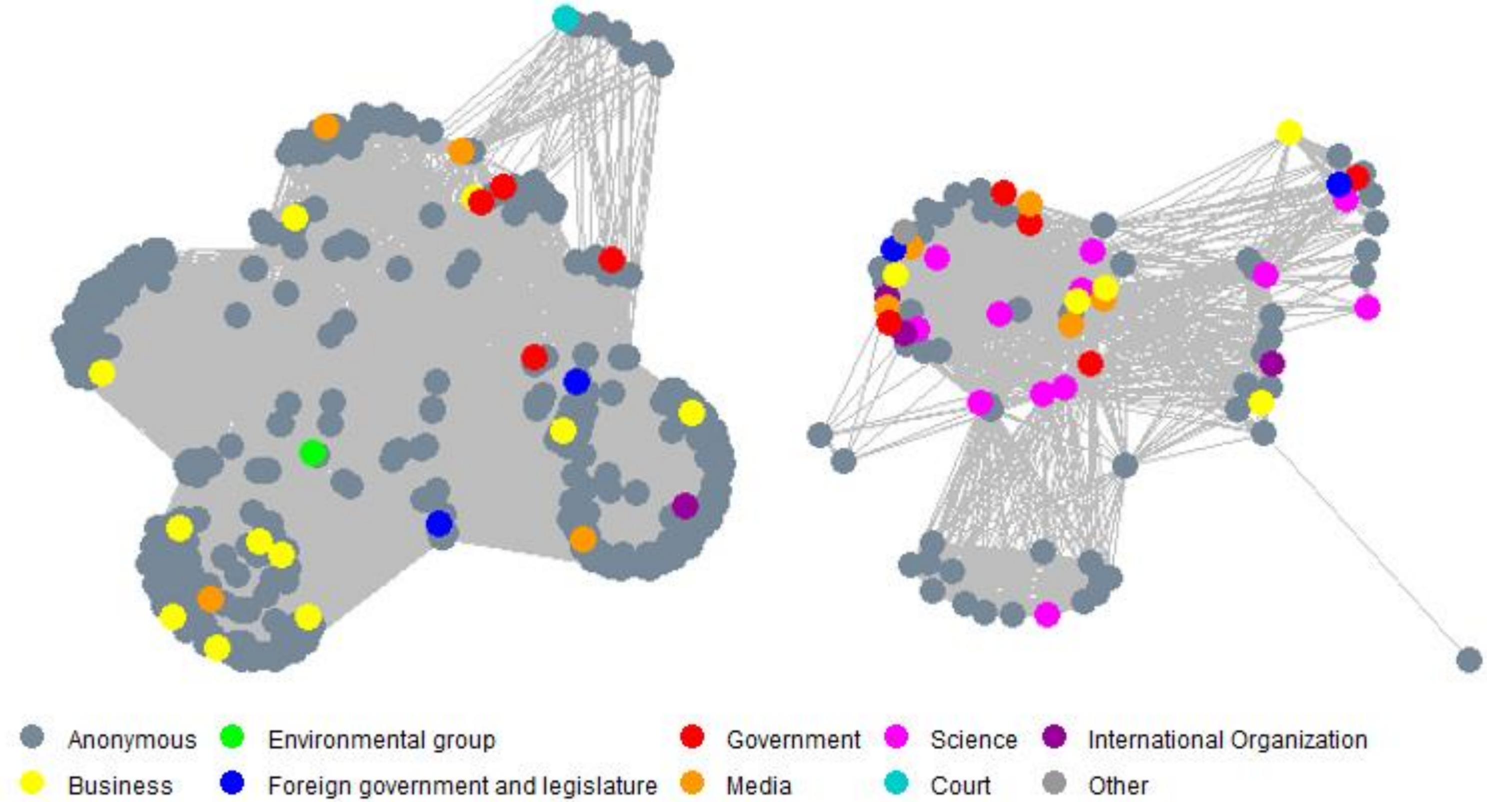

Figure 3. Visualization of the actor congruence network: Opponents on the left and supporters on right.

Domestic governments are represented in both coalitions, thus indicating conflicting domestic views at different levels. For example, this was the case for Heilongjiang, where the provincial government issued a legislative ban on the cultivation, processing, and sale of GM crops, as well as any agricultural products containing GM ingredients (Heilongjiang Government, 2017). At the same time, however, statements from the MARA were posted on Weibo as well, promoting GM crops by citing scientific evidence (e.g., "All GM crops approved for commercialization are safe"). Similar statements had been stressed by the MARA officials in different circumstances, although they also expressed disappointment (e.g., "Our government has been promoting GM crops for many years. Judging from those rumors online, however, the power of promotion has obviously been insufficient."

In our database, all actors identified as scientists were in the supporter coalition, with affiliations with universities and research institutes including Fudan University, Huazhong Agricultural University, China Agricultural University, the Chinese Academy of Science, the Chinese Academy of Engineering, and the Chinese Science Association. These scientists posted statements to support the safety of approved GM crops. Examples included: "GM crops are safe;" "China cannot wait for the commercialization of GM crops. The blockage of commercialization is having a negative impact on its research and development as well;" and "We should allow GM rice on the market within five years." In addition, academics from both the Chinese Academy of Science and the Chinese Academy of Engineering signed a joint letter supporting the commercialization of GM crops in 2017 (BBC, 2013).

Members of the business community appeared in both coalitions, representing agricultural technology companies, biotechnology companies, food companies, and companies in other sectors (e.g., media, trade, and culture communication), as officially verified by Weibo. Statements from companies were quite diverse. For example, supporters posted: "We hope that the public will soon be able to understand GM crops and biotechnology correctly." "Pesticides smell bad, and they are so bad for farmers' health. Don’t you think that that it is actually necessary to research and develop GM crops?” “If you read scientific papers, you will not be able to find any publication about the harmfulness of GM crops; however, there are many papers referring to the harmfulness of using mobile phones.” Members from the business community posted opposing posts, including: “Our company does not use any raw materials that are based on GMOs, and GM food is not suitable for China.” “GM crops are worse than opium.”

The media also play an important role in influencing public opinion through various online news platforms (e.g., CCTV, People’s Daily, and ArnetMiner Academic News). Posts from these sources included interpretations of research results (e.g., “Research has proved the safety of GM crops as food, consistent with findings released by the food standard agencies in the United States, Canada, and Australia”). Others shared different opinions (e.g., “Commercialization of GM rice might be fatal for traditional rice varieties;” “Illegal cultivation of GM rice…Where is the so-called very strict regulation?” and “The labelling of GM products on the market is not clear, which damages consumers’ ‘right to know’”).

As shown in Figure 3, actors of different types appear in both coalitions (except for the actor types Court and Other), possibly due to diverse opinions held by different actors within the same actor type (as discussed above), inconsistency of actors over time, or both.

2.6.5 Time dynamics in the public debate

We analyzed the public debate over time to determine whether various stakeholders had changed their positions over time. Based on recent government actions concerning GM crops (see Section 2.2.1), we split the analysis of the public debate into three periods and searched for differences between these periods. Period 1 (May 2013 to July 2016) covers the time before the official announcement of policy support by the government. Period 2 begins in August 2016, after the official announcement of policy support, and ends in July 2018, right before the government started to cooperate with the media in its campaign for GM crops. Period 3 runs from August 2018 (marking the beginning of this cooperation) through April 2020 (the end of our observation period).

The time dynamics are visualized in Figures 4a, 4b, and 4c[3] by graphing the congruence network and results of the social network cluster analysis for the three different periods, respectively. Different colors indicate different actor types, and different edge shapes indicate different communities, based on the cluster analysis.

It is interesting to note the absence of differences between the conflict lines underlying the three figures. Two competing coalitions were formed in each of the three time periods. For each period, the coalition on the left represents opponents of GM crops, with supporters depicted in the coalition on the right. The opponents were more active in participating in the Weibo debate in all three periods

As shown in Figure 4a, the actor composition of the opponent coalition in Period 1 was more diverse than in subsequent periods. It included members from the business community, the media, environmental groups, governments, courts, and international organizations. The supporter coalition was dominated by scientists, aside from anonymous individuals. The social network cluster analysis reveals five different communities, four belonging to the opponent coalition and the other belonging to the supporter coalition. Four different kinds of opponents included those concerned primarily about the potential risk of GM crops due to distrust of the government (Cluster 1); those doubting the transparency of the current risk assessment and regulations (Cluster 2); those believing that GM crops would have negative effects on public health, the environment, or traditional agriculture (Cluster 3); and those opposing GM crops, either due to long-term scientific uncertainty or for no specific reason (Cluster 4). Cluster 5 includes all actors supporting GM crops for the reasons mentioned in Table 2.

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[3] Given that the absolute spatial distance between two coalitions is meaningless, the empty space between the two coalitions has been removed for a clearer view in Figures 4a, 4b, and 4c.

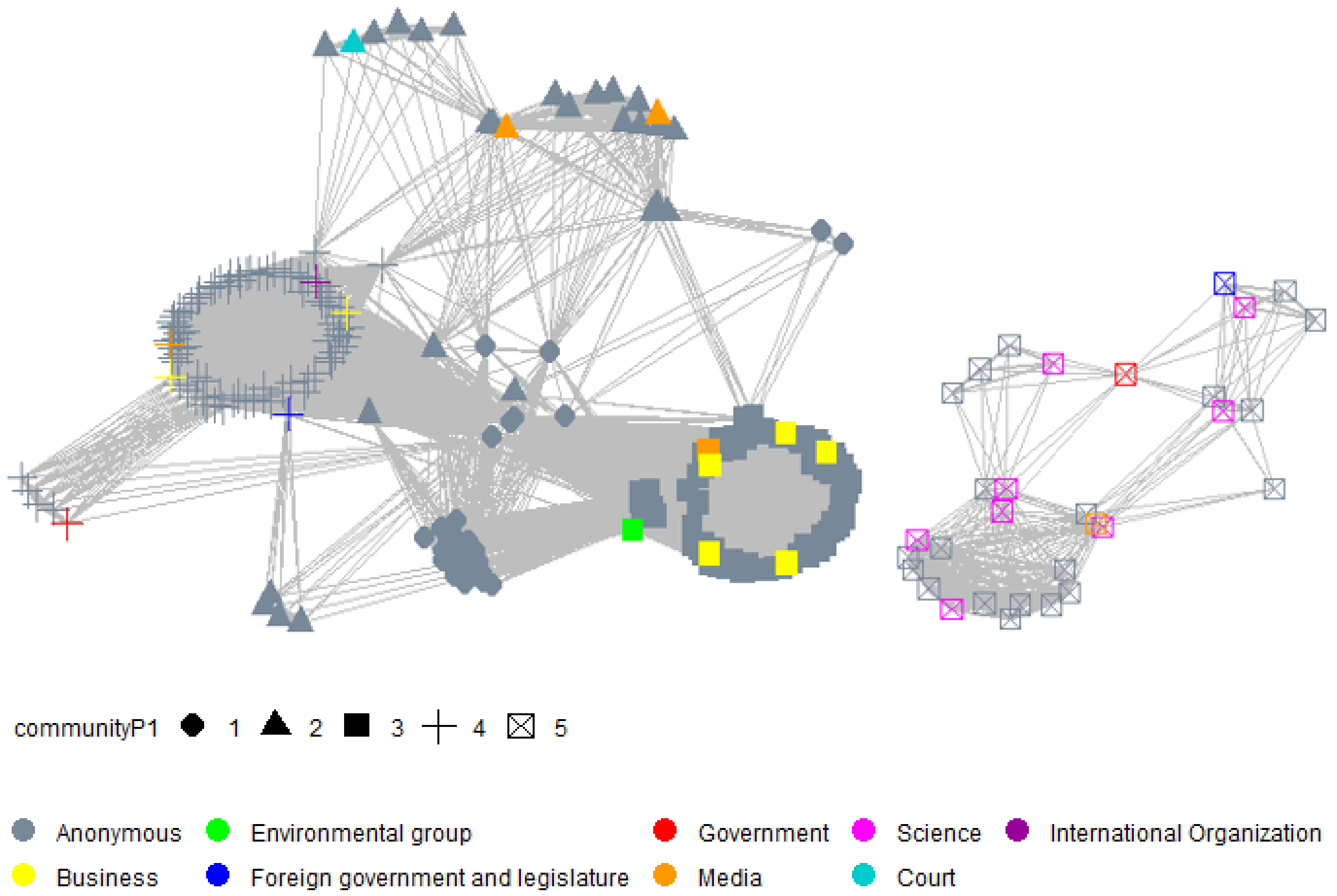

Figure 4a. Visualization of time dynamics of the congruence network and social network cluster analysis, based on the Walktrap algorithm (2013.05-2016.07, 352 statements)

After the government announced its policy support in Period 2, media actors and many other actors stopped posting statements on Weibo in opposition to GM crops. The opponent coalition in this period consisted largely of anonymous individuals, along with some actors from local governments and businesses. In the supporter coalition, business actors joined the scientific actors. The social network cluster analysis for Period 2 reveals four different communities, two belonging to the supporter coalition and the other two belonging to the opponent coalition. The additional cluster in the supporter coalition (as compared to Period 1) includes actors explicitly supporting the promotion and cultivation of GM crops. This cluster nevertheless contains only two statements from the science group: one from the Chinese Academy of Agricultural Sciences and the other from Huazhong Agricultural University. In contrast to the four clusters in the opponent coalition in Period 1, only two opposing clusters are reflected in Period 2. One opposing cluster is small, comprising actors concerned about the negative effects of GMOs on public health, the environment, or traditional agriculture. The other opposing cluster is large, including most of the other reasons listed in Table 2. This opposing cluster could be regarded as a combination of Cluster 1, 2, and 4 from Period 1.

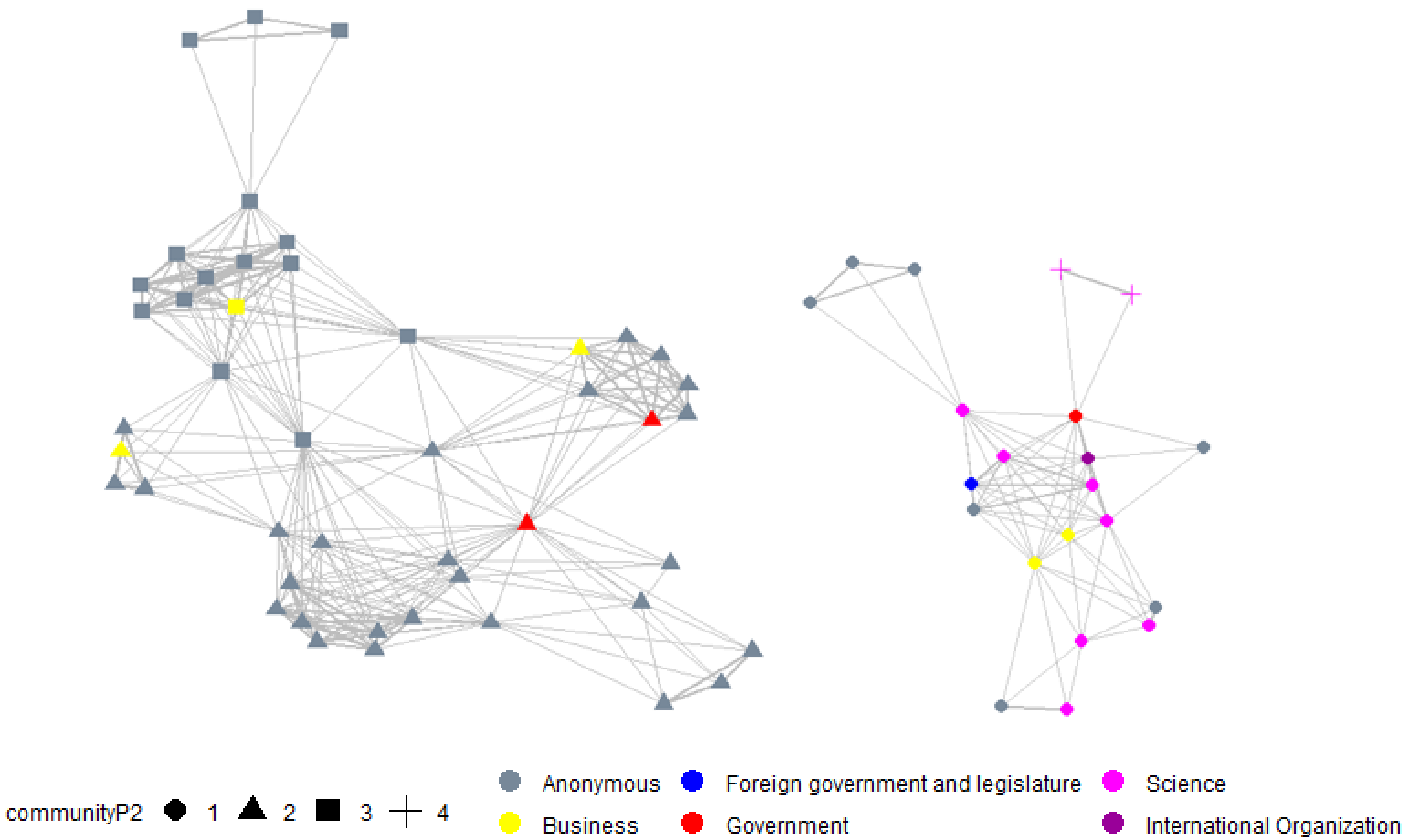

Figure 4b. Visualization of time dynamics of the congruence network and social network cluster analysis, based on the Walktrap algorithm (2016.08-2018.07, 104 statements)

In Period 3, scientists became less active in the supporter coalition, which was gradually taken over by other actor types. Business and media actors gradually left the opponent coalition and entered the supporter coalition. There was a clear change in the behavior of media actors in the different periods, probably reflecting the high level of media support for the government in China. Another possible explanation for the change in media behavior could involve the closer cooperation between the government and media aimed at increasing public biotechnological literacy (MARA, 2018). In any case, these results indicate that the Chinese government has attempted to influence public opinion on GM crops.

The social network cluster analysis for Period 3 reveals four different communities, two belonging to the opponent coalition and the other two belonging to the supporter coalition. The small supporting cluster includes actors convinced that the opposition of others was due to a lack of knowledge concerning biotechnology, those trusting the safety of GMOs, and those supporting the placement of GM crops on the market as feed or food. The large supporting cluster combined all other reasons for support, as summarized in Table 2. In the small opposing cluster, many actors distrusted the government in general and worried about the transparency, assessment, and regulation of GM crops. They therefore opposed the promotion and cultivation of GM crops. The larger opposing cluster includes most of the other reasons mentioned in Table 2, such that it can be regarded as a combination of Clusters 3 and 4 from Period 1.

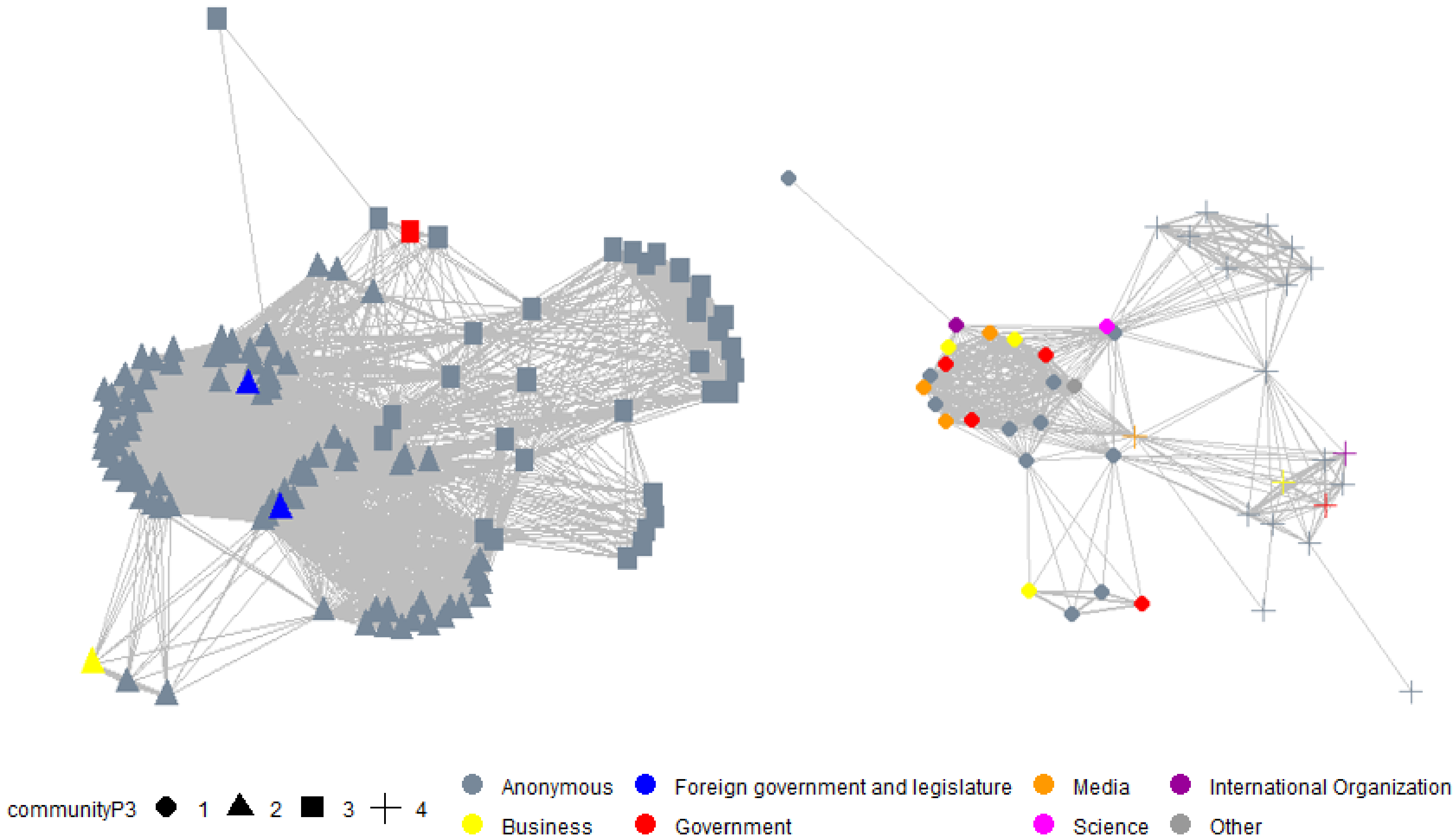

Figure 4c. Visualization of time dynamics of the congruence network and social network cluster analysis, based on the Walktrap algorithm (2018.08-2020.04, 322 statements)

Interestingly, even after the policy support announced in 2016, local governmental actors (e.g., from Heilongjiang, Qinghai, and Taiwan) continued to post statements opposing GM crops. Provincial government officials were eager to prevent unfavorable public opinion, largely out of concern for their career prospects (Chen et al., 2016). Statements from the MARA appeared 1.5 times more often on Weibo than in the period before 2016. This indicates that the Chinese government was more active in its attempts to influence public opinion on GM crops in Period 3.

In general, the results of the social network cluster analysis reveal the underlying conflict lines. It would be politically risky for the policy-makers to lift the blockage of GM crop cultivation in China at this stage, as the debate continued to be dominated by the opposition, albeit weakened. Under these circumstances, policy-makers apparently preferred to maintain political stability instead of exposing themselves to the threat of losing regime legitimacy (Chen et al., 2016; Popović, 2020).

2.7 Conclusion and Policy Implications

Our analysis of Weibo posts between March 2013 and April 2020 reveals a public debate on GM crops that is characterized by strong public resistance against the commercialization of GM crops in China. Statements from opponents outnumbered those from supporters in all years. Consistent with previous studies, the smaller number of supporters might have been due to the availability of other channels (e.g., inside lobbying) that supporters of GM crops (e.g., seed companies) could use to influence decision-makers (Deng et al., 2019; Schaub & Metz, 2020; Tosun & Schaub, 2017). The analysis further shows how the government has attempted to influence public opinion through active participation in the debate and by convincing other actors (e.g., the media) to change sides and join their coalition of support in the debate. Despite these efforts, public resistance to GMOs in China remains strong. The persistent dismissive public opinion on GMOs and the Chinese government's concerns about political stability help to explain its hesitation to lift the current ban and allow additional cultivation of GM crops.

Our study provides scientific evidence to enhance systematic understanding of the public debate on Weibo concerning GM crops and the behavior of various stakeholders in China. Our analysis of Weibo posts reveals that the debate was characterized by two competing advocacy coalitions, regional differences, and changes in coalition membership over time. In general, the debate was dominated by relatively active opponents of GM crops, consisting largely of anonymous individuals. Their strategy involved eliciting emotions and disputing scientific evidence. In contrast, and consistent with findings from previous studies (Augoustinos et al., 2010; Mielby et al., 2013), we found that supporters primarily emphasized scientific evidence about food and environmental safety.

The structure of the debate might change in the coming years, as members of the government, business community, and media are becoming more involved in the debate, in a concerted effort to promote GM crops. This change started in late 2018, when the MARA began its efforts to increase public knowledge about GM crops with the help of the media. Our results also reveal inconsistent behavior on the part of government representatives. Lower-level officials often oppose GM crops, in the attempt to be more in line with public opinion. Similar observations have been made by other scholars, who have attributed them to the desire to avoid ruining their own career prospects (Black et al., 2008; Chen et al., 2016).

The findings of our study have several policy implications. First, they could enhance the Chinese government's understanding of the concerns of citizens and its ability to target these concerns more specifically when promoting the commercialization of GM crops, instead of merely repeating the potential benefits and safety of GM crops based on scientific evidence. One reason for opposition involves distrust of the government. This finding is consistent with a previous study indicating a lack of trust in government supervision in the area of food safety and labelling information (Liu et al., 2019), as well as GMOs in general (Zhang et al., 2010). Studies have demonstrated that trust is crucial in shaping public attitudes toward GMOs (Evenson & Santaniello, 2004; Kikulwe et al., 2011; Zhang et al., 2010). Regaining public trust is therefore vitally important to food policies relating to controversial topics (e.g., GMOs, food labelling), as well as other more general societal issues.

Building on another study about inside lobbying at the corporate level (Deng et al., 2019), our study indicates that the participation of companies in the public debate online is relatively low, but that the mass media serve as an important channel through which the public can access information on GMOs. For companies with lobbying intentions, promoting GMOs through social media (e.g., Weibo) might therefore be a feasible supplement to direct governmental lobbying, given that the MARA also considers socioeconomic and political factors when making decisions (USDA, 2015).

The information that we provide on the regional distribution and time dynamics of the public debate could help major players (e.g., companies with lobbying intentions) to adjust their strategies in time, thereby enhancing their ability to influence the public in specific regions in the future. Our study also contributes to the international food-policy debate, as its implications also apply to other countries aiming to advance the commercialization of GM crops or crops derived with genome editing, even as they face strong public resistance in general. In some cases, public resistance could result in delays for science-based technologies. Learning from the public debate on GMOs in China could help to improve policy design in the future, taking into account concerns from both the public and stakeholders.

Although our study provides a promising starting point for analyzing public debate of GM crops in China, the sample is limited to the most heated debate topics on Weibo in the past seven years. Further research on the GMO debate on Weibo is needed to test the robustness of our findings in a larger sample.

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Fdownload%2FFacts%2520and%2520Trends%2520-%2520China-2017.pdf&usg=AOvVaw1_qSK3kQAXQeYEP5Qg8rB_

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2.9 Appendix

2.9.1 Weibo topics

Table A1. Weibo topics in the study

Topic	Topic	Number of contributions
#不管几比几，不要转基因#	#No Matter What, No to GMOs#	69,000+
#拒绝转基因#	#Rejection to GMOs#	54,000+
#转基因食品#	#GM Food#	25,000+
#崔永元考察转基因#	#Cui Investigating GMOs#	23,000+
#转基因大米#	#GM Rice# (unprocessed)	17,000+
#转基因战争#	#GM War#	8,433
#农业转基因生物安全证书批准清单#	#Approval Lists of Biosafety Certificates#	8,322
#转基因滚出中国#	#GMOs Leave China#	5,974
#崔永元转基因#	#Cui and GMOs#	5,603
#转基因大豆#	#GM Soybeans#	5,487
#转基因作物#	#GM Crops#	5,404
#转基因大豆油#	#GM Soybean Oil#	5,039
#诺奖得主支持转基因#	#Nobel Prize Winners' Supporting GMOs#	2,089
#转基因水稻#	#GM Rice# (processed)	953

Note: Data accessed through April 15, 2020

2.9.2 Results of t Test

Table A2. Comparison of Mean Values for the Number of Statements on GMOs

Two-sample *t* test with unequal variances				
Groups	Mean	Standard Error	Observations	|Difference|
GMO opponents	75.6	82.1	8	62.6
GMO supporters	13	7.7	8	
Pr(|T| > |t|) = 0.068, t = -2.15, Degrees of freedom = 7				

Chapter 3

Getting an Imported Genetically Modified Crop Approved in China: Policy Background and Interpretation of a Time Trend

3. GETTING AN IMPORTED GENETICALLY MODIFIED CROP APPROVED IN CHINA: POLICY BACKGROUND AND INTERPRETATION OF A TIME TREND[4]

ABSTRACT: Genetically modified (GM) crops are subject to regulations at the national and international levels. We review the complex Chinese regulatory system involving different departments and a host of regulatory documents for approving GM crops. We analyzed the approval process of commercializing GM crops in China. For imported GM crops, we analyze how crop characteristics and other factors affect the approval time[5] between 2002 and 2017. The results indicate that GM maize takes significantly more approval time than other GM crops but that other crop characteristics do not significantly affect the approval time. We find that the average time to obtain approval for imported GM crops in China increased by around 16 months after ca. 2010 due to increased public concerns on GM crops. We compare the approval dates and approval time of GM varieties approved in China, the United States, Canada, and the European Union. China approves GM crops, on average, around one year earlier than the European Union but lags, on average, 4.2 years behind the United States and 4.9 years behind Canada. The mean approval time for imported GM crops in China is 3 years shorter than that in the United States and 1.9 years shorter than that in the European Union.

KEYWORDS: imported GM crops, approval time, approval dates, regulatory process, China

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[4] This chapter is based on the article: Jin, Y., Drabik, D., Heerink, N. & Wesseler, J. (2019), "Getting an Imported GM Crop Approved in China", *Trends in Biotechnology,* Vol. 37(6), pp. 566–569.
[5] In the paper, "approval time" indicates the duration of the approval process.

3.1 Introduction

With only six percent of freshwater and seven percent of arable land in the world, China has to nurture nearly 20 percent of the world's population (Wong & Chan, 2016). The tension between available resources and demand for food motivates the country's efforts for food self-sufficiency, that is, national food security, by promoting agricultural biotechnology research to improve the productivity of domestic agriculture. As a result, China has become the world leader in biotechnology research (Li et al., 2014).

Although biotechnology research for major genetically modified (GM)-seed cultivation programs experienced funding cuts due to debates about genetically modified organisms (GMOs) (Cai et al., 2016). The Chinese government issued a statement in early 2015 to reinforce research of agricultural GMOs and their safety management (Ministry of Agriculture [MoA], 2015). The exact expenditure on agricultural biotechnology in China is unknown, but a United States Department of Agriculture (USDA) report argued that it far exceeded the total outlays of the United States and other countries (Anderson-Sprecher & Jie, 2015).

China defines GMOs as animals, plants, microorganisms, and their products whose genomic structures have been modified by genetic engineering technologies for use in agricultural production or processing.[6] So far, China imports five GM crops for further processing: maize, soybeans, canola, cotton, and sugar beets. The only two GM plants allowed for domestic commercial cultivation are *Bacillus thuringiensis*–resistant (Bt) cotton and virus-resistant papaya[7] (Wong & Chan, 2016).

In this paper, we analyze the approval process of commercializing domestic and imported GM crops in China to better understand its regulatory system. We contribute to the literature on the GMO approval process in different countries by taking a close look at the regulatory documents and related departments involved in the GM crop decision-making process in China. Such an overview has been missing so far and

[6] Available at: http://www.lawinfochina.com/Display.aspx?lib=law&Cgid=35608

[7] The latest International Service for the Acquisition of Agri-biotech Applications (ISAAA) system shows many more GM plants allowed for domestic cultivation, including two types of GM rice (Shanyou 63 and Huahui 1, 2009), one type of GM maize (BVLA430101, 2009), three types of GM tomatoes (DaDong 9, Huafan 1, and PK-TM8805R, 1997), one type of GM sweet pepper (PK-SP01, 1999), two types of GM poplars (Bt poplar12 and poplar741, 2003), and one type of GM petunia (petunia-CHS, 1999). However, they have never been commercially planted on a large scale, and some of their biosafety certificates have already expired (Li et al., 2014).

provides essential information for different stakeholders, including domestic and foreign policymakers, and for businesses interested in the pros and cons of investing in new biotechnology. We also examine the factors affecting the approval process and interpret the approval length for imported GM crops in China between 2002 and 2017. To achieve a globally comparative view of the GM crop–approval statute in China, we further investigate and compare the differences in approval dates for the same GM varieties in China, the United States, Canada, and the European Union, and we also investigate and compare the differences in approval lengths for the same GM varieties in China and the European Union.

In the next section, we review China's approval process for GM crops. In Section 3, we describe the data used for the Ordinary Least Squares (OLS) regression to examine the factors affecting the approval times of imported GM crops. We also compare the approval dates and times in different countries. In Section 4, we conclude.

3.2 China's Approval Process for Domestic and Imported GM Crops

Domestic and imported GM crops in China go through similar approval processes to obtain biosafety certificates. After that, imported GM crops are allowed for commercialization as processing materials, while crops need another three documents before they are allowed for cultivation.[8] These additional documents include a seed variety certificate (showing successful registration of a new crop variety), a production license (an official certificate of a new crop variety to be produced), and a marketing license (an official certificate of a new crop variety to be commercialized) (Wong & Chan, 2016).

Bt rice—an insect-resistant, GM rice variety developed in 1989 by scientists from the Chinese Academy of Agricultural Sciences—is a good example of how difficult it can be for a GM crop to make it to the commercialization stage even though the crop has obtained the biosafety certificates and its production is expected to bring significant economic, environmental, and health benefits (Huang et al., 2005, 2015). Bt rice in China has still not obtained seed variety registration, which is a prerequisite for the production license and marketing license.

At the beginning of the approval process, the biotech seed developer—either a

[8] This is because domestic cultivation might result in more potential environmental risks.

company or a research institute—applies for the biosafety certificate. The application in China is not allowed until the variety has been approved in its country of origin for the same use, as China does not allow simultaneous submission (Huang & Yang, 2011), which means application in its country of origin and China at the same time is not possible. To obtain it, the product has to go through various lab experiments to examine its food safety, gene flow, non-target organisms, and other potential factors. A three-phase process then starts. The first phase is field trials (equivalent to small contained trials in the United States) followed by environmental release trials (known as "farmer field trials" in the United States) (Huang et al., 2005). The biotech seed developer needs to provide data and report to the Ministry of Agriculture and Rural Affairs (MARA)[9] for approval to proceed to the next phase. The third phase is pre-production trials on an area larger than two hectares and smaller than 66.7 hectares (MoA, 2005). Farmers receive the seeds and scientists do not influence the cultivation except to periodically monitor it (Huang et al., 2008). Imported GM crops are used as processing materials, not for cultivation; therefore, they do not need to undergo the last phase in China.

In parallel with this three-phase process, research institutions or universities assigned by the MARA conduct food safety tests. The tests evaluate the nutritional and toxicological properties of GM crops and their sensitization and antibiotic resistance. Foreign applicants for GM biosafety certificates need to provide reports about prior research and testing conducted in their own countries (Kim, 2016). They also need to provide documents that the exporting country or other countries have allowed commercialization of the GM product for the same intended use as that applied for in China. The biotech seed developer (domestic or foreign) has to submit a report including all the test results to the MARA for the biosafety certificate, and the MARA makes the final decision within 270 days (Kim, 2016).

After the MARA has issued the biosafety certificates, the domestic GM seed developers need to register new seed varieties for cultivation either at the national or

[9] It used to be called the "Ministry of Agriculture" (MoA). At the beginning of 2018, the MoA was reshuffled as the Ministry of Agriculture and Rural Affairs (MARA). The difference is mainly the integration of the section of agricultural investment and management from previously different ministries, such as the Ministry of Finance, the Ministry of Land and Resources, etc.; detailed differences before and after the reshuffle is available at: http://www.npc.gov.cn/npc/xinwen/2018-03/18/content_2050371.htm (in Chinese). However, the role of the MARA in regulating GMOs did not change significantly from the role of the MoA.

provincial agricultural department according to the *Seed Law* of 2000[10] and 2015[11] (foreign exporters for food, feed, or processing materials with existing biosafety certificates are free from this duty). The registration includes further testing and field trials, some of which are similar to the tests for biosafety certificates (Anderson-Sprecher & Jie, 2014). Finally, the domestic GM crop developer needs to apply for production and marketing licenses from a relevant agricultural administrative department of the State Council (Kim, 2016). Once the biotech seed developer successfully registers a seed variety at the national level, the commercialization of GM crops in each province is automatically permitted.

The GM crop–approval process in China involves several governmental departments and committees. Below, we briefly describe their roles.

The MARA is responsible for agriculture and rural development and is the primary department in charge of the approval process for domestic and imported GM crops. Biotech seed developers apply for GM biosafety certificates at the MARA's Administrative Examination and Approval Office (AEAO), which accepts applications and gives feedback to applicants. The MARA's Agricultural GMO Biosafety Management Office (ABMO) prepares recommendations on the issuance of biosafety certificates based on technical assessment of the National Agricultural GMO Biosafety Committee (NABC). Socio-economic and political factors are also taken into consideration, but it is not clear to what extent (MoA, 2015). The MARA makes the final decisions on issuing biosafety certificates and registering seed variety.

The seed variety registration of a GM crop allows its domestic cultivation (Anderson-Sprecher & Jie, 2015). During the approval process, the MARA asks accredited domestic institutions to verify data provided by seed developers by, for example, conducting field trials (Anderson-Sprecher & Jie, 2014). At the provincial level, the MARA monitors the field trials of GM crops. The MARA also distributes governmental funds for research and development (R&D) in biotech crops and for other innovations from Chinese institutes and universities (Gilmour et al., 2015).

The NABC conducts biosafety assessments for the MARA. The MARA nominates scientists and experts from various disciplines as NABC members (Huang & Wang,

[10] Available at: http://english1.english.gov.cn/laws/2005-09/08/content_30273.htm
[11] Available at:
https://gain.fas.usda.gov/Recent%20GAIN%20Publications/China%20Amends%20Seed%20Law%20to%20Develop%20Seed%20Industry_Beijing_China%20-%20Peoples%20Republic%20of_12-1-2015.pdf

2002). They meet twice a year to evaluate the applications for biosafety certificates. In 2010, the NABC developed a guideline[12] for both environmental and food safety areas to streamline the approval process in China (Anderson-Sprecher & Jie, 2014).

Applicants for seed variety registration can choose either to apply for the national or provincial registration.[13] Established by the MARA, the National Crop Variety Registration Committee (CVRC) oversees the national crop variety registration. CVRC members include experts in research, production, marketing, and management. Provincial crop variety registration committees are established by the provincial agricultural administrative departments.

In Figure 1, we graphically summarize the approval process for GM crops in China. Appendix 1 provides a detailed description of the different regulatory documents addressing the process of obtaining biosafety certificates and licenses.

[12] Available at: http://www.moa.gov.cn/ztzl/zjyqwgz/sbzn/201202/P020120203390882017249.pdf

[13] There is no advantage in approval time when applying at the provincial level. If the variety is suitable for a specific ecological zone, the new variety goes to the provincial level; if the variety is suitable for a variety of ecological zones, the new variety goes to the national level. Where to apply depends on the traits of the new GM variety. The approval time does not differ much between the provincial and national levels (personal communication with companies).

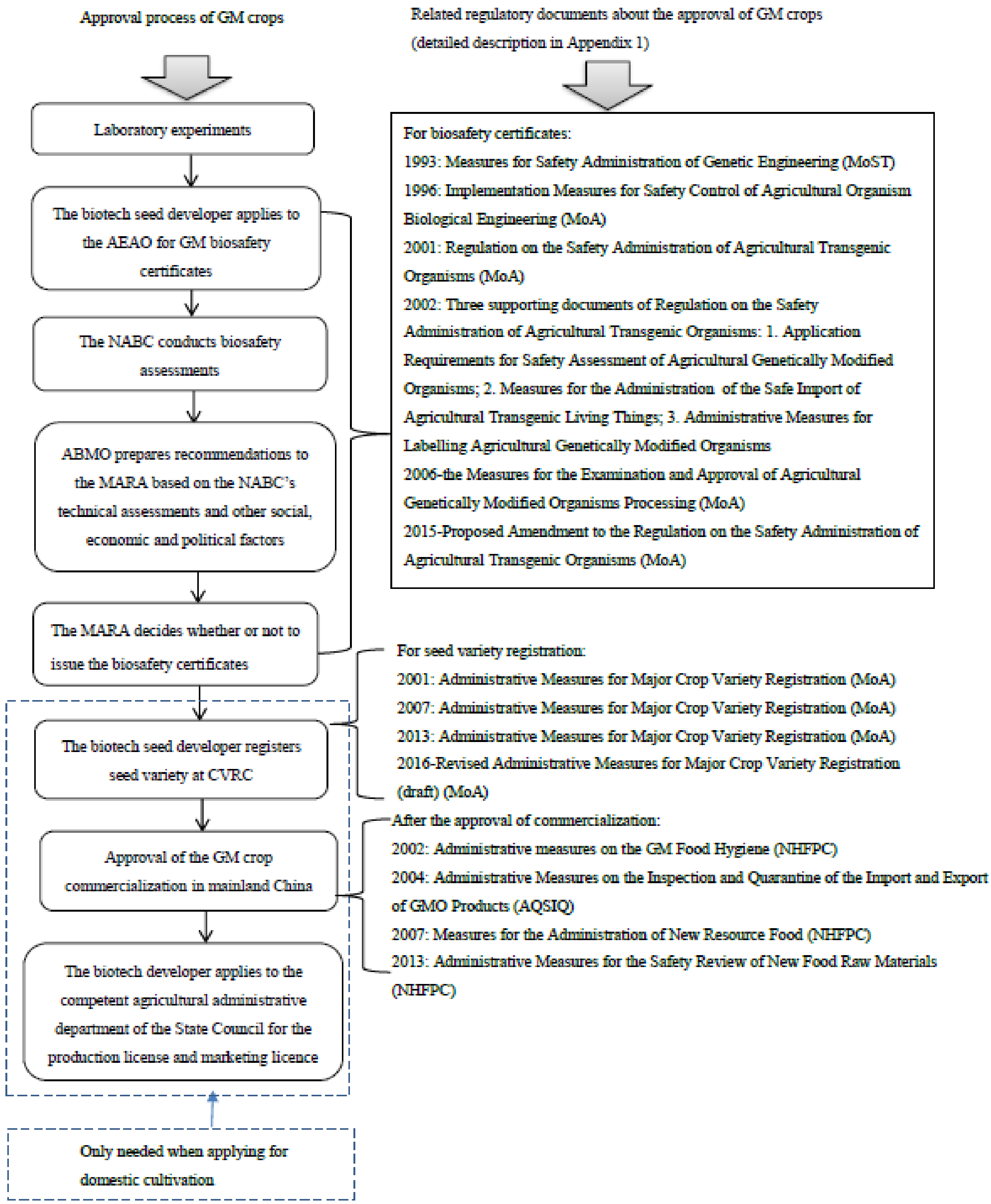

Figure 1. Schematic representation of approval process for GM crops in China

In early 2018, the MoA was reshuffled into the MARA. The reshuffle integrated agricultural investment and management from previously different ministries[14] and therefore expanded the power of the MARA in agricultural management. For example, before the reshuffle, the MoA made the budget on agricultural investment and was reimbursed by the Ministry of Finance; after the reshuffle, the MARA could manage the budget and appropriation more efficiently.

The reshuffle of the MARA did not significantly change its role in regulating GMOs; it is important to mention that, three months after the reshuffle, the MARA released an official report[15] answering a question from a deputy of the National People's Congress about the safety of GMOs. The report confirmed the safety of commercialized GMOs to the public and emphasized the important role of the MARA, local government, and mainstream media in public education on GMOs. Although the MARA mentioned the general public education in 2015, its report was the first official one stating in detail how to increase the public knowledge of GMOs (MoA, 2016). It was a strong indicator of GMO support from the newly reshuffled MARA. Together with more power in finance, land location, and agricultural management, the MARA might play a promoting role in the approval of GM crops in the long run.

The complex approval process contributes to the relatively long approval time and relatively late approval date. In Section 3, we examine the factors affecting the approval process and interpret the trend of approval time for imported GM crops in China between 2002 and 2017.

3.3 The Approval Time of Imported GM Crops in China

We use data from the period 2002 to 2017 to investigate changes in approval time for imported GM crops in China and how crop characteristics and external factors influence it. We include all imported GM crops as reported by the MARA.[16] The approval time is the span (in months) from filing the application form until the biosafety certificate is

[14] The following sections were integrated into the MARA in early 2018: the agricultural investment section from the National Development and Reform Commission, the agricultural development section from the Ministry of Finance, and the section of construction of farmland and water conservancy from the Ministry of Water Resources. The section of fishing boat inspection and its supervision was separated from the MARA after the reshuffle.

[15] Available at: http://www.moa.gov.cn/govpublic/KJJYS/201807/t20180713_6154028.htm

[16] Available at: http://www.moa.gov.cn/ztzl/zjyqwgz/spxx/index.htm

issued. We do not include domestic GM crops because the application dates are not publicly available.[17] For non-GM crops, biosafety certificates are not required before entering the Chinese market. The approval time of obtaining biosafety certificates can be considered the extra time needed by imported GM crops in comparison to non-GM crops.

Figure 2, which is based on Figure 1, highlights the timeline of the approval process for imported GM crops (Huang et al., 2008; MoA, 2015). To apply for the biosafety certificate, the biotech seed developer has to submit an application form to the MARA. After the MARA allows imports of the GM crops for further testing, the GM crops have to go through the environmental release trial and food safety tests. The MARA appoints an independent scientific institute or university to perform these tests. The choice of the institution is based on specialization, location, and availability. The periods of the environmental release trials and food safety tests differ a lot among different GM crops and their varieties. The biotech seed developer has to submit a report including the results of both the environmental release trials and the food safety tests to the MARA for a final decision.[18] The approval process ends when the biosafety certificate is issued.

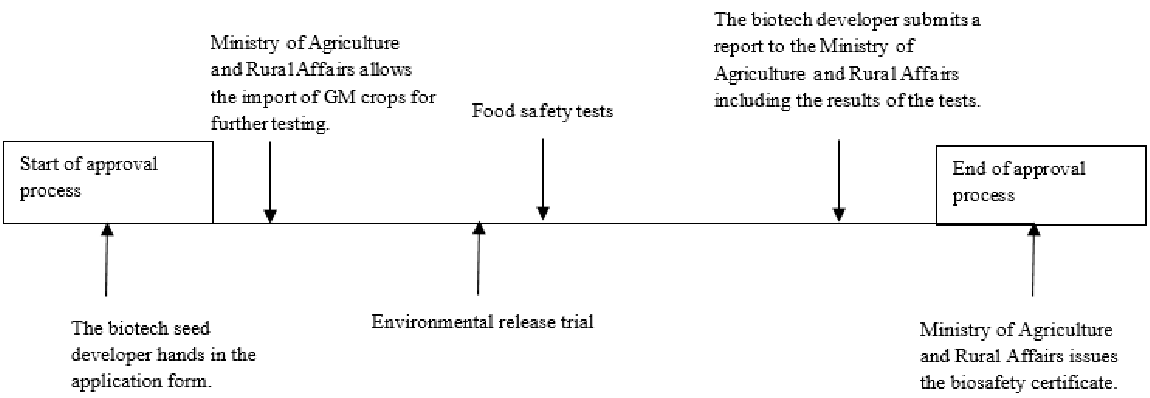

Figure 2. Timeline of approval process for imported GM crops in China

The data we use come from the official website of the MARA[19] and personal communication with two biotech seed developing companies. Based on these data, we use an ordinary least-squares regression to test to what extent crop characteristics and

[17] Please refer to footnote 4.

[18] However, for imported GM crops for cultivation (the only one in China is imported GM cotton), they do not need to go through the environmental release trial in China again (MoA, 2017).

[19] Available at: http://www.moa.gov.cn/ztzl/zjyqwgz/spxx/

other factors affect the approval time and to investigate the trend of approval times between 2002 and 2017. For half the imported GM crop varieties (25 varieties), we obtain the exact dates of application either by personal communication with the companies (21 varieties) or from official documents published by the MARA (4 varieties).[20] The exact dates of application for the remaining half of the varieties are not available, only the years in which the applications were made.[21] In those cases, we assume that July is the starting month. We also perform a sensitivity analysis by randomly choosing a month for these observations (see Appendix 4).[22] We assume that the biotech seed developers are well-informed and rational in choosing the dates of their applications because the members of the biosafety committee meet twice a year (in April and November) to decide whether to issue biosafety certificates and, therefore, unnecessary waiting time could occur if the biotech seed developer submits the application form right after a committee meeting.

Table 1 presents summary statistics for 50 imported GM crop varieties (five crops: canola, cotton, maize, soybeans, and sugar beets) that passed the approval process in China. The average approval time for an imported GM crop variety is 34.3 months. Since 2002, the maximum time for the approval process has been 71 months (MIR162 maize), and the minimum time has been 18 months (MIR604 maize).

[20] Available at: http://www.moa.gov.cn/ztzl/zjyqwgz/spxx/

[21] We tried contacting the remaining companies, but, unfortunately, they were not willing to share the information.

[22] We use Microsoft Excel's functionality RANDBETWEEN (1,12) to do the random selection.

Table 1. Approval time of imported GM crops[23]

Category	Sub-category	No. of variety	No. of months		
			Average	Min	Max
Total		50	34.3	18	71
Year	Before 2010	27	27	18	40
	After 2010	23	43	19	71
Trait type	Insect resistance only	10	34	18	71
	Herbicide tolerance only	23	35	19	68
	Combination or other traits	17	34	23	68
Crop	Canola	7	26	24	32
	Cotton	9	27	21	35
	Maize	19	38	18	71
	Soybean	14	39	19	68
	Sugar beet	1	38	38	38
Company	Company 1	21	34	23	68
	Company 2	14	29	21	58
	Company 3	8	42	18	71
	Other companies[24]	7	37	19	67
No. of traits	Single	37	35	18	71
	Multiple[25]	13	33	23	68

[23] The authors' calculations are based on reports from the MoA.
[24] We anonymize the company names due to request and use numbers to distinguish different large companies. "Company 1" represents the company with the largest market share, and subsequent companies ("Company 2", "Company 3", etc.) have decreasing levels of market share. "Other companies" represents other small companies all together (each company might only have one variety, so we group them together).
[25] It is interesting to see that the approval time for single-trait GM crops is, on average, two months longer than the approval time for multiple-trait GM crops. The potential reason might be that, in our dataset, the approval time for several single-trait GM crops is extremely long, such as DAS-40278-9 maize (67 months), MON 87705 soybean (68 months), and MIR 162 maize (71 months).

The scatter plot of the application dates and the approval times shown in Figure 3 suggests that the approval times have considerably increased since ca. 2010. A t-test for the data set with information on the dates of applications (25 varieties) shows that the approval process of imported GM crops approved after 2010 needed significantly more time than those approved before 2010. Potential reasons for the increased approval time include increasing public concerns after the MARA issued biosafety certificates for Bt rice in 2009. Chinese consumers were initially willing to pay a premium for GM foods, such as GM rice or cooking oil from GM soybeans, because they trusted the government in securing food safety (Li et al., 2003) and held positive attitudes toward science in general (Curtis et al., 2004) as well as toward government-controlled media (Frewer et al., 1998). However, consumer preferences in China for GM foods have changed since ca. 2010. A survey held in 2010 of 4,239 people with various backgrounds in 30 provinces (and municipalities[26]) found that over 55 percent of the interviewees believed that human health and the environment would be harmed by GM crops (Qu et al., 2011). It shows that after the MARA issued the biosafety certificates for Bt rice in 2009, the government-controlled process of GM crop–approval came under increased public pressure. Another potential explanation of the observed change in approval times is the change of the head of the MoA in December 2009. The Minister of Agriculture, who had a background in plant breeding and was supportive of GMO crops, was replaced by a less supportive minister with a background in law.

[26] China has four municipalities that are governed directly by the central government: Shanghai, Beijing, Tianjin, and Chongqing.

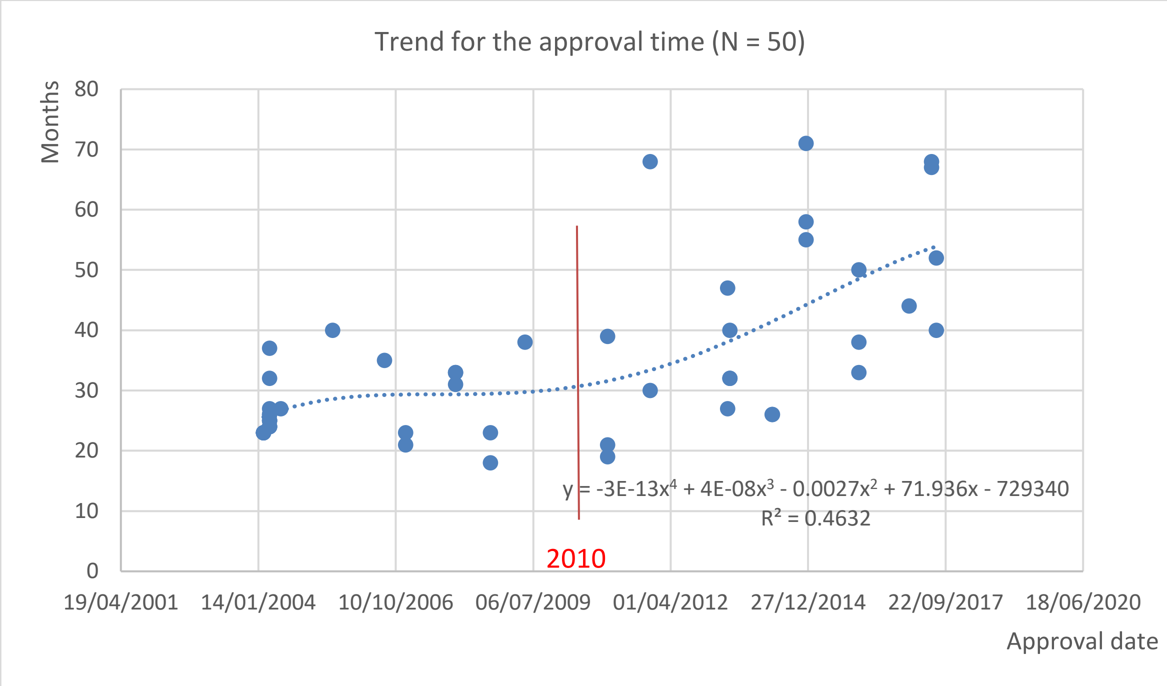

Figure 3. Time trend for approval length of imported GM crops in China between 2003 and 2017 (N=50)[27]

Note: Data from the Chinese Ministry of Agriculture and Rural Affairs. The data were fitted using a fourth-order polynomial function for better fit (R^2=0.4632).

3.3.1 Factors Affecting Approval Time

Following Smart et al. (2016), we use an ordinary least-squares regression to test to what extent crop characteristics and other factors affect approval times. Based on the literature (e.g., Pray et al., 2005; Bradford et al., 2005; Giddings et al., 2013; Smart et al., 2016), we expect a decreasing trend in approval times in China due to the learning effect from previous applications. Smart et al. (2016) suggested that there could be significant differences between different trait types, multiple traits needing more time than a single trait. We expect imported GM cotton might need the shortest approval time because it does not need to undergo field trials in China, as the cultivation of domestic GM cotton has already been approved in China (personal communication with companies). Large companies with big market shares might experience shorter approval times because of the learning effect from previous application experiences.

We specify the model as follows:

[27] The scatter gram for 25 observations with information on the month of application is shown in Appendix 2. A similar upward trend since ca. 2010 can be observed from the graph.

$$AT = c_0 + c_1BA + \sum_{i=1}^{2} c_{2i}TT_i + \sum_{j=1}^{4} c_{3j}CT_j + \sum_{m=1}^{3} c_{4m}COM_m + c_5NR + \varepsilon\ , \qquad (1)$$

where *AT* is the approval time in months, *BA* denotes the period in which a GM crop obtained the biosafety certificate (*BA* = 1 after 2010 and 0 before 2010), TT_i denotes trait type (the reference is insecticide resistance only), CT_j denotes crop type (the reference is cotton), COM_m denotes company (the reference is Company 1), *NR* denotes the number of trait combinations (the reference is single-trait crops), c_0, c_1, c_{2i}, c_{3j}, c_{4m}, and c_5 are unknown parameters, and ε is the error term with standard properties. All explanatory variables are dummy variables that equal 1 if a variable has a given property and 0 otherwise.

Table 2 presents the estimated results. We estimate six models to see if and how the inclusion of additional dummy variables (one by one) influences the approval times for imported GM crops in China. We find that after 2010, it took, on average, between 15 and 16 months longer to approve an imported GM crop than in the period before 2010. This result is robust across all model specifications.

Other factors specified in Table 2 do not significantly influence approval times. The only exception is maize in models 5 and 6, whose approval time has been around 10–11 months longer than that of cotton. The reason might be that the approval of maize is not urgent, since China has relatively sufficient in maize production and a sizable maize stock. China imports GM maize partly to meet its World Trade Organization (WTO) tariff quotas (personal communication with companies). The results in models 2, 3, and 4 do not indicate any significant difference between crop traits, number of traits, or companies in influencing approval times. The result of model 3 differs from the results of Smart et al. (2016) for the Unites States and the European Union. Smart et al. (2016) showed that the approval of single-trait GM crops requires 15–22 percent less time than the approval of multiple traits, while in our model, there is no statistically significant difference. The difference might occur due to the country difference in crop-trait combination. The result in model 2 for China confirms the results of Smart et al. (2016) for the United States and the European Union that there is no evidence for statistically significant differences between trait types.

Table 2. Factors related to the approval time (dependent variable) for imported GM crops in China, 2002-2017

Category		1	2	3	4	5	6
Year	Before 2010	reference	reference	reference	reference	reference	reference
	After 2010	15.63***	15.96***	15.58***	14.79***	16.18***	16.66***
		(3.28)	(3.36)	(3.33)	(3.41)	(3.70)	(3.97)
Trait type	Insect resistance		reference				reference
	Herbicide tolerance		2.19				6.50
			(4.46)				(5.18)
	Combination or other traits		-0.51				1.28
			(4.68)				(5.05)
Crop	Canola					6.13	7.40
						(5.88)	(6.40)
	Cotton					reference	reference
	Maize					11.13**	9.54*
						(4.54)	(5.16)
	Soybean					6.49	5.48
						(4.95)	(5.51)
	Sugar beet					18.41	14.33
						(11.93)	(12.54)
Company	Company 1				reference		reference
	Company 2				-4.17		-3.65
					(3.98)		(4.93)
	Company 3				5.10		5.80
					(4.86)		(5.53)
	Other companies				-1.31		-2.53
					(5.16)		(5.41)
No. of traits	Single			reference			
	Multiple			-0.59			
				(3.78)			
	Constant	27.11***	26.12***	27.28***	28.03***	19.59***	17.18***
		(2.23)	(4.08)	(2.51)	(2.83)	(4.08)	(5.38)
	Observations	50	50	50	50	50	50
	R-squared	0.32	0.33	0.32	0.37	0.42	0.46

Note: Standard errors in parentheses. ***, **, * indicate statistical significance at 1, 5, and 10 percent levels.

3.3.2 Comparison of Approval Dates and Approval Lengths in Different Countries

For a globally comparative view of the GM crop–approval statute in China, we further investigate and compare the differences in approval dates and approval lengths for the same GM varieties in different countries. Of all the imported GM crop varieties that have been approved in China, 46 have also been approved in the United States, 47 have been approved in Canada, and 32 have been approved in the European Union (for which we have the data, that is). Chinese regulations mandate that biotech seed developers are allowed to apply for biosafety certificates in China only when a GM crop has been approved in the country of origin for the same use. The regulation causes asynchronous approval, which means that due to the country-specific approval process, the approval of new GM varieties does not happen simultaneously worldwide. The asynchronous approval of GM crops may have significant negative trade impacts (Faria & Wieck, 2015).

As shown in Figure 4, for the same GM varieties approved in both China and the United States, approval in China on average lags 1,544 days (4.2 years) behind the United States. However, the rule has its exceptions: China approved soybean CV127 286 days earlier and sugar beet H7-1 a full 1,170 days earlier than the United States.[28] The suspension of sugar beet H7-1 in the United States occurred after its original approval because an environmental impact statement from biotech developers was required (Smart et al., 2016); the approval process for sugar beet H7-1 can be considered skewed by the subsequent lawsuit. Apart from these two exceptions, GM canola has the shortest average time lag of 1,236 days (3.4 years), and GM cotton has the longest average time lag of 1,821 days (5.0 years). For the same GM varieties approved in both China and Canada, approval in China on average lags 1,783 days (4.9 years) behind. GM cotton has the shortest time lag of 1,404 days (3.8 years) on average, and GM canola has the longest time lag of 3,010 days (8.2 years) on average. For the same GM varieties approved in both China and the European Union, approval in the European Union on average lags 360 days (1 year) behind. GM cotton in the European Union has the longest average time lag of 1,422 days (3.9 years). It is interesting to see that, although the European Union's approval generally lags behind China's, the European Union approved one variety of sugar beet 561 days (1.5 years) earlier than

[28] Please refer to Table 3 in Appendix 3 for more detailed information.

China, and it approves GM soybeans, on average, 60 days earlier. The reason is not clear and needs further research.

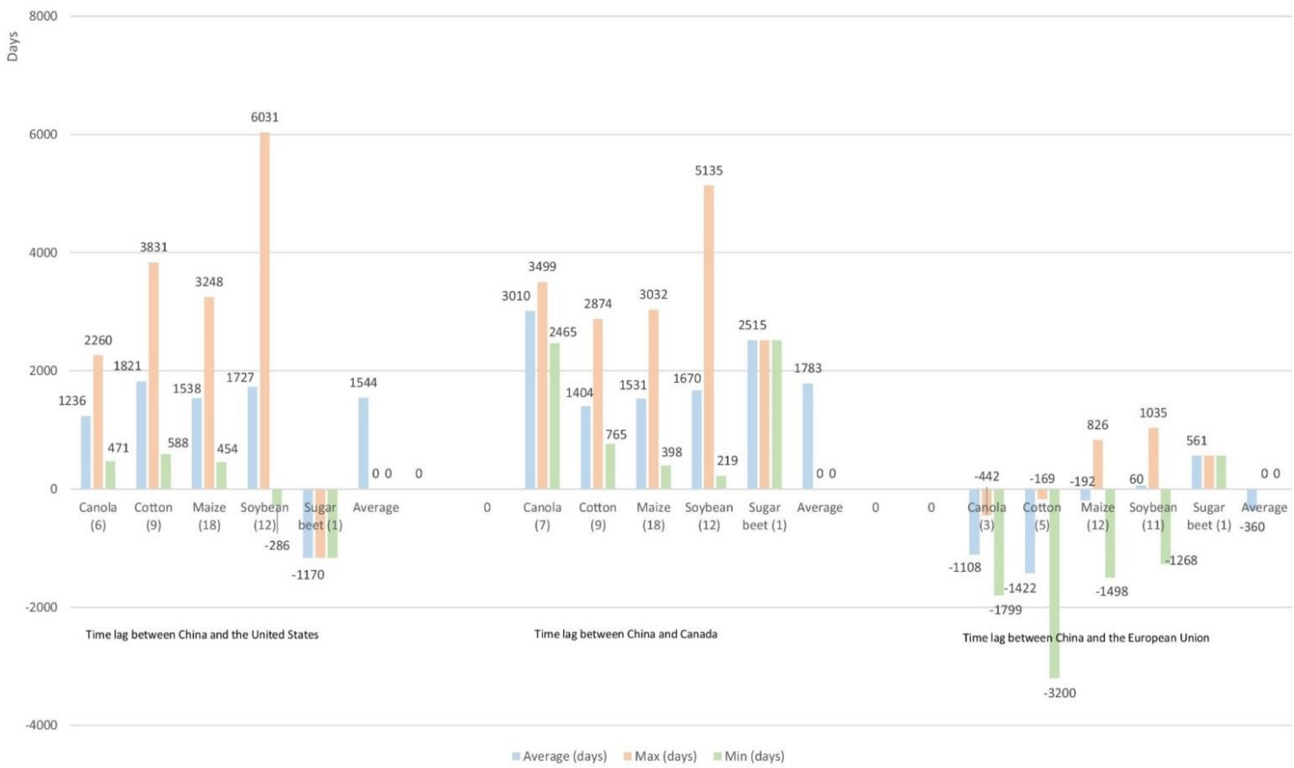

Figure 4. Comparison of GM crop–approval dates in China versus the United States, Canada, and the European Union

Note: Data from the MARA, the US Department of Agriculture, the Government of Canada, and Smart et al. (2017). A positive (negative) time lag indicates how many days later (earlier) China approved a GM variety compared to the other country. The number of GM crop varieties is in parentheses. Total numbers of varieties are different because 46 varieties passed the approval processes in both China and the United States, 47 in both China and Canada, and 32 in both China and the European Union.

We compare the approval length of 19 varieties (due to data limitation) that were approved in China, the United States, and the European Union. The approval length in China is, on average, 1,044 days (2.9 years); the approval length in the United States is, on average, 2,150 days (5.9 years); and the approval length in the European Union is, on average, 1,760 days (4.8 years).

Comparing all the varieties approved in China, Canada, the United States, and the European Union, China certainly did not enter the market as a first mover in the area of GM technology. China approves GM crops, on average, around one year earlier than the European Union but more than four years later than the United States and Canada. However, once China enters the market, its approval length is relatively short based on the dataset. Compared to other countries, the average approval length in China is 3 years shorter than that in the United States and 1.9 years shorter than that in the European Union. However, further research with more approved varieties in China are needed to confirm these results. The current situation of GM technology in China is relevant to the future of New Plant Breeding Techniques (NPBTs), which might see a similar approval process and have similar trade impacts for potential commercialization.

3.4 Conclusions

China has a complex regulatory system involving various departments and a host of regulatory documents for approving domestic and imported GM crops. The approval of GM crops for import as processing materials in China starts with an application to the MARA, is followed by domestic environmental release trials and food safety tests, and ends with the issuance of biosafety certificates. The complex approval process contributes to relatively long approval times and relatively late approval dates. Trends of approval time for imported GM crops from 2002 to 2017 are investigated as well as the factors affecting approval to better understand its complex underlying process. The results show that the average time to obtain approvals for imported GM crops to China increased on average by around 16 months after ca. 2010. This trend contrasts with that in the European Union, which is decreasing (Smart et al., 2016). The results also show that maize takes significantly more approval time than other crops, but other crop characteristics of imported GM crops do not significantly affect their approval times.

Worldwide, we compare the approval dates and approval times of GM varieties approved in China, the United States, Canada, and the European Union. China approves GM crops, on average, around one year earlier than the European Union but lags, on average, 4.2 years behind the United States and 4.9 years behind Canada. The mean approval time for imported GM crops in China is 3 years shorter than that in the United States and 1.9 years shorter than that in the European Union. The differences in the approval dates and approval times result from the different approval processes in the different countries.

Research has shown that slow approval processes hamper the commercialization of new GM crops, and the largest potential constraint of commercialization is regulatory delay (Kalaitzandonakes et al., 2007; Bayer et al., 2010). China, as many other countries, experiences this delay, most particularly since 2010 when biosafety certificates for GM rice were issued by the MARA. Because increasing national food security and improving agricultural productivity are major agricultural policy goals, the Chinese government has started to take action again in policy support since 2016. The "13th Five-Year Plan for Science and Technology Innovation"[29] aims to promote the commercialization of new domestic GM crops by 2020 (MoA, 2016). In the same year, the MARA revealed a roadmap for commercializing GM crops, starting with cash crops "not for food use" (e.g., cotton), followed by crops used as input for feed and industrial use (e.g., maize), and finally by staple food crops (e.g., rice).

Although more than 10 million tons of GM soybean oil have been sold with compulsory GM labelling each year in China since the early 2000s (Huang et al., 2017), most Chinese agri-business managers still oppose GM food adoption because they expect lower profits (Deng et al., 2017), and Chinese scientists do not have higher acceptance of GM food (Huang et al., 2017) than non-scientists. There still seems a long way to go in improving public acceptance for GM crop in addition to the long and costly regulatory approval process. The No. 1 Central Document of 2015, which is the most important guideline document in China, mentioned that the Chinese government wanted to emphasize, not only on research of agricultural GMOs and their safety management, but also general public education about GMOs (MoA, 2015). In July 2018, the MARA released a report detailing how to increase public knowledge of GMOs to promote their commercialization. The strategy included closer cooperation between local governments and mainstream media.

The consequences of this policy strategy for promoting commercialization and increasing public knowledge for the GM approval process are not yet known. A direct positive impact on approval length at first glance might not exist because the same main governmental agencies are involved in the approval process. At second glance, the overall policy climate toward GMOs might be positively affected, with an overall positive effect on the approval process (Smart et al., 2016; Wesseler & Zilberman, 2017). The potential change in the trend will be of great interest to those working with genome-editing technologies in plant breeding for more accurate expectations (Purnhagen et al., 2018; Pray et al., 2018), as the current expectations are generally that genome-editing will be accepted by the public more easily (Gao et al., 2018).

[29] Available at: http://www.gov.cn/zhengce/content/2016-08/08/content_5098072.htm

Possibilities for accelerating the Chinese approval process include immediate approval for the import and processing of GMOs that have received approval in their countries of origin. Although the issue is controversial, this may substantially reduce trade disruptions caused by asynchronous approval and increase the comparative advantage of food production in China.

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3.6 Appendix

3.6.1 Review on Regulatory Documents in Biosafety Regulation in China

In 1993, the Chinese Ministry of Science and Technology (MoST) issued the first biosafety regulation, which was entitled *Measures for Safety Administration of Genetic Engineering*.[30] The regulation targeted all genetic engineering work then underway and was the starting point of GMO regulation in China. It was very general and focused on how a domestic institution should apply for laboratory experiments of GMOs and conduct genetic engineering work. It included general principles, safety classes and safety evaluations, application and approval of applying for and conducting genetic engineering work, safety control measures, and legal responsibilities.[31] However, it did not include issues related to trade regulations and labelling systems (Huang et al., 2012).

In 1996, the MoA[32] issued the *Implementation Measures for Safety Control of Agricultural Organism Biological Engineering*, which targeted the safety assessment and management of GMO research trials. The purpose of this document was to set timely, transparent, and science-based regulation procedures for agricultural biotech products. It detailed biosafety regulation procedures for each stage of GMO development (Huang & Yang, 2011; Huang et al., 2012). The safety regulation followed a case-by-case procedure and covered plants, animals, and microorganisms (Huang et al., 2008; Huang et al., 2012). Similar to the 1993 version of *Measures for Safety Administration of Genetic Engineering*, it did not concern trade regulations and labelling systems (Huang et al., 2012).

In 2001, the MoA decreed the amended *Regulation on the Safety Administration of Agricultural Transgenic Organisms*[33] to replace the 1996 version of the document. In comparison to 1996, the 2001 version included trade regulation and a labelling

[30] Available at: http://www.google.nl/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKEwiQ4riH_OzTAhVKcBoKHUmfBtoQFggjMAA&url=http%3A%2F%2Fextwprlegs1.fao.org%2Fdocs%2Ftexts%2Fchn19138.doc&usg=AFQjCNHWn9XdmvCJ8Nemqok4R0mwIVMZ2A&sig2=G7vcvVPD-dQnvKeRUoI6ew

[31] Available at: http://www.google.nl/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKEwiQ4riH_OzTAhVKcBoKHUmfBtoQFggjMAA&url=http%3A%2F%2Fextwprlegs1.fao.org%2Fdocs%2Ftexts%2Fchn19138.doc&usg=AFQjCNHWn9XdmvCJ8Nemqok4R0mwIVMZ2A&sig2=G7vcvVPD-dQnvKeRUoI6ew

[32] At the beginning of 2018, the Ministry of Agriculture (MoA) was reshuffled into the Ministry of Agriculture and Rural Affairs (MARA).

[33] Available at: http://english.biosafety.gov.cn/image20010518/5421.pdf

system of GM food products (Huang & Yang, 2011; Huang et al., 2012). It specified the requirements for GMO safety assessment, import safety approval of GMOs, and labelling, production, and marketing permits. Likely reasons for the revision and amendment of the document might have been rising public concerns and the need to import GM products due to rapid development. Since June 2001, both domestic and imported GM products have needed safety certificates from the MoA to ensure food safety for human consumption, animals, and the environment. Three supporting documents[34] of the amended *Regulation on the Safety Administration of Agricultural Transgenic Organisms* were released in 2002, which are mentioned in Figure 1.

The amended *Regulation on the Safety Administration of Agricultural Transgenic Organisms* was the first regulation about GMO labelling in China. China implemented a mandatory labelling system for a list of GM foods published on the MoA website, including soybeans, maize, canola, cotton, tomatoes, and products derived from them. The regulations targeted not only the final products but also the GM technology as a production process. The mandatory labelling system required food companies, including processors, retailers, and food producers, to show clearly whether the targeted product or ingredient contained or was derived from genetically engineered materials (Gruere & Rao, 2007; Wong & Chan, 2016; MoA, 2017), such as "soybean oil – transgenic soybean as raw material." When the GM ingredient was no longer detectable in the final processed product, a statement was required on the product that it was made from transgenic raw materials but no longer contained the GM ingredient in the final product (MoA, 2017).

In 2006, the MoA released *Measures for the Examination and Approval of Agricultural Genetically Modified Organisms Processing.*[35] The document regulated the production of agricultural GM products that used GMOs as raw materials. Individuals or entities who would like to process agricultural GMOs in China needed to apply for a processing license issued by a provincial agriculture department of the government.

In 2015, the MoA released *Proposed Amendment to the Implementation Regulations on Safety Assessment of Agricultural Genetically Modified Organisms.*[36]

[34] Available at: https://bch.cbd.int/mainstreaming/china-desk%20study.pdf
[35] Available at: http://www.asianlii.org/cn/legis/cen/laws/moteaafagmop912/
[36] Available at: https://gain.fas.usda.gov/Recent%20GAIN%20Publications/Amendment%20of%20the%20Ag%20GM

Compared to the 2001 version, in which the MoA was supposed to decide within three months after the application deadline, the amendment provided the MoA more flexibility by removing timelines for approvals. The amendment also considered economic and social elements, such as public opinions. The MoA plans to increase public involvement in the approval process by creating a procedure for collecting public opinions on agricultural biotechnology applications (Anderson-Sprecher & Jie, 2015).

After getting a biosafety certificate, a biotech seed developer of GM crops needs to continue applying for a seed variety certificate. Compared to the 2001 and 2007 versions, the 2013 edition of the *Measures for Major Crops Variety Registration*[37] first mentioned that the variety trials included three kinds of tests: regional tests, production tests, and tests for distinctness, uniformity, and stability (DUS). The DUS testing is conducted at the MoA New Plant Variety Test Center. The 2013 edition also included standard rules for withdrawing the seed varieties from the market if they were not successful (Anderson-Sprecher & Jie, 2014).

The 2013 version of the *Measures for Major Crops Variety Registration* also contained two important changes compared to the former editions. First, the new version streamlined and simplified the cumbersome process of seed variety registration into two scenarios. In the first scenario, when an integrated company owns the registered capital of more than 100 million RMB (Chinese currency), it is allowed to conduct its own testing for its self-owned varieties. In the second scenario, if the seed varieties already have provincial approval and more than two years of testing data from many locations, then it is not necessary to repeat regional and production testing when applying for approval at the national level. The second important change was that seed companies with business in breeding, production, and marketing that were certificated by the MoA could individually conduct regional and production testing for their own variety registration (Anderson-Sprecher & Jie, 2014).

In February 2016, the MoA released the revised *Administrative Measures for Major Crops Variety Registration* (draft)[38] and collected comments in the following

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O%20Safety%20Assessment%20Regulations%20_Beijing_China%20-%20Peoples%20Republic%20of_6-26-2015.pdf

[37] Available at: https://gain.fas.usda.gov/Recent%20GAIN%20Publications/Draft%20Measures%20for%20Major%20Crops%20Variety%20Registration_Beijing_China%20-%20Peoples%20Republic%20of_3-12-2013.pdf

[38] Available at: https://gain.fas.usda.gov/Recent%20GAIN%20Publications/China%20Revised%20Crop%20Variety%20Registration%20Measure_Beijing_China%20-%20Peoples%20Republic%20of_2-24-2016.pdf

months. The new draft complied with the new *Seed Law* (the 2015 version)[39] and made two important modifications to the previous version. First, crops requiring variety registration were reduced to rice, wheat, corn, cotton, and soybeans (leaving out rapeseeds and potato seeds). Second, a seed variety registered in one province could be introduced to other provinces within the same ecological region without having to go through the seed variety registration system again (Zhang, 2016).

In general, after a GM crop is approved for commercialization, the *Administrative Measures for the Safety Review of New Food Raw Materials*[40] will apply to it for the examination of hygiene from the National Health and Family Planning Commission.[41] The Ministry of Environmental Protection[42] will start to monitor domestic GM crops with respect to the environment. For imported GM crops, the General Administration of Quality Supervision, Inspection, and Quarantine[43] will start to administer the approval of imported GM crops inspection and quarantine at the port.

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[39] Available at: https://gain.fas.usda.gov/Recent%20GAIN%20Publications/China%20Amends%20Seed%20Law%20to%20Develop%20Seed%20Industry_Beijing_China%20-%20Peoples%20Republic%20of_12-1-2015.pdf

[40] Available at: http://www.pkulaw.cn/fulltext_form.aspx?Db=chl&Gid=206623

[41] The National Health and Family Planning Commission has not existed since early 2018, and its duties were taken over by the National Health and Wellness Committee. No updated regulatory document is available so far.

[42] The Ministry of Environmental Protection has not existed since early 2018, and its duties were taken over by the Ministry of Ecology and Environment. No updated regulatory document is available so far.

[43] The General Administration of Quality Supervision, Inspection, and Quarantine has not existed since early 2018, and its duties were taken over by the National Administration of Market Supervision and Management. No updated regulatory document is available so far.

3.6.2 Trend for the Approval Time (months) of Imported GM Crops

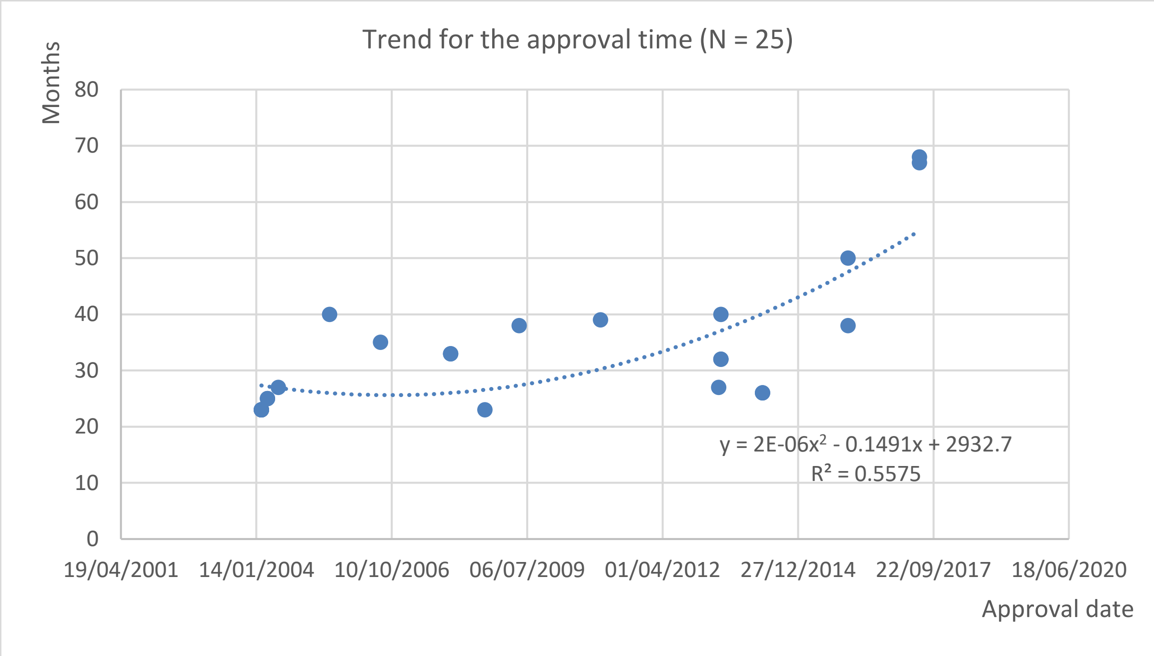

Figure 5. Time trend for approval length of imported GM crops in China between 2003 and 2017 (N=25)

3.6.3 Comparison of GM Crops – Approval Dates in China, the United States, Canada, and the European Union

Table 3. Comparison of GM crop–approval dates (in days) in China, the United States, and Canada [44]

China & the USA	**Average (days)**	**Max (days)**		**Min (days)**	
Canola (6)	1236	2260	T45 canola	471	Topas19/2(HCN92) canola, Ms1Rf1, and Ms1Rf2 canola
Cotton (9)	1821	3831	COT102 cotton	588	GHB614 cotton
Maize (18)	1538	3248	Bt176 maize	454	59122 maize
Soybean (12)	1727	6031	A5547-127 soybean	-286	CV127 soybean
Sugar beet (1)	-1170	-1170	H7-1 sugar beet	-1170	H7-1 sugar beet
Average	1544				
China & Canada	**Average (days)**	**Max (days)**		**Min (days)**	
Canola (7)	3010	3499	Ms1Rf1 canola	2465	Oxy-235 canola
Cotton (9)	1404	2874	MON 531 cotton	765	MON88913 cotton
Maize (18)	1531	3032	Bt176 maize	398	59122 maize
Soybean (12)	1670	5135	A5547-127 soybean	219	CV127 soybean
Sugar beet (1)	2515	2515	H7-1 sugar beet	2515	H7-1 sugar beet
Average	1783				

[44] A calculation based on the MoA (http://www.moa.gov.cn/ztzl/zjyqwgz/spxx/201307/t20130702_3509313.htm), the USDA (https://www.aphis.usda.gov/aphis/ourfocus/biotechnology/permits-notifications-petitions/petitions/petition-status), a government report of Canada (https://www.canada.ca/en/health-canada/services/food-nutrition/genetically-modified-foods-other-novel-foods/approved-products.html), and the data from Smart et al. (2016) for the European Union.

China & the EU	Average (days)	Max (days)		Min (days)	
Canola (3)	-1108	-442	T45 canola	-1799	GT73/RT73 canola
Cotton (5)	-1422	-169	MON15985 cotton	-3200	GHB614 cotton
Maize (12)	-192	826	GA21 maize2	-1498	MON87427 maize
Soybean (11)	60	1035	305423 soybean	-1268	A5547-127 soybean
Sugar beet (1)	561	561	H7-1 sugar beet	561	H7-1 sugar beet
Average	-360				

Note: The numbers in parentheses indicate the number of GM crop varieties. There are 46 varieties that passed both the approval processes in China and the USA; there are 47 varieties that passed both the approval processes in China and Canada; there are 32 varieties that passed both the approval processes in China and the European Union. The positive number in time lag indicates how many days later China approved the GM variety than the other country. The negative number in time lag indicates how many days earlier China approved the GM variety than the other country.

3.6.4 Results and Sensitivity Analyses

Table 4. Factors related to the approval time (dependent variable) for imported GM crops in China, 2002–2017 (hard data)

Category		**1**	**2**	**3**	**4**	**5**	**6**
Year	Before 2010	Reference	Reference	Reference	Reference	Reference	Reference
	After 2010	12.31** (4.46)	15.09*** (4.47)	13.50*** (4.34)	11.01** (4.40)	11.80** (5.32)	14.32** (6.69)
Trait type	Insect resistance		Reference				Reference
	Herbicide tolerance		6.92 (5.20)				5.26 (6.38)
	Combination or other traits		-4.30 (6.03)				0.05 (7.83)
Crop	Canola					1.27 (9.59)	2.71 (9.85)
	Cotton					Reference	Reference
	Maize					6.72 (6.24)	2.27 (7.09)
	Soybean					5.67 (6.61)	-1.04 (7.96)
	Sugar beet					14.27 (12.59)	8.64 (12.82)
Company	Company 1				Reference		Reference
	Company2				-10.57 (6.38)		-8.93 (10.96)
	Other companies				13.60 (7.99)		9.20 (10.14)
No. of traits	Single			Reference			
	Multiple			-9.15 (5.39)			
	Constant	28.14*** (2.96)	24.80*** (4.50)	29.45*** (2.95)	28.90*** (2.73)	23.73*** (5.03)	24.10*** (6.50)
	Observations	25	25	25	25	25	25
	R-squared	0.25	0.39	0.34	0.43	0.33	0.49

Note: Standard errors in parentheses. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively. The numbers in parentheses indicate standard errors. Reference categories are marked. For example, in Model 6, the reference category refers to the insect-resistant cotton produced by Company 1 before 2010. In this scenario, there are no GM crops from Company 3.

Table 5. Factors related to the approval time (dependent variable) for imported GM crops in China, 2002–2017 (sensitivity analysis: January)

Category		1	2	3	4	5	6
Year	Before 2010	Reference	Reference	Reference	Reference	Reference	Reference
	After 2010	17.09*** (3.27)	17.38*** (3.35)	17.08*** (3.32)	15.66*** (3.30)	17.48*** (3.68)	17.09*** (3.84)
Trait type	Insect resistance		Reference				Reference
	Herbicide tolerance		1.86 (4.46)				7.28 (5.01)
	Combination or other traits		-0.59 (4.67)				1.40 (4.88)
Crop	Canola					4.71 (5.85)	5.50 (6.18)
	Cotton					Reference	Reference
	Maize					11.05** (4.52)	8.47* (4.99)
	Soybean					5.76 (4.93)	5.06 (5.33)
	Sugar beet					16.99 (11.87)	13.16 (12.12)
Company	Company 1				Reference		Reference
	Company 2				-3.15 (3.86)		-2.47 (4.77)
	Company 3				9.10* (4.72)		10.53* (5.34)
	Other companies				0.69 (5.00)		-0.35 (5.23)
No. of traits	Single			Reference			
	Multiple			-0.05 (3.77)			
	Constant	28*** (2.22)	27.21*** (4.07)	28.01*** (2.51)	27.99*** (2.75)	21.01*** (4.06)	17.56*** (5.20)
	Observations	50	50	50	50	50	50
	R-squared	0.36	0.37	0.36	0.44	0.45	0.53

Note: Standard errors in parentheses. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively. The numbers in parentheses indicate standard errors. Reference categories are marked. For example, in Model 6, reference category refers to the insect-resistant cotton produced by Company 1 before 2010.

Table 6. Factors related to the approval time (dependent variable) for imported GM crops in China, 2002–2017 (sensitivity analysis: December)

Category		1	2	3	4	5	6
Year	Before 2010	Reference	Reference	Reference	Reference	Reference	Reference
	After 2010	14.85*** (3.43)	15.27*** (3.50)	14.75*** (3.48)	14.63*** (3.62)	15.33*** (3.88)	16.53*** (4.21)
Trait type	Insect resistance		Reference				Reference
	Herbicide tolerance		2.97 (4.65)				5.85 (5.50)
	Combination or other traits		-0.46 (4.87)				0.87 (5.36)
Crop	Canola					7.42 (6.18)	8.66 (6.79)
	Cotton					Reference	Reference
	Maize					11.19** (4.77)	10.98* (5.48)
	Soybean					7.73 (5.20)	6.84 (5.85)
	Sugar beet					19.70 (12.53)	15.88 (13.31)
Company	Company 1				Reference		Reference
	Company 2				-4.29 (4.23)		-3.42 (5.24)
	Company 3				1.63 (5.17)		1.98 (5.87)
	Other companies				-3.16 (5.48)		-4.55 (5.75)
No. of traits	Single			Reference			
	Multiple			-1.26 (3.95)			
	Constant	26.37*** (2.33)	24.97*** (4.24)	26.74*** (2.62)	27.86*** (3.01)	18.30*** (4.29)	16.27*** (5.75)
	Observations	50	50	50	50	50	50
	R-squared	0.28	0.29	0.28	0.31	0.37	0.41

Note: Standard errors in parentheses. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively. The numbers in parentheses indicate standard errors. Reference categories are marked. For example, in Model 6, reference category refers to the insect-resistant cotton produced by Company 1 before 2010.

Table 7. Factors related to the approval time (dependent variable) for imported GM crops in China, 2002–2017 (sensitivity analysis: Excel random generation)

Category		**1**	**2**	**3**	**4**	**5**	**6**
Year	Before 2010	Reference	Reference	Reference	Reference	Reference	Reference
	After 2010	16.77***	17.11***	16.67***	16.03***	17.25***	17.61***
		(3.37)	(3.45)	(3.42)	(3.51)	(3.79)	(4.08)
Trait type	Insect resistance		Reference				Reference
	Herbicide tolerance		1.77				5.50
			(4.59)				(5.32)
	Combination or other traits		-1.20				0.21
			(4.81)				(5.19)
Crop	Canola					7.16	8.46
						(6.04)	(6.57)
	Cotton					Reference	Reference
	Maize					11.60**	10.29*
						(4.66)	(5.31)
	Soybean					7.61	7.26
						(5.09)	(5.66)
	Sugar beet					19.44	16.02
						(12.25)	(12.89)
Company	Company 1				Reference		Reference
	Company 2				-3.81		-2.87
					(4.10)		(5.07)
	Company 3				5.34		6.27
					(5.01)		(5.68)
	Other companies				-1.82		-2.96
					(5.52)		(5.56)
No. of traits	Single			Reference			
	Multiple			-1.36			
				(3.89)			
	Constant	26.70***	26.14***	27.11***	27.51***	18.56***	16.48***
		(2.29)	(4.19)	(2.58)	(2.92)	(4.19)	(5.53)
	Observations	50	50	50	50	50	50
	R-squared	0.34	0.35	0.34	0.38	0.43	0.48

Note: Standard errors in parentheses. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively. The numbers in parentheses indicate standard errors. Reference categories are marked. For example, in Model 6, the reference category refers to the insect-resistant cotton produced by Company 1 before 2010.

Chapter 4

The Cost of Postponement of Bt Rice Commercialization in China

4. THE COST OF POSTPONEMENT OF BT RICE COMMERCIALIZATION IN CHINA[45]

ABSTRACT: To maintain self-sufficiency in rice production and national food security, the Chinese government strongly supports research that aims at increasing the productivity of rice cultivation. Rice with genetic material from *Bacillus thuringiensis* (Bt rice) is transgenic rice that can reduce lepidopteran pest damage and the use of insecticides. It was developed in the 1990s and earned biosafety certificates in 2009. However, because of political reasons, its commercialization in China has been postponed, and, to date, Bt rice is not grown in China. We assess the opportunity cost of postponement of Bt rice commercialization in China between the years 2009 and 2019 and consider the external costs of pesticide use and potential technology spill-overs of Bt rice. We estimate the cost of postponement of Bt rice over the analyzed period to be 12 billion United States (US) dollars per year.

KEYWORDS**:** Bt rice, cost of postponement, China, technology, trade

4.1 Introduction

With only six percent of the world's fresh water and seven percent of its arable land, China has to nurture nearly a fifth of the world's population (Wong & Chan, 2016). The arable land per capita in China decreased from 0.11 hectares in 1990 to 0.09 hectares in 2016, well below the world average of 0.19 hectares per capita (World Bank, 2017b). Although rice is the predominant staple food in the country, the land allocated to its production decreased from 33.1 million hectares in 1990 to 30.7 million hectares in 2017 (National Bureau of Statistics of China [NBSC], 2018). On the other hand, the amount of imported rice increased from 0.6 million metric tons in 2011 to 4.0 million tons in 2017, making China the biggest rice importer in the world (NBSC, 2018).

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[45] This chapter is based on the article: Jin, Y., Drabik, D., Heerink, N. & Wesseler, J. (2019). The cost of postponement of Bt rice commercialization in China. *Frontiers in Plant Science* 10:1226. https://doi.org/10.3389/fpls.2019.01226

The United States (US) Census Bureau estimates that the Chinese population will reach 1.4 billion around 2026, which will further reduce the arable land per capita and increase the demand for rice. To maintain self-sufficiency in rice production and national food security, the Chinese government strongly supports research that aims to increase the productivity of rice cultivation. One of the priorities has, therefore, been the development of insect-resistant rice, such as rice with genetic material from *Bacillus thuringiensis* (Bt rice).

Bt rice is transgenic rice in which genes from the soil bacterium *Bacillus thuringiensis* have been transferred into the rice genome to reduce lepidopteran pest damage and the necessity of using insecticides (Huang et al., 2005). The yield of Bt rice can be up to 60 percent higher than conventional rice when no pesticides are used (Wang et al., 2010).

Chinese rice farmers apply more pesticides than farmers in most other countries (Huang et al., 2000). Huang et al. (2005) show, however, that Bt rice requires 80 percent less pesticide than conventional rice and reduces labour input (Rozelle et al., 2005). The simultaneous increase in production and reduction of input both contribute to the absolute increase of the total factor productivity of Bt rice, which is about 15 percent higher than conventional rice (Rozelle et al., 2005).

The adoption of Bt rice can also improve farmers' health due to lower exposure to pesticides (Huang et al., 2015). Bt rice is also compatible with biological control and soil health management, although it should be noted that, to the best of authors' knowledge, no study examines its environmental effects at a larger scale or for a longer period (Cohen et al., 2008).

The cultivation of Bt rice in China requires special approval (Jin et al., 2019). The biosafety regulation system in China consists of three phases: field trials, environmental release trials, and preproduction trials. Before applying for field trials, Chinese scientists had spent 20 years investigating the thermal stability, digestibility, toxicity, and nutrient composition of Bt rice as well as the allergenicity of the Cry proteins it produces (Li et al., 2015). During various phases of the biosafety procedures, no food safety concern was raised. Bt rice is also found to be safe for aquatic ecosystems (e.g., Li et al., 2014) and has not shown any detrimental effects on non-target insect pests (Niu et al., 2017). It is expected to pose negligible risks to the non-target functional guilds in future large-scale Bt rice agroecosystems in China (Dang et al., 2017).

On October 22, 2009, China's Ministry of Agriculture (MoA)[46] issued biosafety certificates for two Bt rice lines (Cry1Ab/Ac Huahui No. 1 and Cry1Ab/Ac Bt Shanyou 63) (Chen et al., 2011). The issuance of the certificates indicates that the two lines are considered as safe as conventional rice, both to humans and the environment, and thus to be ready for commercialization. However, their official commercialization has been continuously postponed and is still pending. The biosafety certificates expired in 2014 but were renewed until the end of 2019.

The postponement of Bt rice commercialization is largely due to low public acceptance, like other genetically modified (GM) crops (e.g., Chen et al., 2014). Most Chinese business managers oppose food derived from GM crops because they fear lower profits (Deng et al., 2017). Although almost half of consumers know little about GM food, they believe it has adverse effects on human health and the environment (Qu et al., 2011). In addition, Chinese scientists do not show higher acceptance of GM food than non-scientists (Huang et al., 2017). Therefore, the government is hesitant to let China step forward as the first country to commercialize Bt rice.

More recently, however, the Chinese government has taken actions in policy support of the GM rice. In 2016, the "13th Five-Year Plan for Science and Technology Innovation" set an aim to push forward the commercialization of new domestic types of GM crops by 2020 (MoA, 2016).[47] In the same year, the MoA revealed a roadmap for commercialization of transgenic crops, starting with cash crops 'not for food use' (e.g., cotton) followed by crops for feed and industrial use (e.g., maize and soybeans),

[46] The Ministry of Agriculture (MoA) transformed into the Ministry of Agriculture and Rural Affairs (MARA) in early 2018. The main difference after the transformation is the integration of sections of agricultural investment and management from different ministries, such as the Ministry of Finance and the Ministry of Land and Resources, into the MARA. More details (in Chinese) are available at http://www.npc.gov.cn/npc/xinwen/2018-03/18/content_2050371.htm. The role of the MARA in regulating genetically modified organisms (GMOs) has not changed significantly in comparison to the role of the MoA.

[47] http://www.gov.cn/zhengce/content/2016-08/08/content_5098072.htm (in Chinese)

then non-staple food crops (e.g., sugar beets), and finally staple food crops (e.g., rice) (MoA, 2016; United States Department of Agriculture [USDA], 2016).

Xie et al. (2017) estimate that each one-year postponement of commercializing insect-resistant GM maize in China leads to the opportunity costs in the range of 4–14 billion US dollars for the overall economy. Moreover, postponement of commercializing Bt rice has high opportunity costs because of its foregone potential economic and environmental benefits. In this respect, it is important to consider the foregone benefits of lower pesticide use associated with Bt rice as well as its technology spill-overs on the international rice price. These effects have been neglected so far in the relevant literature, and no economic analysis of the cost of postponement (CoP) of Bt rice commercialization in China is available. Our paper aims to bridge this gap in the literature.

To achieve our objective, we combine the Economic Surplus Model (ESM) with the Pesticide Environmental Accounting (PEA) Tool. The ESM has been widely used to assess the benefits and costs of technical changes in agriculture (Alston et al., 1998). A sample of previous uses of the ESM includes Wesseler et al. (2017), who estimated the foregone benefits of delayed approval of staple crops (bananas, cow peas, and maize) in Africa; Bayer et al. (2010), who quantified the regulatory costs of Bt rice and Bt eggplants and ringspot-virus-resistant papayas and virus-resistant tomatoes in the Philippines; and Krishna and Qaim (2007), who investigated the welfare and distributional effects of the introduction of the Bt technology among eggplant farmers and consumers in India.

We estimate the external costs of individual chemicals in rice production using the PEA, which is considered an appropriate tool for estimating the benefits of technologies replacing pesticides (Leach &Mumford, 2008; Praneetvatakul et al., 2013).

We provide essential information for different groups of stakeholders, including domestic and foreign policymakers determining the commercialization of GM crops in general, particularly Bt rice, and for businesses interested in investing in new biotechnology.

4.2 Model for Assessment of the Policy

The Economic Surplus Model (Alston et al., 1998) is a tool for ex-ante assessment of the consequences of current technology improvements. We use it to calculate the welfare change between the counterfactual state of affairs had China commercialized Bt rice and the actual state of affairs due to the postponement of its commercialization. We model China as a large, open economy in rice trade. We set 2009 as the base year, since that is the year when Bt rice first received its biosafety certificate (MoA, 2009). Since then, Bt rice has been officially ready for commercialization.

The most important policy in China's price intervention program is the minimum supporting price. Since 2004, the minimum supporting price has been implemented for rice to maintain national food security and increase farmers' incomes.[48] Because of the increased total supply of rice, the Chinese government has to continuously buy rice from farmers to prevent the price from falling, even when massive stores of it already exist (Huang & Yang, 2017). Figure 1 compares the minimum supporting price and domestic market price between 2009 and 2018.

[48] For wheat in 2006 and maize in 2008.

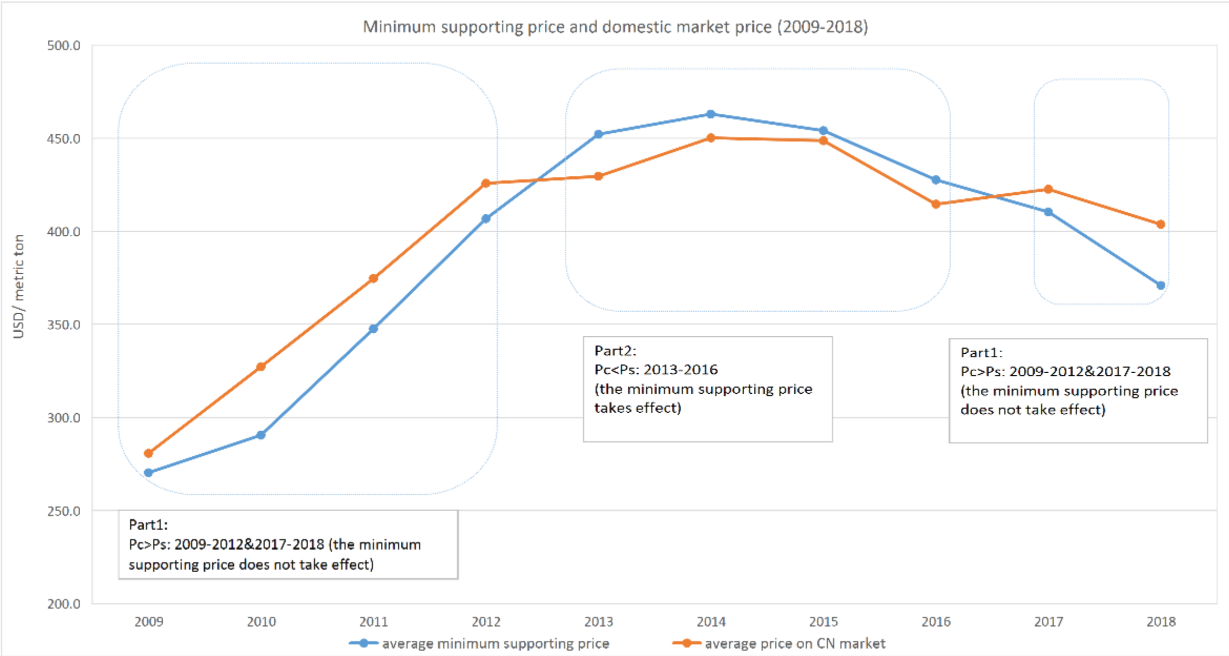

Figure 1. Minimum supporting price and domestic market price (2009-2018)

Apart from the price intervention program, the Chinese government also implements a direct subsidy program for rice (and other grains). However, because the impact of agricultural subsidies on grain production has been shown to be negligible (Huang et al., 2011), we do not include this direct subsidy in the ESM.

We divide the ten-year period in Figure 1 into two parts. Part 1 consists of the periods when the minimum price was lower than the domestic price (2009 to 2012 and 2017 to 2018), in which case the minimum price did not take effect. Part 2 consists of the period when the minimum price exceeded the domestic price (2013 to 2016).

We assume that the rest of the world (ROW) agrees to trade in Bt rice but that it does not locally cultivate it.[49] The technology spill-over arises when the ROW follows China's adoption of Bt rice by also locally cultivating it. When the ROW cultivates Bt rice, the ROW supply curve shifts to the right, although typically not as much as the domestic Chinese supply does (Alston et al., 1998). The technology spill-over has an

[49] Recent developments support this assumption. For example, in January, 2018, Bt rice was approved by the US Food and Drug Administration (FDA, 2018) and Environmental Protection Agency (EPA). This approval means that Bt rice can be consumed and imported to the United States but cannot be cultivated there.

effect in China and the ROW by decreasing the world price. A lower world price benefits consumers in both China and the ROW, but producers in China lose due to the spill-over.

For the ESM to include the external costs of pesticide use that were introduced above, we assume there are no further research costs after 2009, since that was when the biosafety certificates of Bt rice were issued. Based on this assumption, the potential annual net benefits are the sum of foregone economic[50] and environmental benefits. This means that the potential annual net benefits (AB_t) after commercialization are equal to the sum of the change of annual welfare (ΔTS_t) and annual external costs of pesticides (TEC_{pt}):

$$AB_t = \Delta TS_t + TEC_{pt} ,$$

where *t* denotes the year (*t* = 0 corresponds to 2009).

We calculate the net present value of the potential annual benefits in 2009 and 2019 using the following equations:

$$NPV_{2009} = \sum_{t=0}^{\infty} (1+\mu)^{-t} AB_t$$

and

$$NPV_{2019} = \sum_{t=10}^{\infty} (1+\mu)^{-t} AB_t ,$$

[50] In the model, we use the annual total production of rice in the rice seasons (single or double-cropping rice) that have been taken into consideration. Therefore, different rice seasons in different regions in China will not influence the results. An important limitation of Bt rice is that it is developed to control lepidopteran pests but no other rice pests, such as plant hoppers. Herbicide is still needed for Bt rice to control weeds. Field trials of Bt rice revealed that pesticide is still needed (for non-lepidopteran pests) but that its amount could decrease significantly due to the resistance of Bt rice to lepidopteran pests.

where μ denotes the discount rate of an infinite stream of annual benefits. The CoP is then given by the difference between NPV_{2009} and NPV_{2019}.

4.3 Data Sources

The data come from both primary and secondary sources. The primary data are from the preproduction trial of Bt rice in China (R. Hu, private communication, 2017) and include the maximum adoption rate, yield, and input costs (Appendix 1). For the ESM, we calculate proportionate yield change and proportionate input cost change (per hectare) based on pesticide cost, labour cost, seed cost, fertilizer cost, and other costs. Because it takes time for farmers to adopt a new technology, we employ a logistic adoption function with a 55 percent ceiling.

All the secondary data come from official statistics and the literature (Table 1). The rice supply elasticity and the rice demand elasticity for China are based on Zhuang and Abbott (2007). The rice supply elasticity and rice demand elasticity for the ROW are based on Mohanty et al. (2017). The domestic price is from ChinaGrain (2018), and the minimum supporting price is from the Ministry of Agriculture and Rural Affairs (MARA). Because we do not have data on rice stocks, we assume that, in both China and the ROW, the annual consumption and production of rice are equal after adjusting for trade. The data on domestic production are available for the period from 2009 to 2016 from the official website of the NBSC. The rice production quantity for the ROW is available for the period from 2009 to 2016 from the Rice Yearbook of the USDA. For the remaining three years for which data are not yet available, we assume the quantities are the same as in 2016 (the same holds for prices after 2018).

Table 1. Parameterization and simulated results for the Economic Surplus Model in the period 2009-2019

Raw parameters	unit	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019*	source
Initial domestic rice price	US dollar/ton	280.69	327.25	374.63	425.86	429.61	450.25	448.76	414.61	422.65	403.77	403.77	ChinaGrain (2018)
Initial CN rice consumption	million tons	194.67	195.53	201.08	206.33	205.41	205.41	211.32	210.15	210.15	210.15	210.15	NBSC (2018)
Initial CN rice production	million tons	195.1	195.76	201	204.24	203.61	203.61	208.23	207.08	207.08	207.08	207.08	NBSC (2018)
Initial ROW rice consumption	million tons	656.2	672.71	697.8	695.71	712.68	711.12	700.43	713.3	713.3	713.3	713.3	USDA (2018)
Initial ROW rice production	million tons	655.77	672.47	697.88	697.8	710.89	712.91	703.52	716.38	716.38	716.38	716.38	USDA (2018)
Supply shift relative to the initial equilibrium	unit free	0.02	0.11	0.2	0.2	0.19	0.18	0.17	0.16	0.15	0.14	0.13	R. Hu, private comm. (2017)
Simulated results													
Equilibrium rice price after adopting new technology	US dollar/ton	280.10	323.17	366.15	416.11	419.80	440.29	438.95	406.40	415.46	397.36	397.82	
CN rice consumption after adopting new technology	million tons	194.82	196.39	202.68	207.99	207.05	207.00	212.94	211.62	211.41	211.33	211.24	
CN rice production after adopting new technology	million tons	195.98	201.03	210.92	214.30	213.82	213.51	217.94	216.00	214.74	214.23	213.72	
ROW rice consumption after adopting new technology	million tons	656.60	675.14	702.39	700.34	715.61	715.70	704.89	713.03	716.83	716.60	716.36	
ROW rice production after adopting new technology	million tons	655.44	670.50	694.15	694.03	708.84	709.19	699.89	713.03	713.50	713.69	713.88	

Note: 2019* means that we use the value of the latest year to estimate the value in 2019

Based on the data above, we calibrate the intercepts and slopes of supply curves and demand curves in China and the ROW. We use the calibrated parameters to simulate the new equilibrium price after commercializing Bt rice as well as new equilibrium quantities for the production and consumption in China and the ROW.

Since the biosafety certificates of Bt rice were already been issued in 2009, we set the probability of success to one, meaning that the new technology has already been successful in reality. For the same reason, we assume there are no further research costs after 2009. As for the discount rate, in our analysis, we apply both three- and five-percent rates to see the implications for the stream of benefits and costs from 2009 to 2019 (Bayer et al., 2010).

Tabashnik (2015) notes that some of the environmental, health, and economic benefits of Bt crops fade over time due to the evolution of pest resistance. We take this effect into account by considering a technology depreciation factor. For lack of data, we adopt the depreciation factor for Bt eggplant (Bayer, 2007). The factor equals one in the first four years. Starting in the fifth year, it decreases by five percentage points annually until it reaches 65 percent; from then, it remains constant at that level.

To calculate the external costs of pesticide use, we choose the three most commonly used rice pesticides in China (China Agrochemical Industry Network, 2012): Imidacloprid, Cartap hydrochloride, and Chlorantraniliprole. The percentage of the active ingredient of a certain pesticide and its application rates come from the product instructions. The base value of the external cost is calculated by Leach and Mumford (2008), and we use the US Inflation Calculator[51] to convert it to 2009 US dollars. We use the Environmental Impact Quotient (EIQ) calculator[52] to get the EIQ values for the three pesticides. We compare these values with the reference values for each category (Leach & Mumford, 2008) and determine whether a pesticide has a low, mediate, or high level of toxicity. Based on the data from the World Bank (2018) and

[51] Available at: https://www.usinflationcalculator.com/

[52] Available at: https://nysipm.cornell.edu/eiq/calculator-field-use-eiq/

the NBSC (2009), we compare the ratio of China's share of employment in agriculture to the average share of agricultural employment in Germany, the United Kingdom (UK), and the US (weighted by gross domestic product [GDP]). We also compare the ratio of China's GDP per capita to the weighted average GDP per capita in Germany, the UK, and the US. Appendix 2 contains the details of the calculations.

4.4 Results

4.4.1 Base Model

Using the PEA tool, we estimate the annual external costs of the uses of Chlorantraniliprole, Imidacloprid, and Cartap hydrochloride in China to be 1.8 million US dollars (0.06 dollars per hectare of agricultural land). (We calculated this amount using the equation and data presented in Appendix 2.) Considering that China banned a series of pesticides with a high level of toxicity in 2002,[53] the current pesticides used for rice are relatively environmentally friendly, which is also reflected in the annual external costs of pesticides.

Considering China as a large, open economy, the CoP of commercializing Bt rice from 2009 to 2019 is 104 billion US dollars under the three-percent discount rate and 94 billion US dollars under five-percent discount rate. We use the capital recovery factor (CRF) to calculate the annual CoP, which considers the time value of money and converts the CoP into a stream of equal payments from 2009 to 2019 at both the three- and five-percent discount rates. Under both discount rates, China loses approximately the same amount (12 billion US dollars) annually from 2009 to 2019 (Table 2).

[53] Available at: http://www.chinapesticide.org.cn/fgzcwj/906.jhtml

Table 2. Results of base model simulation (billion US dollars)

Discount rate (r)	NPV2009	NPV2019	CoP	CRF (unit free)	Annual CoP
3%	372	360	104	0.117	12.22
5%	224	212	94	0.130	12.15

Notes: Capital Recovery Factor (CRF) = $[i(1+i)^n]/[(1+i)^n-1]$, where n=2019-2009=10.

4.4.2 Effect of the Technology Spill-over

Different levels of technology spill-over in the ROW have implications for economic impacts on China (Table 3).

Table 3. Sensitivity analysis of technology spillover

	unit	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019*
0% spillover												
Rice price	US dollar/ton	280.10	323.17	366.15	416.11	419.80	440.29	438.95	406.40	415.46	397.36	397.82
CN rice consumption	million tons	194.82	196.39	202.68	207.99	207.05	207.00	212.94	211.62	211.41	211.33	211.24
CN rice production	million tons	195.98	201.03	210.92	214.30	213.82	213.51	217.94	216.00	214.74	214.23	213.72
ROW rice consumption	million tons	656.60	675.14	702.39	700.34	715.61	715.70	704.89	717.41	716.83	716.60	716.36
ROW rice production	million tons	655.44	670.50	694.15	694.03	708.84	709.19	699.89	713.03	713.50	713.69	713.88
25% spillover												
Rice price	US dollar/ton	279.95	322.17	364.08	413.73	417.41	437.86	436.55	404.39	413.69	395.78	396.35
CN rice consumption	million tons	194.85	196.60	203.08	208.39	207.46	207.40	213.34	211.97	211.72	211.61	211.51
CN rice production	million tons	195.95	200.86	210.62	213.99	213.82	213.51	217.94	216.00	214.50	214.01	213.51
ROW rice consumption	million tons	656.70	675.74	703.51	701.48	716.76	716.81	705.98	718.42	717.70	717.41	717.11
ROW rice production	million tons	655.36	670.01	693.24	693.11	707.90	708.28	699.00	712.21	712.79	713.03	713.27
50% spillover												
Rice price	US dollar/ton	279.81	321.16	362.01	411.34	415.01	435.42	434.15	402.38	411.92	394.20	394.88
CN rice consumption	million tons	194.89	196.81	203.47	208.80	207.86	207.79	213.74	212.33	212.03	211.90	211.78
CN rice production	million tons	195.92	200.70	210.32	213.68	213.82	213.51	217.94	216.00	214.27	213.79	213.31
ROW rice consumption	million tons	656.80	676.34	704.64	702.61	717.91	717.93	707.07	719.42	718.57	718.22	717.87
ROW rice production	million tons	655.28	669.52	692.33	692.18	706.97	707.37	698.11	711.39	712.09	712.37	712.66
75% spillover												

Rice price	US dollar/ton	279.66	320.16	359.94	408.96	412.62	432.99	431.75	400.37	410.16	392.63	393.42
CN rice consumption	million tons	194.93	197.02	203.86	209.21	208.26	208.18	214.13	212.69	212.34	212.19	212.05
CN rice production	million tons	195.89	200.53	210.01	213.37	213.82	213.51	217.94	216.00	214.03	213.57	213.10
ROW rice consumption	million tons	656.90	676.94	705.76	703.74	719.06	719.05	708.16	720.43	719.43	719.03	718.62
ROW rice production	million tons	655.20	669.04	691.42	691.26	706.03	706.46	697.22	710.57	711.38	711.71	712.04
100% spillover												
Rice price	US dollar/ton	279.51	319.15	357.87	406.58	410.22	430.55	429.35	398.36	408.39	391.05	391.95
CN rice consumption	million tons	194.96	197.23	204.25	209.61	208.67	208.57	214.53	213.05	212.65	212.48	212.32
CN rice production	million tons	195.86	200.37	209.71	213.06	213.82	213.51	217.94	216.00	213.79	213.35	212.90
ROW rice consumption	million tons	657.00	677.55	706.88	704.87	720.22	720.17	709.25	721.44	720.30	719.84	719.38
ROW rice production	million tons	655.11	668.55	690.51	690.34	705.09	705.55	696.34	709.75	710.67	711.05	711.43

Note: 2019* means that we use the value of the latest year to estimate the value in 2019

We assume that the ROW's proportionate reduction in price due to the spill-over changes by 25, 50, 75, and 100 percent compared to the base proportionate reduction in price. Figure 2 shows the results.

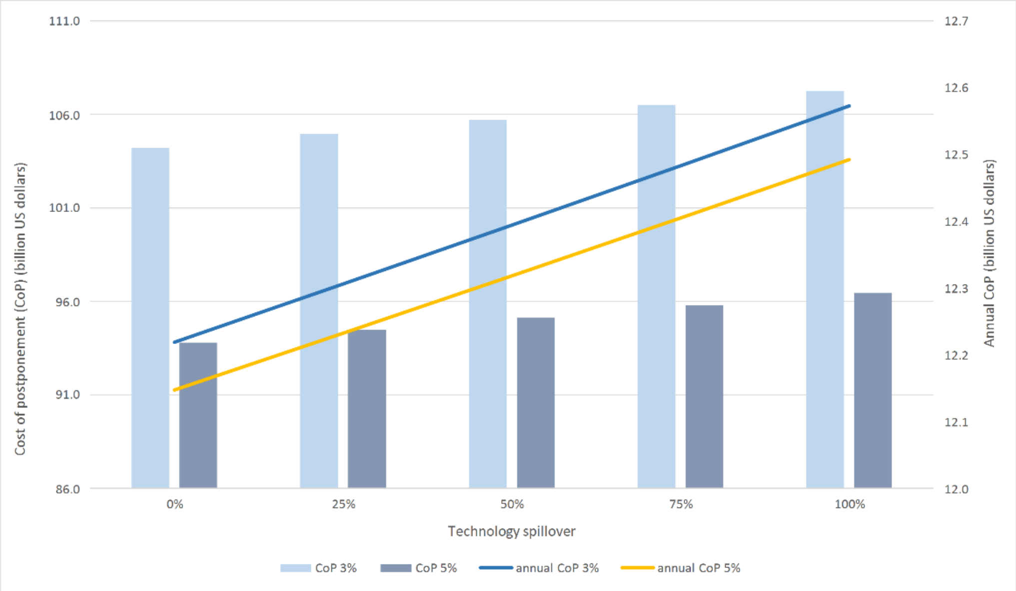

Figure 2. Cost of postponement and technology spillover

With the increase in technology spill-over, the world rice price decreases. The lower world price benefits consumers in both China and the ROW. During the ten years under study, China was a net importer in all years except for 2009 and 2010. Figure 2 shows the effects of technology spill-over during this ten-year period. The total and annual CoP both increase when the level of technology spill-over increases. The percentage change in CoP is small, however. For example, at both three- and five-percent discount rates, the annual CoP increases by around 350 million US dollars when the technology spill-over rises from 0 to 100 percent: The relative change from the initial value is less than three percent.

4.4.3 Effects of the Maximum Adoption Rate and Rate of Diffusion

We model the annual adoption rate (A_t) for Bt rice using the logistic function

$$A_t = \frac{\rho_{\max}}{1+e^{-\alpha-\beta t}},$$

where ρ_{max} denotes the maximum adoption rate, α represents a constant of integration, and the parameter β represents the rate of diffusion, which measures the rate at which adoption A_t increases with time t (Alston et al., 1998).

For the maximum adoption rate, no data is available, since Bt rice has not been approved for cultivation yet. The maximum adoption rate we use in the baseline is 55 percent, which corresponds to a preproduction trial (R. Hu, private communication, 2017). We assume the adoption rate for the first year is five percent (A_1 = 0.05). Since it took three years for the adoption rate to reach 55 percent in the preproduction trial in the period from 2002 to 2004, we set A_3 = 0.54 under the assumption that the adoption rate almost reached its maximum. Based on these assumptions, the calibrated parameters are α = -5.45 and β = 3.15. In further sensitivity analyses (Figure 3 and Table 4), we set the maximum adoption rate to 0.45, 0.55, 0.65, 0.75, 0.85, and 0.95 (and recalibrate the parameters α and β accordingly).

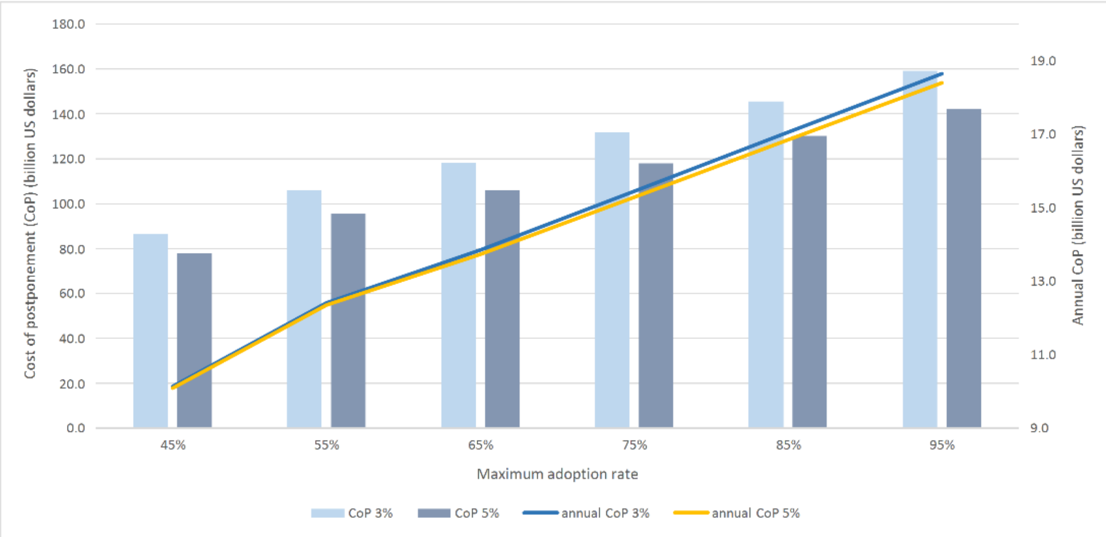

Figure 3. Cost of postponement and maximum adoption rate

Table 4. Sensitivity analysis of maximum adoption rate

	unit	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019*
45% maximum adoption rate												
α	unit free	-5.01	-5.01	-5.01	-5.01	-5.01	-5.01	-5.01	-5.01	-5.01	-5.01	-5.01
β	unit free	2.93	2.93	2.93	2.93	2.93	2.93	2.93	2.93	2.93	2.93	2.93
Adoption rate	unit free	0.05	0.32	0.44	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Rice price	US dollar/ton	280.10	322.96	367.85	417.89	421.59	442.10	440.73	407.89	416.76	398.52	398.90
CN rice consumption	million tons	194.82	196.43	202.36	207.68	206.75	206.71	212.65	211.35	211.18	211.11	211.04
CN rice production	million tons	195.98	201.30	208.94	212.46	211.96	211.71	216.17	214.37	213.35	212.93	212.51
ROW rice consumption	million tons	656.60	675.27	701.47	699.50	714.75	714.86	704.07	716.66	716.19	716.00	715.80
ROW rice production	million tons	655.44	670.40	694.90	694.72	709.54	709.87	700.55	713.64	714.02	714.18	714.34
55% maximum adoption rate												
α	unit free	-5.45	-5.45	-5.45	-5.45	-5.45	-5.45	-5.45	-5.45	-5.45	-5.45	-5.45
β	unit free	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15
Adoption rate	unit free	0.05	0.38	0.54	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55
Rice price	US dollar/ton	280.10	322.03	366.30	416.12	419.80	440.29	438.95	406.40	415.46	397.36	397.82
CN rice consumption	million tons	194.82	196.63	202.66	207.99	207.05	207.00	212.94	211.62	211.41	211.33	211.24
CN rice production	million tons	195.98	202.51	210.74	214.30	213.82	213.51	217.94	216.00	214.74	214.23	213.72
ROW rice consumption	million tons	656.60	675.83	702.31	700.34	715.61	715.70	704.89	717.41	716.83	716.60	716.36
ROW rice production	million tons	655.44	669.94	694.22	694.03	708.84	709.19	699.89	713.03	713.50	713.69	713.88
65% maximum adoption rate												
α	unit free	-4.58	-4.58	-4.58	-4.58	-4.58	-4.58	-4.58	-4.58	-4.58	-4.58	-4.58
β	unit free	2.09	2.09	2.09	2.09	2.09	2.09	2.09	2.09	2.09	2.09	2.09
Adoption rate	unit free	0.05	0.26	0.55	0.64	0.65	0.65	0.65	0.65	0.65	0.65	0.65

Rice price	US dollar/ton	280.10	323.68	366.15	414.59	418.05	438.48	437.17	404.91	414.15	396.19	396.73
CN rice consumption	million tons	194.82	196.28	202.68	208.25	207.35	207.29	213.24	211.88	211.64	211.54	211.44
CN rice production	million tons	195.98	200.37	210.92	215.87	215.64	215.31	219.71	217.62	216.13	215.53	214.93
ROW rice consumption	million tons	656.60	674.84	702.39	701.07	716.45	716.53	705.70	718.16	717.47	717.19	716.92
ROW rice production	million tons	655.44	670.75	694.15	693.44	708.15	708.51	699.23	712.42	712.98	713.20	713.43
75% maximum adoption rate												
α	unit free	-4.46	-4.46	-4.46	-4.46	-4.46	-4.46	-4.46	-4.46	-4.46	-4.46	-4.46
β	unit free	1.83	1.83	1.83	1.83	1.83	1.83	1.83	1.83	1.83	1.83	1.83
Adoption rate	unit free	0.05	0.23	0.55	0.71	0.74	0.75	0.75	0.75	0.75	0.75	0.75
Rice price	US dollar/ton	280.10	324.12	366.15	413.30	416.36	436.69	435.38	403.42	412.84	395.03	395.65
CN rice consumption	million tons	194.82	196.19	202.68	208.47	207.63	207.58	213.53	212.15	211.87	211.75	211.64
CN rice production	million tons	195.98	199.80	210.92	217.21	217.40	217.09	221.47	219.24	217.53	216.83	216.13
ROW rice consumption	million tons	656.60	674.57	702.39	701.68	717.26	717.35	706.50	718.90	718.11	717.79	717.47
ROW rice production	million tons	655.44	670.96	694.15	692.94	707.49	707.84	698.57	711.81	712.45	712.72	712.98
85% maximum adoption rate												
α	unit free	-4.46	-4.46	-4.46	-4.46	-4.46	-4.46	-4.46	-4.46	-4.46	-4.46	-4.46
β	unit free	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69
Adoption rate	unit free	0.05	0.21	0.55	0.77	0.83	0.85	0.85	0.85	0.85	0.85	0.85
Rice price	US dollar/ton	280.10	324.33	366.15	412.17	414.73	434.91	433.61	401.93	411.54	393.86	394.57
CN rice consumption	million tons	194.82	196.14	202.68	208.66	207.91	207.87	213.83	212.41	212.10	211.97	211.84
CN rice production	million tons	195.98	199.53	210.92	218.37	219.10	218.86	223.23	220.86	218.92	218.13	217.34
ROW rice consumption	million tons	656.60	674.45	702.39	702.22	718.05	718.17	707.31	719.65	718.76	718.39	718.03
ROW rice production	million tons	655.44	671.06	694.15	692.50	706.86	707.18	697.91	711.20	711.93	712.23	712.52
95% maximum adoption rate												
α	unit free	-4.49	-4.49	-4.49	-4.49	-4.49	-4.49	-4.49	-4.49	-4.49	-4.49	-4.49
β	unit free	1.60	1.60	1.60	1.60	1.60	1.60	1.60	1.60	1.60	1.60	1.60

Adoption rate	unit free	0.05	0.21	0.55	0.83	0.92	0.94	0.95	0.95	0.95	0.95	0.95
Rice price	US dollar/ton	280.10	324.45	366.15	411.16	413.16	433.15	431.83	400.44	410.23	392.70	393.49
CN rice consumption	million tons	194.82	196.12	202.68	208.83	208.17	208.15	214.12	212.68	212.32	212.18	212.03
CN rice production	million tons	195.98	199.37	210.92	219.41	220.74	220.61	224.98	222.48	220.31	219.43	218.55
ROW rice consumption	million tons	656.60	674.38	702.39	702.69	718.81	718.98	708.12	720.40	719.40	718.99	718.59
ROW rice production	million tons	655.44	671.12	694.15	692.12	706.24	706.52	697.25	710.60	711.41	711.74	712.07

Note: 2019* means that we use the value of the latest year to estimate the value in 2019

In another set of sensitivity analyses (Figure 4 and Table 5), we examine the effect of the rate of diffusion (β) on CoP (holding ρ_{max} and α at their baseline levels) because the speed of adopting new technology is important when the cultivation area is large. We vary the parameter β between 1 to 6.

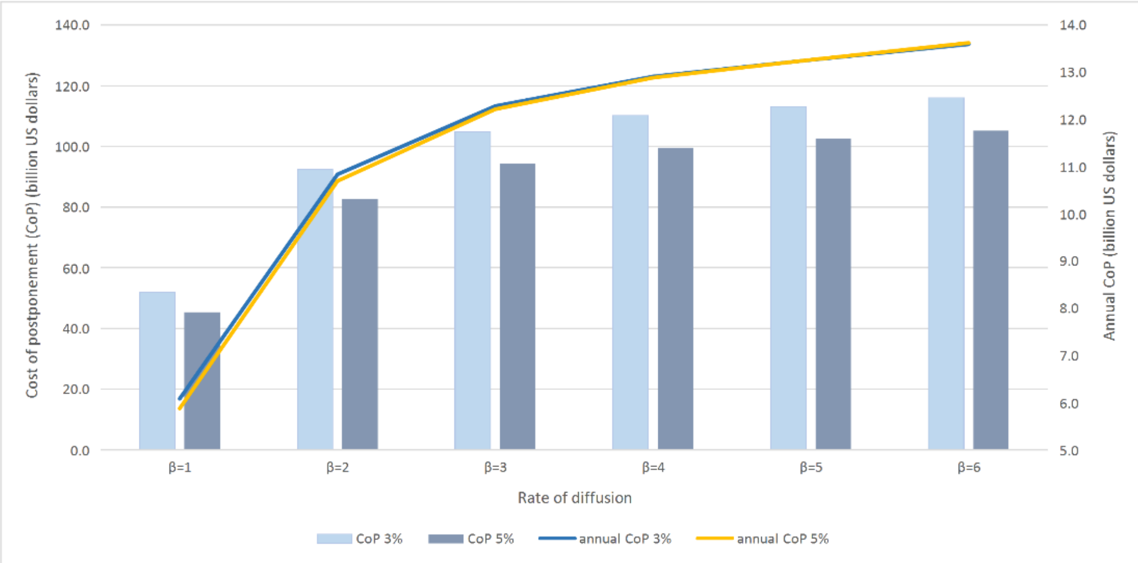

Figure 4. Cost of postponement and rate of diffusion

Table 5. Sensitivity analysis of rate of diffusion

	unit	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019*
β=1												
Rice price	US dollar/ton	397.84	327.02	373.95	424.00	425.79	443.93	440.66	407.00	415.66	397.43	397.84
CN rice consumption	million tons	211.24	195.58	201.21	206.64	206.05	206.42	212.66	211.51	211.37	211.31	211.24
CN rice production	million tons	213.69	196.06	201.79	206.15	207.59	209.89	216.24	215.35	214.53	214.15	213.69
ROW rice consumption	million tons	716.35	672.84	698.16	696.59	712.72	714.02	704.11	717.11	716.73	716.56	716.35
ROW rice production	million tons	713.89	672.36	697.58	697.08	711.18	710.55	700.52	713.27	713.58	713.72	713.89
β=2												
Rice price	US dollar/ton	280.49	325.83	369.25	416.81	419.91	440.31	438.95	406.40	415.46	397.36	397.82
CN rice consumption	million tons	194.72	195.83	202.10	207.87	207.04	207.00	212.94	211.62	211.41	211.33	211.24
CN rice production	million tons	195.40	197.60	207.30	213.58	213.71	213.50	217.94	215.99	214.74	214.23	213.72
ROW rice consumption	million tons	656.33	673.55	700.71	700.01	715.56	715.69	704.88	717.41	716.83	716.60	716.36
ROW rice production	million tons	655.66	671.78	695.51	694.30	708.88	709.19	699.89	713.03	713.50	713.69	713.88
β=3												
Rice price	US dollar/ton	280.18	322.51	366.39	416.12	419.80	440.29	438.95	406.40	415.46	397.36	397.82
CN rice consumption	million tons	194.80	196.53	202.64	207.99	207.05	207.00	212.94	211.62	211.41	211.33	211.24
CN rice production	million tons	195.87	201.89	210.65	214.29	213.82	213.51	217.94	216.00	214.74	214.23	213.72
ROW rice consumption	million tons	656.55	675.54	702.26	700.34	715.60	715.70	704.89	717.41	716.83	716.60	716.36
ROW rice production	million tons	655.48	670.18	694.26	694.03	708.84	709.19	699.89	713.03	713.50	713.69	713.88
β=4												
Rice price	US dollar/ton	279.46	320.32	366.16	416.11	419.80	440.29	438.95	406.40	415.46	397.36	397.82
CN rice consumption	million tons	194.98	196.99	202.68	207.99	207.05	207.00	212.94	211.62	211.41	211.33	211.24
CN rice production	million tons	196.93	204.72	210.91	214.30	213.82	213.51	217.94	216.00	214.74	214.23	213.72
ROW rice consumption	million tons	657.04	676.85	702.39	700.34	715.61	715.70	704.89	717.41	716.83	716.60	716.36

ROW rice production	million tons	655.08	669.11	694.16	694.03	708.84	709.19	699.89	713.03	713.50	713.69	713.88
β=5												
Rice price	US dollar/ton	278.16	319.86	366.15	416.11	419.80	440.29	438.95	406.40	415.46	397.36	397.82
CN rice consumption	million tons	195.29	197.08	202.68	207.99	207.05	207.00	212.94	211.62	211.41	211.33	211.24
CN rice production	million tons	198.85	205.32	210.92	214.30	213.82	213.51	217.94	216.00	214.74	214.23	213.72
ROW rice consumption	million tons	657.92	677.12	702.39	700.34	715.61	715.70	704.89	717.41	716.83	716.60	716.36
ROW rice production	million tons	654.37	668.89	694.15	694.03	708.84	709.19	699.89	713.03	713.50	713.69	713.88
β=6												
Rice price	US dollar/ton	276.57	319.79	366.15	416.11	419.80	440.29	438.95	406.40	415.46	397.36	397.82
CN rice consumption	million tons	195.68	197.10	202.68	207.99	207.05	207.00	212.94	211.62	211.41	211.33	211.24
CN rice production	million tons	201.20	205.40	210.92	214.30	213.82	213.51	217.94	216.00	214.74	214.23	213.72
ROW rice consumption	million tons	659.00	677.16	702.39	700.34	715.61	715.70	704.89	717.41	716.83	716.60	716.36
ROW rice production	million tons	653.49	668.86	694.15	694.03	708.84	709.19	699.89	713.03	713.50	713.69	713.88

Note: 2019* means that we use the value of the latest year to estimate the value in 2019

Both figures confirm that the economic benefits are larger the more farmers adopt Bt rice and the faster they adopt it. For example, when the maximum adoption rate increases by ten percent (from 55 to 65 percent), the annual CoP increases by around 1.5 billion dollars. When the rate of diffusion gets larger, the speed of the increase in both CoP and annual CoP gets smaller. At both three and five-percent discount rates, the annual CoP doubles when the rate of diffusion changes from 1 to 6.

4.5 Actionable Recommendations

The results show that the continuous postponement of Bt rice introduction in China has come at a substantial economic cost that includes not only the direct economic losses of efficiency at higher prices of rice for consumers but also human health and environmental costs.

These costs have to be weighed against consumer concerns about Bt rice. Consumers, including those in China, tend to ignore the environmental benefits of crop production in their purchasing behavior. The introduction of Bt rice in combination with information about its environmental benefits, such as lower pesticide use and reduced greenhouse gas emission (Wesseler et al., 2011), may overcome some of the potential consumer resistance. Further, linking the introduction of Bt rice with a labelling policy might also increase consumer acceptance, as reported, for example, in the US (Kolodinsky & Lusk, 2018).

Our study suggests two main actionable policy recommendations. First, as further delays in the approval for Bt rice cultivation results in substantial costs, it should immediately be approved for cultivation. Second, for addressing potential consumer concerns, its introduction should be accompanied by a mandatory labelling of consumer products derived from Bt rice.

An additional policy recommendation is to link the approval of Bt rice cultivation with an information campaign about its environmental benefits. Further, Bt rice is just one example among several new crops developed using advances in plant breeding. The results presented for Bt rice carry over to many other crops, including Vitamin A–enriched rice (Wesseler & Zilberman, 2014), insect-resistant vegetables, such as eggplants and tomatoes (Groeneveld et al., 2011), and GMOs in general (Barrows et al., 2014). Studies show that delaying approval for the cultivation of these crops comes at substantial economic costs (see, for example, Zilberman et al., 2018). They not only directly benefit both farmers and consumers but also substantially benefit the environment, including, in some cases, substantial reductions in greenhouse gas emissions (Smyth et al., 2011). Policymakers in China should take these implications more explicitly into consideration when determining the approval of Bt rice and other crops developed using advanced plant-breeding technologies.

4.6 Discussion

So far, no study has reported any adverse side effects of consuming food products derived from GM crops anywhere in the world (Paarlberg, 2009). Many scientific studies, to the contrary, present evidence that GM crops can be safely used in food and feed and are nutritionally equivalent to their non-GM counterparts (Snell et al., 2012; Bawa and Anilakumar, 2013). This also holds for the case of Bt rice (Li et al., 2015; Li et al., 2014).

As a major producer, consumer, and trader of rice, China issued biosafety certificates for Bt rice in October, 2009, which were renewed in December, 2014 until the end of 2019; however, the commercialization of Bt rice in China has been continuously postponed and is still pending. We estimate the forgone benefits due to this postponement to be around 12 billion US dollars per year in the studied period (2009 to 2019).

This postponement is largely due to the low level of understanding and acceptance of GM crops in China (Li et al., 2016). Other challenges in commercializing Bt rice include resolving trade policy impediments and developing insect resistance–management strategies (High et al., 2004; Liu et al., 2016). In January, 2018, the US

Food and Drug Administration and the US Environmental Protection Agency declared that Bt rice was not more dangerous than conventional rice and received legal clearance for import and consumption in the United States, indicating that Bt rice is likely to be approved in other countries in the future.

An important limitation of Bt rice is that it was developed to control lepidopteran pests but no other rice pests. Also, some lepidopteran pests are likely to increase their resistance to Bt rice after commercialization (Li et al., 2014); therefore, insect resistance–management strategies are required before commercializing Bt rice. However, waiting for the identification of new genes to control non-lepidopteran pests or the development of new plant breeding technologies might result in sunk research and investment costs in Bt rice.

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4.8 Appendix

4.8.1 Parametrization for the Economic Surplus Model

Parameter	Description	Values and unit	Source
E(Y)	Proportionate yield change	0.045 (per hectare)	Personal communication
E(C)	Proportionate change in input cost	-21.4% (per hectare)	Personal communication
r	Discount rate (ESM)	discuss at 3% and 5%	Bayer et al. (2010)
ε_a	Domestic rice supply elasticity	0.273	Zhuang & Abbott (2007)
η_a	Domestic rice demand elasticity	-0.352	Zhuang & Abbott (2007)
ε_b	ROW rice supply elasticity	0.236	Mohanty et al. (2017)
η_b	ROW rice demand elasticity	-0.291	Mohanty et al. (2017)
$1-\delta$	Depreciation factor of technology	65%	Bayer (2007)
A	Maximum adoption rate	55%	Personal communication
q	Probability of adopting Bt rice	0.5	Assumption

Note: The depreciation factor of technology starts in the 5th year and drops by five percentage points annually until 65%.

4.8.2 The Pesticide Environmental Accounting (PEA) Tool

The annual total external costs of a pesticide p (TEC_p) can be calculated as

$$TEC_p = rate_p \frac{active_p}{100} \sum_{c=1}^{3} \left[EC_c F_c \left(F_{agemp} |_{c=1,2,3} \right) \right] F_{gdppc},$$

where $rate_p$ denotes the application rate of a pesticide p in kilograms of formulated product per hectare and $active_p$ denotes the percentage of active ingredient in the formulated product (Prannetvatakul et al., 2013).

The PEA uses the Environmental Impact Quotient (EIQ) calculator to adjust the base values of economic costs to differences between relative toxicities of pesticides. There are eight events within three large categories in the EIQ with 472 active pesticide compounds in total: (*i*) farm workers,[54] (*ii*) consumers,[55] and (*iii*) the environment.[56] In the study, we aggregate eight events into three categories and convert EIQ values to external costs for the three categories with subscript c = 1, 2, or 3 representing the categories (*i*), (*ii*), or (*iii*), respectively. The PEA tool converts EIQ values for the three categories to external costs by multiplying the external cost base values with a factor F_c that has three levels: 0.5 if the pesticide has a relatively low toxicity level; 1.0 if it has a medium toxicity level; and 1.5 if it has a relatively high toxicity level. Leach and Mumford (2008) define the ranges of toxicity level for each category.

EC_c is the base value of external costs calculated by Leach and Mumford (2008) converted to 2009 US dollars. The parameter F_{agemp} denotes the ratio of China's share of employment in agriculture to the average share of agricultural employment in the Unites States (US), the United Kingdom (UK), and Germany weighted by the gross domestic product (GDP). F_{agemp} takes into consideration that, in China, more people are

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[54] The effects on applicators and pickers.

[55] The effects of pesticide residues on groundwater leaching and food consumption.

[56] The effects on aquatic life, bees, birds, and beneficial insects.

engaged in agriculture than in the other three countries, thus having more direct contact with pesticides.

The parameter F_{gdppc} denotes the ratio of China's GDP per capita to the average GDP per capita in the US, the UK, and Germany, weighted by the GDPs of those countries. F_{gdppc} considers that, due to lower labour costs in China, lower costs of monitoring and cleaning up lead to lower external costs (Praneetvatakul et al., 2013).

4.8.3 Parametrization of the Pesticide Environmental Accounting Tool

	$rate_p$	$active_p$	EC_1	EC_2	EC_3	F_1	F_2	F_3	Fagemp (c =1,2,3)			Fgdppc
Chlorantraniliprole	0.001	0.2	1.8	6.09	2.76	0.5	0.5	0.5	20.243	1	1	0.085
Imidacloprid	0.041	0.7	1.8	6.09	2.76	0.5	0.5	0.5	20.243	1	1	0.085
Cartap hydrochloride	0.003	0.98	1.8	6.09	2.76	0.5	0.5	0.5	20.243	1	1	0.085
Source	Personal calculation based on data from www.taobao.com		Cornell EIQ calculator: https://nysipm.cornell.edu/eiq/calculator-field-use-eiq			Leach and Mumford (2008)			Personal calculation based on data from World Bank (2018) and NBSC (2009)			

Chapter 5

The CRISPR Dilemma of a Chinese Rice Farmer

5. THE CRISPR DILEMMA OF A CHINESE RICE FARMER [57]

ABSTRACT: The recently developed Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR) technology for rice, which makes it resistant to two most destructive insect pests of rice, is an alternative to insect-resistant GM rice. We advance an economic framework to determine ex ante the planting share of CRISPR rice in China under uncertainty of pest severity, analyze which factors affect it most, and estimate the annual benefit of adoption. Using our baseline data, we estimate the planting share of CRISPR rice to be 35.5 percent. Moreover, the annual benefit of growing CRISPR rice with conventional rice compared to conventional rice alone is 1.84 billion US dollars.

KEYWORDS: CRISPR rice, China, Uncertainty, Optimal planting share, Monte Carlo simulations

[57] This chapter is based on the article: Jin, Y. & Drabik, D., The CRISPR Dilemma of a Chinese Rice Farmer, submitted to *Applied Economic Perspectives and Policy*.

5.1 Introduction

Rice is the staple food for more than half of the population in China, and its area amounts to 30 million hectares, accounting for 25 percent of the total arable land in China (National Bureau of Statistics of China [NBSC], 2018). This vast area of agricultural land reflects the importance of rice in feeding not only the domestic population but also many people in the rest of the world. However, rice suffers from the damage of insect pests with the annual loss in billions of US dollars (Lu et al., 2018). Response of Chinese rice farmers has been notorious overuse of pesticides, which have adverse effects on farmers' health and the environment (Damalas & Eleftherohorinos, 2011), with the application rates amounting to 57 percent above the recommended levels (Zhang et al., 2015). One of the solutions to the pesticides overuse issues is to develop insect-resistant rice.

Scientists expected much from genetically modified (GM) insect-resistant rice. The classic example is Bacillus thuringiensis (Bt) rice, which was developed in the 1990s and received the biosafety certificates in 2009. However, because of political reasons, its commercialization in China has been postponed. To date, Bt rice is not grown, although it has been approved for imports and consumption in the United States (Food and Drug Administration of United States [FDA], 2018).

Recent advances in Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR) technology for rice (Lu et al., 2018) present an alternative to the insect-resistant GM rice. In 2018, Chinese scientists developed CRISPR rice with resistance to planthoppers and stem borers—the two most destructive insect pests of rice (Chen et al., 2011). Compared to GM rice, CRISPR rice[58] has a higher chance of making it to the market because it is similar to the rice developed by traditional breeding techniques, such as hybrid breeding, because no new gene is added. Furthermore, a mutation producing a gene structure similar to CRISPR rice can also occur in nature. At this moment, it is already known that in some countries, such as the United States, CRISPR rice will not be considered as a GM product (US Department of Agriculture [USDA], 2018), and will thus

[58] There are different kinds of CRISPR rice with different traits, such as herbicide-tolerant and blast-resistant. CRISPR rice in this paper specifically refers to the insect-resistant CRISPR rice developed by Lu et al. (2018).

not need to be labeled once commercialization is permitted. China, however, has not yet issued specific regulations on CRISPR technology.

There is a growing literature on CRISPR rice with different traits. Apart from the CRISPR rice with the trait of insect resistance (Lu et al., 2018), which our study is based on, Wang et al. (2016) developed CRISPR rice with enhanced blast resistance. Four genes known as a regulator of grain number, panicle architecture, grain size, and plant architecture have been targeted (Li et al., 2016). Sun et al. (2016) developed herbicide-tolerant rice with CRISPR technology.

CRISPR technology can contribute to meeting the increasing demand for food and help with the global environmental challenges we face. In addition, it can arguably produce identical results to conventional methods in a much more predictable, faster, and less costly manner (Gao, 2018). Considering these advantages, how China regulates CRISPR rice could significantly affect the welfare of different rice stakeholders not only in China but also globally due to technology spillovers, just as China's regulation of GM rice has affected the social welfare of various stakeholders (Jin et al., 2019).

Because GM insect-resistant rice is not allowed for commercialization in China, the role of CRISPR rice is important in the sense that it has both the trait of insect resistance (similar to GM rice) and the potential of being regulated as a non-GM product. Compared to conventional rice, CRISPR rice in lab trials with no insect pests produces an approximately 36 percent lower yield (Lu et al., 2018). However, when there are insect pests, the relative yield is ambiguous, meaning that partly planting CRISPR rice would be advisable only if CRISPR rice outperformed conventional rice with the damage of insect pests.[59] This trade-off indicates an optimal planting share for CRISPR rice.

The main objective of our ex-ante study is to estimate the annual benefit of CRISPR rice adoption under uncertainty of pest severity, and which factors are the most influential to the optimal planting share of CRISPR rice. Providing numerical estimates of the planting share is a valuable exercise (especially from the point of view of policymakers and seed developers) but we recognize that these estimates need to be evaluated against the uncertainty of underlying model parameters. To achieve our objective, we develop a

[59] Partial adoption of CRISPR rice instead of full adoption is most likely because there will always be some farmers who choose not to adopt the new technology.

microeconomic model of a rice farmer who decides on the allocation of her land into conventional and CRISPR rice under uncertainty over insect pest severity, taking the yields differential into account. Lacking sufficient historical data for some variables of our model, we make several modeling choices and simplifying assumptions. This relates especially to the assumption of a representative farmer. While differing climatic and agronomic conditions in different provinces in China would result in province-specific optimal planting shares, we decided to zoom out to analyze the situation at the national level. Increasing the granularity of the model would require making extra assumptions on several parameters in our ex ante study. Despite the assumptions, we believe our work contributes to the literature by quantifying the value of including the CRISPR rice into the farmer's production process compared to growing conventional rice alone. The theoretical framework we advance makes it possible to simulate counterfactuals that are useful to evaluate impacts of future actions of the Chinese government with respect to CRISPR rice.

The economics of GM technology has been well studied. Qaim (2009) analyzed the economics of GM crops regarding micro-level and macro-level impact of first-generation GM crops contributing to the design of efficient regulations and innovation systems in modern agriculture. Brookes and Barfoot (2014) assessed the global value of crop biotechnology in agriculture at the farm level and economic impacts on yields, key costs of production, direct farm income and effects based on soybeans, corn, cotton, and canola. The potentially substantial benefits of adopting GM technology, coupled with the technical, social, and economic uncertainties surrounding gene drives, suggest that a responsible course of action is to move forward while maintaining regulatory flexibility and conducting research to resolve key uncertainties (Mitchell et al., 2017).

Our contribution to the existing and growing literature on CRISPR rice is to economically assess its market potential considering uncertainty of insect pest severity and provide a framework to assess the influence of its factors. For example, Mora et al. (2012) assessed the main drivers influencing the application of GM animal techniques in livestock and pharmaceutical chains but did not cover the GM crop area. Vyska et al. (2016) investigated the trade-off between disease resistance and crop yield in a biological model but did not consider its economic implications. Wossen et al. (2017) analyzed the trade-off between productivity gains and risk reductions to understand farmers' adoption decisions about drought-tolerant maize varieties in Nigeria. Based on endogenous switching regression model, they concluded that adoption had a win-win outcome by improving productivity and reducing risk. While ex-post analysis on GM crops is important, ex-ante analysis on new technologies such as CRISPR is urgent. Bartkowski et al. (2018) discussed the economic, ethical, and policy implications of CRISPR technology given that CRISPR crops blur the boundary between nature and technology and result in non-traceability of modifications. However, they did not go into the details about market potential and determinants of the optimal share.

Our results have implications for at least three groups of market agents in China. First, farmers (through information campaigns) could use them to decide whether to plant CRISPR rice and, if so, how much. Second, policymakers can use the results as a point of departure to work out the contours of future policies and regulations regarding CRISPR technology and managing uncertainty over market effects due to potentially severe insect pest outbreaks. Third, seed developers and pesticide suppliers will be directly affected by the future share of CRISPR rice in the total land area dedicated to rice production.

5.2 A Model

Consider a representative farmer who grows both CRISPR rice (denoted by index $i = 1$) and conventional rice ($i = 2$) on separate fields. The separation assumption reflects the need for different pesticide application rates as well as possible segregation costs implied by the country's regulatory framework. The total area of CRISPR rice is L_1 and of conventional rice L_2. The farmer uses all available land for rice ($\bar{L}$), which is fixed in a given year, which implies $L_1 + L_2 = \bar{L}$. Although rice can possibly be harvested twice a year, depending on climatic conditions and geographical location (Peng et al., 2009), our representative farmer does it only once. This assumption does not affect our empirical results as we use annual aggregate production data for China.

Before planting rice, the farmer faces uncertainty over pest severity. To keep things traceable, we assume two states of nature (indexed by j): a severe state ($j = S$), associated with a pest outbreak and a less severe state ($j = N$), in which the pest occurrence is weak.[60] The probability of the severe state is q and the probability of the less severe state is $1-q$.

Farmers typically apply pesticides throughout the growing season and can tell for sure which state of nature has occurred only after a certain time into the season (e.g., the harvest), after which the pest cannot cause any further damage to the yield. Therefore, we assume the farmer makes his decision about how much pesticide to use before the uncertainty of the pest severity is revealed (similarly to the land allocation). The farmer will, therefore, choose the optimal pesticide rate (X_i, in kilograms per hectare). Notice that because our model is static, and the unit of time measurement is a year, X should be thought of as the sum of amounts of pesticide applied per hectare in a year. CRISPR rice has an insect-resistant trait and, therefore, the intensity of pesticide use for CRISPR rice is lower than for conventional rice, that is, $X_1 < X_2$.

In either scenario, the farmer derives her revenues from selling CRISPR and conventional rice, whose production critically depends on the rice yield. Let Y_i denote the yield of rice type *i* in the absence of pest damage (i.e., in the extreme case when the pest intensity is zero). These yields correspond to points *a* and *b* in Figure 1. In a controlled lab environment, Y_1 is significantly lower than Y_2 (e.g., Lu et al. (2018) report a 36-percent difference). As pest intensity increases, yields of both rice types decline. However, because CRISPR rice is insect-resistant, the yield decline will be slower (depicted by the flatter curve in Figure 1) compared to conventional rice.

[60] In reality, the severity of the pest would be a random variable with a continuous distribution. Because the pesticide use is not the focus of this paper, we model the severity as a binary variable in our theoretical framework.

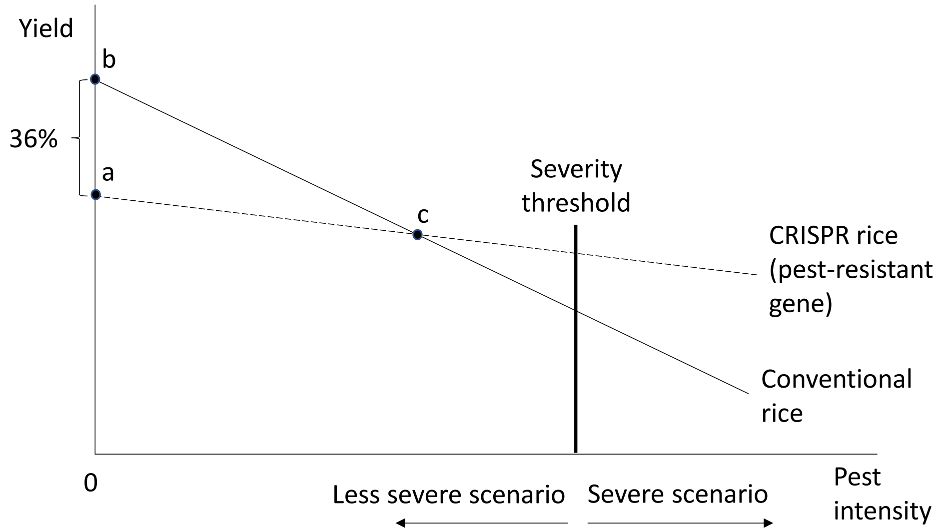

Figure 1. Pest intensity and rice yield under no pest abatement

Consider a pest intensity threshold below which the damage is considered less severe and above it is severe. Lacking empirical data, we assume this threshold is to the right of point *c* — the intersection of the two yield curves. This is probably not a strong assumption given the insect resistance of CRISPR rice, which slows down the yield decline with respect to pest intensity. Notice that the yield of CRISPR rice is higher than the yield of conventional rice in the severe pest scenario, but the outcome does not necessarily reverse in the less severe scenario. Only when pest intensity is between points *a* and *c*, the yield of CRISPR rice is lower than the yield of conventional rice.

Denote $\alpha_i \in (0,1)$ as the proportion of the maximum yield left after the severe pest damage if no damage abatement actions are taken. The yield loss is then $(1-\alpha_i)Y_i$. CRISPR rice has a higher percentage of yield left than conventional rice because it has the insect-resistant trait, implying that $0<\alpha_2<\alpha_1<1$. The farmer can take precautionary measures and apply pesticides to reduce potential loss. Following Lichtenberg and Zilberman (1986), we denote $G_j(X_i)$ as the abatement function for rice type *i* in state *j*. It measures the share of the potential loss that can be averted. More specifically, $G_j(X_i)=1$ denotes the complete eradication of the destructive capacity, and $G_j(X_i)=0$ represents zero elimination of the loss. The actual yield of rice type *i* in state *j* can thus be written as $\alpha_i Y_i + G_j\left(X_i\right)\left(1-\alpha_i\right)Y_i$. With this yield, we can write the production of rice type *i* in state *j* as

$$Q_{ij} = \left[\alpha_i Y_i + G_j\left(X_i\right)\left(1-\alpha_i\right)Y_i\right]L_i . \qquad [1]$$

The price of a pesticide is *m* dollars per kilogram. The cost related to pesticide use for CRISPR and conventional rice is proportional to the planted area: mX_1L_1 and mX_2L_2. Other costs related to the production of CRISPR rice are aggregated in the non-linear term AL_1^{ε}. It can be thought of as consisting of two parts. First, the cost of fertilizer, machinery, and other costs that are proportional to the land use and, second, strictly convex (in land) segregation cost related to the production of CRISPR rice that the farmer faces as a result of the national regulatory framework. The strict convexity of the non-linear part of the CRISPR rice cost is represented by the parameter $\varepsilon > 1$, which represents the elasticity of the non-linear part of the cost with respect to the planted area of CRISPR rice (e.g., the larger the area under CRISPR rice, the more efforts the farmer must spend to ensure the two types of rice are segregated to prevent gene flow).[61] The positive parameter *A* is determined at the calibration stage. The farmer does not incur segregation costs for conventional rice; therefore, all other costs for conventional rice are captured in the constant cost per hectare denoted by φ.[62] The values of parameters *A* and φ depend on the state of nature (e.g., more mechanization is likely to be needed in the severe pest state). The total production cost in state *j* (c_j) can then be expressed as

[61] Gene flow is a natural process that inevitably happens. CRISPR rice is a self-pollinating plant but cross-pollination of rice in a field can occur at relatively low rates. In addition, pollen-mediated gene flow of CRISPR rice is expected to disperse to nearby weedy and wild relatives (Lu and Snow, 2005). Therefore, segregation of CRISPR rice is necessary and might be expensive when the planting area is large (Gruère et al., 2011).

[62] It could be argued that other costs are also non-linear with respect to land use. For example, if rice production were expanded to previously unused lands or hillier areas, the cost would likely rise more than proportionally. However, we assume the total area devoted to rice is fixed at $\bar{L}$, making these considerations less of a concern. In the past ten years, the total rice planting area in China has been hovering around 30 million hectares (NBSC, 2018).

$$c_j = mX_1L_1 + A_jL_1^{\varepsilon} + \left(mX_2 + \varphi^j\right)L_2 . \quad [2]$$

Denoting the market price of rice type *i* as p_i, the farmer's profit in state *j* is equal to

$$\pi_j = p_1Q_{1j} + p_2Q_{2j} - c_j . \quad [3]$$

Following previous empirical studies on the behavior of Chinese farmers (e.g., Liu, 2013; Jin et al., 2017; Chen et al., 2018), we model the representative farmer as a risk averter with a strictly concave Bernoulli utility function $u\left(\pi\right)$. The farmer maximizes the expected utility (*EU*) by choosing the optimal area of land for CRISPR rice (L_1)[63] and pesticide rates X_1, and X_2

$$\max_{\{L_1,X_1,X_2\}} EU = qu\left(\pi_S\right) + \left(1-q\right)u\left(\pi_N\right). \quad [4]$$

The optimal values for L_1, X_1, and X_2 satisfy the first-order conditions

$$\frac{\partial EU}{\partial L_1} = q\frac{du}{d\pi_S}\frac{\partial \pi_S}{\partial L_1} + \left(1-q\right)\frac{du}{d\pi_N}\frac{\partial \pi_N}{\partial L_1} = 0 \quad [5]$$

$$\frac{\partial EU}{\partial X_1} = q\frac{du}{d\pi_S}\frac{\partial \pi_S}{\partial X_1} + \left(1-q\right)\frac{du}{d\pi_N}\frac{\partial \pi_N}{\partial X_1} = 0 \quad [6]$$

$$\frac{\partial EU}{\partial X_2} = q\frac{du}{d\pi_S}\frac{\partial \pi_S}{\partial X_2} + \left(1-q\right)\frac{du}{d\pi_N}\frac{\partial \pi_N}{\partial X_2} = 0 . \quad [7]$$

It can be shown that the Hessian corresponding to first-order conditions [5] – [7] is negative definite, meaning that L_1, X_1, and X_2 satisfying [5] – [7] are unique expected

[63] The area of conventional rice can readily be determined as $\bar{L} - L_1$.

utility maximizers.[64] Finally, the optimal planting share of CRISPR rice (ρ) is equal to $\rho = L_1/\bar{L}$.

5.3 Specific Functional Forms

Two general functions from the model outlined above need to be specified to make the model operational empirically. These are the abatement function $G(X)$ and the Bernoulli utility function $u(\pi)$. There are several possible functional forms that capture the required properties of the abatement function (i.e., it is monotonically increasing in *X*, and its values are between zero and one). In the empirical part of the paper, we use the exponential function $G_j(X) = 1 - e^{-\lambda_j X}$, which requires only one parameter [$\lambda_j \in (0,1)$] to be calibrated in each state of nature (Lichtenberg & Zilberman, 1986). The higher the parameter is, the faster the abatement function approaches its maximum. It is reasonable to assume that for a given pesticide application rate, the effectiveness of the abatement activity will be higher in the less severe scenario compared to the severe one; that is, we require that $1 - e^{-\lambda_N X} > 1 - e^{-\lambda_S X}$, which implies $\lambda_S < \lambda_N$. The implication of this condition is illustrated in Figure 2, where the curve corresponding to the share of loss abated in the less severe scenario is above the curve for the severe scenario for any pesticide application rate.

[64] We do not present the derivation of the Hessian in this paper because it is lengthy given the nested structure of the expected utility function. We are, however, happy to share it with the interested reader.

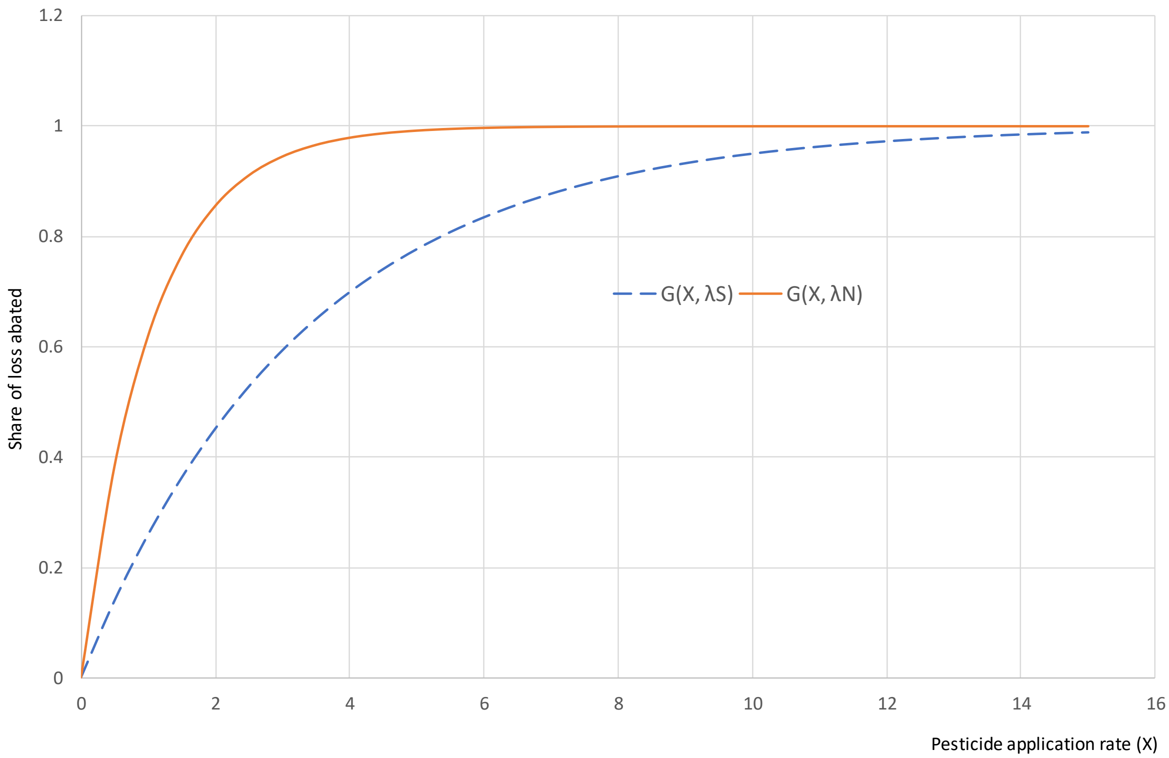

Figure 2. Output damage abatement functions for severe (*S*) and less severe (*N*) scenario

Regarding Bernoulli utility function, we assume it takes exponential form $u(\pi) = -e^{-r\pi}$. This is a popular functional form in the empirical literature on uncertainty (e.g., Zuhair et al., 1992; Bodnar, et al., 2018; Lu et al., 2018). It has only one parameter (*r*), which represents constant absolute risk aversion. This is convenient, as by changing this parameter in the sensitivity analysis later, we can investigate the influence of (constant absolute) risk aversion of the farmer on the model outcomes of interest. Moreover, the parsimony of this function regarding the number of parameters reduces data needs when calibrating our model.

5.4 Data and Model Calibration

Data in this study come from the literature on CRISPR and conventional rice and are summarized in Table 1 together with the sources. Where the data on CRISPR rice are not available (e.g., pesticide application rate and the cost), we use the data from Bt rice field trials (Huang et al., 2005) as a proxy since both rice types are insect-resistant.

We set the price of CRISPR rice equal to the price of conventional rice in the baseline. However, previous literature on the price relationships between similar GM and conventional crops (e.g., Pray et al., 2001) argues that farmers growing GM crops can afford to accept a lower market price because the total costs of cultivating GM crops are less than the costs of non-GM crops due to less input use (e.g., pesticides or labour), and the benefits of reduced inputs outweigh the higher seed costs. Therefore, in Monte Carlo simulations later, we relax the baseline assumption and require that the price of CRISPR rice not exceed the price of conventional rice (i.e., $p_1 \leq p_2$). Similarly, our baseline assumption is that other costs per hectare of conventional rice under weak and severe pest are equal (i.e., $\varphi_N = \varphi_S$). We relax this assumption in the sensitivity analysis as well and investigate what effect different relative costs per hectare of conventional rice have on the optimal planting ratio.

The parameter *r* of the exponential Bernoulli utility function equals constant absolute risk aversion, and in the baseline we set it to $r = 0.09$ as reported in the study of Chen et al. (2018). The higher this value, the more risk averse the farmer is, ceteris paribus.

To reduce the number of calibrated parameters (due to a lack of necessary data), we set the calibrating constants A_S and A_N of the convex part of the CRISPR cost function equal; that is, they do not depend on the state of nature. We believe this is a reasonable assumption to make as the (segregation) cost of CRISPR rice is likely to be rather insensitive to the severity of the pest. With this assumption, there are four unknown parameters (λ_S, λ_N, *A*, and ε) and one variable (L_1) to be calibrated using the baseline data.

Table 1. Data and sources

Parameter	Symbol	Baseline value	Source	Minimum	Maximum	Source of max./min.
Price of CRISPR rice (1000 $/ton)	p_1	0.164	Index Mundi (2020)	0.164	0.356	Historical data from 1997-2006, Index Mundi (2020)
Price of conventional rice (1000 $/ton)	p_2	0.182	Assumed based on Pray et al. (2001)	0.164	0.356	Historical data from 1997-2006, Index Mundi (2020)
Share of max. CRISPR rice yield after the most severe insect pest damage	α_1	0.810	Average of the interval provided by He et al. (2016)	0.650	0.970	He et al. (2016)
Share of max. conv. rice yield after the most severe insect pest damage	α_2	0.640	Average of the interval provided by Xu et al. (2017)	0.400	0.880	Xu et al. (2017)
Price of pesticide (100 $/kg)	m	0.001	Personal communication	0.001	0.002	30% variation
Max. yield of CRISPR rice (ton/hectare)	Y_1	6.975	$0.9 \times Y_1$ based on communication with experts	4.883	9.068	30% variation
Max. yield of conv. rice (ton/hectare)	Y_2	7.750	NBSC (2020a)	7.625	7.875	Historical data from 1997-2006, NBSC (2020a)
Total rice area (million hectares)	$\bar{L}$	28.50	NBSC (2020b)	26.50	31.80	Historical data from 1997-2006, NBSC (2020b)
Shape parameter of the abatement function under weak pests	λ_N	0.967	Calibrated	0.677	1.256	30% variation

Shape parameter of the abatement function under severe pests	λ_S	0.005	Calibrated	0.004	0.007	30% variation
Parameter of other costs of CRISPR rice	A	0.175	Calibrated	0.122	0.227	30% variation
Probability of severe insect pests	q	0.341	Jiaan Cheng (2009)	0	1	definition
Segregation cost parameter	ε	1.466	Calibrated	1.435	1.497	30% variation and ε>1
Constant absolute risk aversion	r	0.090	Chen et al. (2018)	0.070	0.110	Chen et al. (2018)
Other costs per hectare of conventional rice under weak pest (1000 $/hectare)	φ_S	0.862	R. Hu, priv. communication (2018)	0.603	1.120	30% variation
Other costs per hectare of conventional rice under severe pest (1000 $/hectare)	φ_N	0.862	R. Hu, priv. communication (2018)	0.603	1.120	30% variation
Cost per hectare of CRISPR rice (1000 $/hectare)	UC_1	0.521	Assumed the same as for Bt rice; R. Hu, priv. communication (2018)	Confidence interval is not provided here because UC_1 is not directly used in Monte Carlo simulations.		
Elasticity of land used for CRISPR rice with respect to the marginal cost of CRISPR rice production	η	0.450	Assumed	Confidence interval is not provided here because η is not directly used in Monte Carlo simulations.		

The first-order conditions [5] – [7] (more precisely their specific equivalents presented by [5'] – [7'] in Appendix) in principle determine λ_S, λ_N, and L_1. To calculate the parameters A and ε we need two more equations. Based on equation [2], the cost of cultivating CRISPR rice is

$$C_1 = mX_1L_1 + AL_1^{\varepsilon}, \tag{8}$$

from which the corresponding marginal cost equals $MC_1 = mX_1 + \varepsilon AL_1^{\varepsilon-1}$.

Denote η as the elasticity of land use with respect to the marginal cost of CRISPR rice

$$\eta = \frac{\partial L_1}{\partial MC_1}\frac{MC_1}{L_1} = \frac{mX_1 + \varepsilon AL_1^{\varepsilon-1}}{\varepsilon(\varepsilon-1)AL_1^{\varepsilon-1}}. \tag{9}$$

We can use equation [8] to calculate the cost per hectare of CRISPR rice (UC_1) as $UC_1 = C_1/L_1 = mX_1 + AL_1^{\varepsilon-1}$, from which $AL_1^{\varepsilon-1} = UC_1 - mX_1$. Substituting the right-hand side of the previous equation into [9] and rearranging, we obtain

$$\eta(UC_1 - mX_1)\varepsilon^2 - (UC_1 - mX_1)(1+\eta)\varepsilon - mX_1 = 0, \tag{10}$$

which is a quadratic equation in ε that can be solved as long as the values of other parameters (η, UC_1, m, X_1) are known. Finally, the calibrating constant A can be obtained by rearranging the unit cost function as

$$A = (UC_1 - mX_1)/L_1^{\varepsilon-1}. \tag{11}$$

In summary, we obtain the four unknown parameters and one variable by simultaneously solving equations [5'], [6'], [7'] (Appendix), [10], and [11].

The per-hectare cost of CRISPR rice is not known at the moment as the rice is not grown commercially yet. To overcome this information gap, we use the cost of Bt rice instead and set UC_1 = 521.3 US dollars per hectare (R. Hu, private communication, 2018). Regarding the elasticity of land use with respect to the marginal cost of CRISPR rice, we assume η = 0.45 as CRISPR rice is not grown yet. We let the model guide us in choosing the specific value of this parameter.

We recognize we pose some structure on the underlying data: we use specific functions to operationalize the theoretical model; we constraint the space for some parameters and require specific relationships between them (e.g., $0<\lambda_S,\lambda_N<1$ and $\lambda_S<\lambda_N$); we require strict convexity for one part of the CRISPR cost function (i.e., $\varepsilon>1$) for the optimization problem to have a unique optimal solution; and we require that the optimal use of land for CRISPR rice be positive and not exceed the total allocation of land for rice. The toll we pay to have all these restrictions satisfied simultaneously is a narrow maneuvering space for the elasticity η in the baseline. Empirically, we find the lower bound to be 0.42 and the upper bound 0.48; therefore, our choice of η is in the middle. It should be noted that η is an auxiliary parameter that we use only in the baseline. In the Monte Carlo simulations later, we vary parameter ε , which is directly linked to η as per [10].

Numerically solving equations [5'], [6'], [7'], [10], and [11], we obtain λ_S = 0.005, λ_N = 0.967; A = 0.175, ε = 1.466, and L_1 = 10.12 million hectares.

5.5 Baseline Model Results

The optimal planting share of CRISPR rice in the baseline is 35.5 percent (=10.12/28.5), and the expected profit from planting both types of rice equals 12.32 billion US dollars. This result, however, does not solve the farmer's dilemma mentioned in the title of this paper. Namely, for a given probability of pest outbreak, would the farmer be better off planting both types of rice or sticking to conventional rice instead? Using our baseline model, we calculate that the farmer's expected profit in a counterfactual scenario with conventional rice only and the same probability of severe pest outbreak as in the baseline is 10.48 billion US dollars. Thus, in the baseline, the farmer benefits from cultivating both types of rice 1.84 billion US dollars annually. It would also be possible to calculate the effect of cultivating CRISPR rice only; we do not do this, however, as it is very likely that there will always be farmers who will choose not to adopt the new technology.

Table 2 sheds more light on the discussion above by presenting results decomposed by the pest severity and rice type. The first row presents profits in billion US dollars, while the second row quantifies profit per hectare. It can be checked that the expected profit when both types of rice are planted is 12.32 billion US dollars at the baseline probability of severe pest outbreak of 14/41.

Table 2. Profits from rice production under various scenarios

	Severe pest			Weak pest		
	Both types planted			Both types planted		
	CRISPR	Conv.	Only conv.	CRISPR	Conv.	Only conv.
Total profit from a rice type i (billion $)	4.16	1.19	1.84	6.29	9.65	14.96
Profit per hectare ($/ha)	410	60	60	620	520	520

The first thing to notice in the first row of Table 2 is that profits in the severe case are significantly lower compared to the weak pest case. Looking at the relative difference, the gap for CRISPR rice is -33.8 percent, but it is much more pronounced for conventional rice (-87.7 percent). This suggests that the profitability of conventional rice is much more sensitive to the uncertainty around the pest outbreak than is CRISPR rice (which has an insect-resistant trait). This result is also in line with the observed reversal of the profitability of conventional rice relative to CRISPR rice (i.e., 9.65 billion vs 6.29 billion in the weak pest case compared to 1.19 billion vs 4.16 billion in the severe case) in the first row in Table 2.

Based on profits per hectare, we expect the farmer to favor CRISPR rice as it can bring almost 20 percent more profit per unit of land in the weak pest scenario (620/520 - 1) and nearly seven times more in the severe pest scenario (410/60). The values in Table 2 also indicate that growing both rice types simultaneously is beneficial to the farmer as the difference between profits in the severe and weak pest case for conventional rice is -87.7 percent (1.84/14.96 - 1) but decreases to -66.4 percent (5.35/15.94 - 1) when both types are grown.

The representative farmer in our model is risk averse. The certainty equivalent corresponding to the baseline values and the assumed exponential Bernoulli utility function is 11.10 billion US dollars. The resulting risk premium is thus 1.22 billion US dollars (12.32 billion – 11.10 billion), that is, an amount of money the farmer would be willing to pay to obtain the amount equal to the certainty equivalent without having to deal with the uncertainty related to the pest severity.

Clearly, the baseline results we have just presented depend on the chosen parameters. To check how robust they are, in the following section, we run sensitivity analysis using Monte Carlo simulations.

5.6 Sensitivity Analysis of the Baseline Results

We start by generating a PERT distribution for each parameter of interest (Table 1) from which we then randomly draw the parameter values 100,000 times, each time running the model and recording the results. We use the PERT distribution because of its minimum prior information requirements: the maximum, minimum, and the most probable value (mode) of a parameter. Better than other distributions, the PERT distribution constructs a smooth curve with the expectation that the resulting value will be around the most likely value (Davis, 2008).

Table 1 presents the baseline values of the parameters that we use as the mode of the PERT distribution. If a parameter has natural limits (e.g., probability of pest severity), we use those for the minimum and maximum. In the remaining cases, we rely on the previous literature (e.g., percentage of conventional yield left after the severe pest damage), historical data (e.g., market price of per-hectare conventional rice), or in the absence of sources, we set the lower (upper) bound to be 30 percent below (above) the baseline value. Table 1 provides the sources of individual confidence intervals. We perform the Monte Carlo simulations in *R×64 3.4.3* software (R Core Team, 2019; Hasselman, 2018; Fletcher, 2012).

Before we turn to the results of the sensitivity analysis, we would like to mention that not all results of the 100,000 model runs were considered. First, we excluded the infeasible solutions, that is, those where the planting share was either negative or greater than one. These solutions can occur in numerical simulations for some assemblages of model parameters. Second, for other constellations of exogenous parameters, the model was not able to find an optimal solution (problems with convergence), which is most likely due to the model's non-linearities. In the end, we included the results of 89,934 model runs (i.e., almost 90 percent) in the sensitivity analysis.

Figure 3 depicts the kernel density function of the optimal planting share based on the successful 90 percent of model runs. The median of the planting share is 26.9 percent, and the mean is 30.6 percent. These values need to be juxtaposed with the percentage calculated in the baseline (35.5 percent). Clearly, the uncertainty over model parameters translates also into the value of the planting share. For completeness, the standard deviation of the distribution in Figure 3 is 18.2 percentage points.

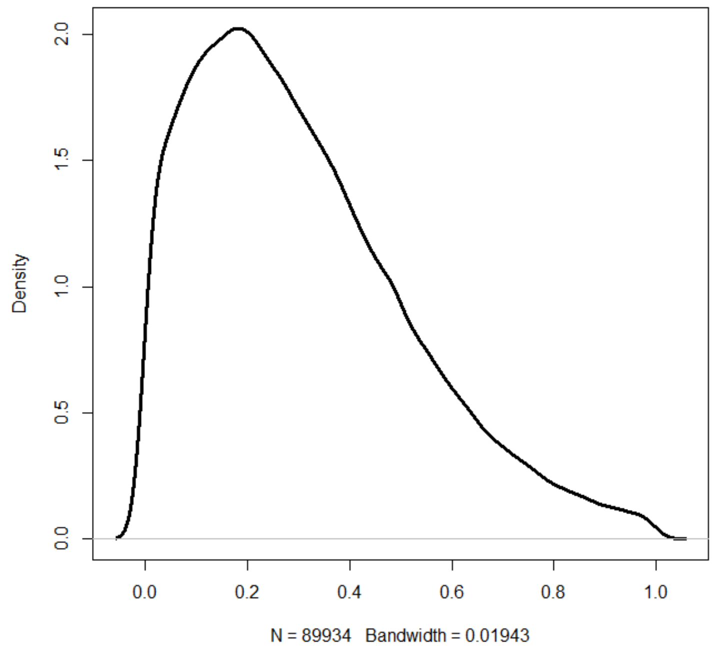

Figure 3. Kernel density function of the optimal planting share of CRISPR rice

Note: The horizontal axis represents the optimal planting share of CRISPR rice. The median and the mean are 26.9 and 30.6 percent, respectively; the standard deviation is 18.2 percentage points. The actual values on the horizontal axis are between zero and one. However, the R software does not truncate the kernel density function at zero and one and slightly extends it beyond the given limits instead.

Table 3 shows more detailed sensitivity results for the optimal planting share, expected profit, certainty equivalent, and risk premium. We distinguish between the case where both rice types are planted and where the farmer grows only conventional rice. Both scenarios are run in one iteration, and the process is repeated 100,000 times. In each iteration, we randomly draw from the distributions of individual parameters. With those parameters, we calculate the variables of interest for both types of rice and for conventional rice only. Due to the change in the model structure in the second scenario, the number of feasible and optimal model runs decreases from 89,934 (as reported in Figure 3) to 55,917.

Table 3. Results of the Monte Carlo simulations (N = 55,917) (billion US dollars)

	Min	**1st quartile**	**Median**	**Mean**	**3rd quartile**	**Max**	**Standard deviation**
CRISPR rice and conventional rice							
Optimal share (%)	0.00	14.10	26.85	30.63	43.33	99.98	18.20
Expected profit	0.75	13.81	17.21	17.54	21.00	57.89	5.14
Certainty equivalent	0.27	12.80	16.05	16.39	19.68	57.50	5.00
Risk premium	0.00	0.65	1.05	1.14	1.54	5.61	0.66
Conventional rice only							
Expected profit	0.00	10.93	14.81	15.10	19.14	38.25	5.72
Certainty equivalent	0.00	9.54	13.23	13.52	17.35	37.48	5.58
Risk premium	0.00	0.88	1.47	1.57	2.14	6.38	0.91
Value of co-planting CRISPR rice	-12.46	0.85	1.83	2.44	3.38	32.39	2.24

Table 3 shows that the expected profit and certainty equivalent of the risk-averse farmer growing rice are greater when both types of rice are grown compared to conventional rice only. This confirms the baseline result that the farmer benefits from diversifying her production by including CRISPR rice. Notice also that the farmer requires a smaller price premium when her rice production is more diversified, a result fully in line with the previous discussion.

So what is the value of co-planting CRISPR rice in addition to conventional rice? We define it as the difference between farmer's expected profit with both types of rice and with conventional rice only. The last row in Table 3 gives the estimates. The median of the value of co-planting CRISPR rice equals 1.83 billion US dollars, and the mean is 2.44 billion US dollars, suggesting a distribution of the values skewed to the right. Overall, in 99 percent of the cases we find a positive value of co-planting CRISPR rice. The results are depicted in Figure 4. It should be noted that the values in the last row of Table 3 do not equal a simple difference between the expected profit values in the lines above. It is because the presented values in either scenario do not (necessarily) correspond to the same model run.

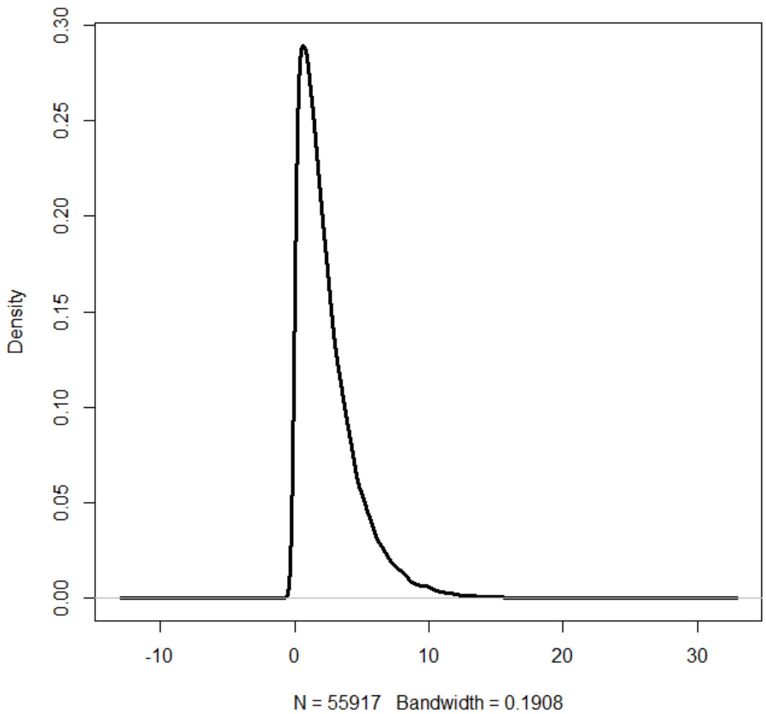

Figure 4. Kernel density function of adopting CRISPR rice

Note: The horizontal axis represents values in billion US dollars. The median, mean, and standard deviation are 1.83, 2.44, and 2.24 billion US dollars, respectively.

5.7 What Affects the Optimal Planting Share of CRISPR Rice Most?

The information about the share of land to be devoted to CRISPR rice and its determinants is likely to be of interest to several market agents, especially the seed industry and the government. Different units of the various parameters do not make a direct comparison of their influence on the optimal share possible. However, converting the dependent variable (optimal share) and independent variables (exogenous parameters) into logs, we can use an ordinary least square regression on the converted variables to obtain coefficients, which by construction will represent elasticities of the optimal share with respect to individual parameters. The higher the absolute value of an elasticity, the stronger the effect of a parameter on the optimal planting share. Table 4 presents the results.

The signs of all regression parameters are significant at the one-percent level and consistent with theoretical expectations (any exception is the shape parameter of the abatement function under weak pests, which is not significant). The five most influential parameters are ε, p_2, Y_2, p_1, and Y_1. At the risk of extending the results too far, we see three main groups of factors affecting the optimal planting share of CRISPR rice in China: the regulatory environment (especially the segregation costs that is associated with the parameter ε), the market situation (represented by the market prices of CRISPR and conventional rice, p_1 and p_2), and the state of the technology (proxied by the potential yields of CRISPR and conventional rice, Y_1 and Y_2). Of the three groups of factors, seed quality (translated into potential yield) is the one over which seed producers have direct control.

Regarding the relationship between farmer's (constant absolute) risk aversion (r) and the optimal planting share of CRISPR rice, the positive and highly significant coefficient means that a more risk averse farmer tends to prefer a higher share of CRISPR rice (as it brings higher expected profit compared to conventional rice alone). The negative sign of the coefficient on the total rice acreage indicates that growing urbanization in China could increase the acreage ratio of CRISPR rice to the detriment of conventional rice (provided that commercialization of CRISPR rice is allowed in the future).

Table 4. Relative impacts of exogenous parameters on the optimal planting share

Parameter	Symbol	Estimate
Price of CRISPR rice (1000 $/ton)	p_1	5.51***
Price of conventional rice (1000 $/ton)	p_2	-6.67***
Share of max. CRISPR rice yield after the most severe insect pest damage	α_1	2.10***
Share of max. conv. rice yield after the most severe insect pest damage	α_2	-1.68***
Price of pesticide (100 $/kg)	m	0.44***
Max. yield of CRISPR rice (ton/hectare)	Y_1	4.50***
Max. yield of conv. rice (ton/hectare)	Y_2	-5.95***
Total rice area (million hectares)	$\bar{L}$	-0.85***
Shape parameter of the abatement function under weak pests	λ_N	0.01
Shape parameter of the abatement function under severe pests	λ_S	-0.46***
Parameter of other costs of CRISPR rice	A	-2.14***
Probability of severe insect pests	q	0.22***
Segregation cost parameter	ε	-7.72***
Constant absolute risk aversion	r	0.11***
Other costs per hectare of conventional rice under weak pest (1000 $/hectare)	φ_N	1.14***
Other costs per hectare of conventional rice under severe pest (1000 $/hectare)	φ_S	2.15***
Intercept		4.29***
	Adjusted R^2	**0.82**

Note: *** indicates statistical significance at < 0.001 percent level.

5.8 Conclusions

The CRISPR technology has been booming in the past decade, and it has enhanced plant breeding by making it more precise, faster, and cheaper (Gao, 2018). With respect to CRISPR rice, scientists expect to try alternatives or complementary approaches to insect resistance by combining other engineering methods to minimize adverse effects on yield (Lu et al., 2018), which is one of the current disadvantages that hampers the potential commercialization. CRISPR rice has the trait of insect resistance, like GM rice, while at the same time, it is similar to the rice developed by traditional breeding techniques. Therefore, there is a chance that CRISPR rice will not be considered as a GM product in China. The advantage is evident since a slow approval process is hampering the commercialization of new GM crops (Jin et al., 2019), and the largest potential constraint to commercialization is a regulatory delay (Kalaitzandonakes et al., 2007).

The future of CRISPR rice is quite uncertain under the background of the controversial debate of genome editing regulation in China. One thing is clear: to improve the optimal share of planting CRISPR rice under uncertainty of insect pest severity, which we estimate to be around 35 percent under our baseline assumptions, scientists need to improve the technical performance of CRISPR rice to make it possible to enter the market regardless of the government regulation on the strictness of segregation.

One of the messages of our paper is that there is a very high probability of positive economic benefit of planting CRISPR rice together with conventional rice as compared to focusing on conventional rice alone. Our mean estimate of this benefit is 2.44 billion US dollars annually under the uncertainty over the pest severity.

Although our results show significant potential for CRISPR rice to enter the Chinese market, we are aware of the fact that they might be affected by the assumptions we had to make. First, not all data are available, especially those related to the production of CRISPR rice. In that case, we adopted information for Bt rice, which, although similar, is not the same as CRISPR rice. Second, we have modeled the optimal planting share of CRISPR rice solely from the perspective of a farmer who does not take into account environmental externalities related to pesticide and fertilizer use, to mention but a few. These considerations might be important in the future, should the Chinese government regulate these negative environmental externalities more strictly. We expect that the inclusion of these effects would increase the share of CRISPR rice. Third, we have considered a representative farmer for China. However, the climatic and production conditions in China vary, as do production costs of rice in different regions. Further research zooming into the regional differences is certainly needed. That said, once the new data for CRISPR (and conventional) rice become available, the framework we have outlined in this article can readily be (updated and) used to produce more precise results.

The decision of China about approval and commercialization of CRISPR rice will be crucial for the United States and the European Union as China is a large global producer of rice. Inconsistent regulatory rules in different countries about CRISPR technology might affect international trade by the coexistence with conventional products. The regulations will also influence the direction of research and development of plant-breeding companies, their focus on the potential target markets, as well as the future development of CRISPR technology in general.

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5.10 Appendix

Using the functional forms specified the earlier section of the paper, first-order conditions [5] – [7] corresponding to the specific functional forms of the model can be written as

$$\frac{\partial EU}{\partial L_1} = qre^{-r\pi_S} \left\{ \begin{array}{l} p_1\left[\alpha_1 Y_1 + \left(1-e^{-\lambda_S X_1}\right)\left(1-\alpha_1\right)Y_1\right] + p_2\left[-\alpha_2 Y_2 - \left(1-e^{-\lambda_S X_2}\right)\left(1-\alpha_2\right)Y_2\right] \\ -\left[mX_1 + \varepsilon A L_1^{\varepsilon-1} - \left(\varphi_S + mX_2\right)\right] \end{array} \right\}$$
$$+\left(1-q\right)re^{-r\pi_N} \left\{ \begin{array}{l} p_1\left[\alpha_1 Y_1 + \left(1-e^{-\lambda_N X_1}\right)\left(1-\alpha_1\right)Y_1\right] + p_2\left[-\alpha_2 Y_2 - \left(1-e^{-\lambda_N X_2}\right)\left(1-\alpha_2\right)Y_2\right] \\ -\left[mX_1 + \varepsilon A L_1^{\varepsilon-1} - \left(\varphi_N + mX_2\right)\right] \end{array} \right\} = 0$$

[5']

$$\frac{\partial EU}{\partial X_1} = qre^{-r\pi_S}\left\{p_1\left(1-\alpha_1\right)Y_1 L_1 \lambda_S e^{-\lambda_S X_1} - mL_1\right\} +$$
$$\left(1-q\right)re^{-r\pi_N}\left\{p_1\left(1-\alpha_1\right)Y_1 L_1 \lambda_N e^{-\lambda_N X_1} - mL_1\right\} = 0$$

[6']

$$\frac{\partial EU}{\partial X_2} = qre^{-r\pi_S}\left\{p_2\left(1-\alpha_2\right)Y_2\left(\bar{L}-L_1\right)\lambda_S e^{-\lambda_S X_2} - m\left(\bar{L}-L_1\right)\right\} +$$
$$\left(1-q\right)re^{-r\pi_N}\left\{p_2\left(1-\alpha_2\right)Y_2\left(\bar{L}-L_1\right)\lambda_N e^{-\lambda_N X_2} - m\left(\bar{L}-L_1\right)\right\} = 0$$

[7']

Notice that the term L_1 can be canceled out in [6'] as can be $L_2 = \bar{L} - L_1$ in [7'], such that the first-order conditions for X_1 and X_2 do not directly dependent on the areas of land, which makes intuitive sense because *X* represents the application of pesticide per hectare. However, there is also an indirect effect via the profits π_S and π_N (in the exponents of [6'] and [7']), which depend on the allocation of the total area of land to L_1 and L_2.

Chapter 6

General Discussion

6. GENERAL DISCUSSION

6.1 Overview of Findings

The general objective of this study is to examine the approval process and stakeholders' views on GM crops and the economic impacts of adopting new rice biotechnology in China. I first examined stakeholder participation in the online public debate on GMOs in China and how the debate influences the reactions of stakeholders over time. This provided the general setting for the GMO environment in China, where stakeholders form competing coalitions to influence the public. China has a complex GMO regulatory process, which contributes to relatively long approval times and relatively late approval dates. I then examined the factors affecting the approval process and interpreted the trend of approval time for imported GM crops in China. Although Bt rice has undergone all the safety assessments and environmental trials in the regulatory process, its commercialization and cultivation are pending. Next, I assessed the opportunity cost of postponing Bt rice commercialization in China due to regulatory delay. Recently, CRISPR rice has presented an alternative to GM rice, which is similar to the rice developed by traditional breeding techniques since no new gene is inserted. I finally estimated the annual benefit of growing CRISPR rice ex ante and determined the most influential factors on its adoption and optimal planting share.

To achieve the overall objective of this study, four research questions were addressed. To synthesize the study, the following is a summary of the answers in the four chapters.

Research question 1: What are the main characteristics and trends of the public debate on GMOs in China?

To the best of my knowledge, this is the first study to analyze the online debate about adopting GMOs in China. I analyzed posts on Weibo, a Chinese microblog website, using discourse network analysis to identify coalitions and communities within each coalition. Two competing coalitions emerged, one supporting GM crops and the other opposing them. The supporter coalition included members from the government, international organizations, the business community, media, science, foreign governments, and the legislature, while the opponent coalition included members of the government, foreign governments, business, media, environmental groups, international organizations, and courts. The opponent coalition comprised six times more actors than the supporters, indicating that the opponents of GM crops were, on average, more active in striving to influence the public. In general, the debate was dominated by relatively active opponents of GM crops, consisting largely of anonymous individuals. Their strategy involved eliciting emotions and disputing scientific evidence. In contrast, and consistent with findings from previous studies (Augoustinos et al., 2010; Mielby et al., 2013), supporters primarily emphasized scientific evidence about food and environmental safety.

Both coalitions represented domestic governments, indicating conflicting domestic views at different levels, such as the case of Heilongjiang province. In our database, all actors identified as scientists were in the supporter coalition. The participation of companies with lobbying intentions on Weibo trying to influence the public's opinion on GM crops was relatively low. In addition, time dynamics showed how stakeholders change their behavior over time. Members of the government, business, and media have been more involved in the debate as supporters recently, which started in late 2018, when the MARA began efforts to increase public knowledge about GM crops with the help of the media.

Based on social network cluster analysis, Chapter 2 explored the reasons that opponents generally participated much more actively in the online debate. The opponents of GM crops seem more variegated due to various concerns, such as those concerned primarily about the potential risk of GM crops due to distrust of the government (Cluster 1); those doubting the transparency of current risk assessment and regulations (Cluster 2); those believing that GM crops would harm public health, the environment, or traditional agriculture (Cluster 3); and those opposing GM crops due either to long-term scientific uncertainty or no specific reason (Cluster 4). However, the clusters varied among different time periods.

Chapter 2 illuminated the GMO environment in China, which is crucial for understanding the strict regulatory process of GMOs and the current decisions of policymakers.

Research question 2: What is the approval process of commercializing GM crops in China, and what are the factors affecting the approval length for imported GM crops in China?

This is the first study to quantitatively analyze the factors affecting the approval length for imported GM crops in China. Chapter 3 first reviewed the complex Chinese regulatory system involving many departments and a host of regulatory documents for approving GM crops. The approval of GM crops for import as processing materials in China starts with an application to the MARA, followed by domestic environmental release trials and food safety tests and ending with issuing biosafety certificates. This complex approval process contributes to relatively long approval times and relatively late approval dates. To better understand this, I investigated approval-time trends for imported GM crops from 2002 to 2017 and the factors affecting approval. For imported GM crops, I analyzed how crop characteristics and other factors affected approval times between 2002 and 2017. The results indicated that GM maize took significantly longer to be approved than other GM crops but that other crop characteristics did not significantly affect approval times. The average time to obtain approval for imported GM crops in China increased by around 16 months after ca. 2010 due to increased public concerns about GM crops, which Chapter 2 analyzed. This trend contrasts with that in the European Union, which is decreasing (Smart et al., 2017). Worldwide, I compared the approval dates and approval times of GM varieties approved in China, the United States, Canada, and the European Union. China approves GM crops, on average, around one year earlier than the European Union but lags, on average, 4.2 years behind the United States and 4.9 years behind Canada. The mean approval time for imported GM crops in China is three years less than that in the United States and 1.9 years shorter than that in the European Union.

Research question 3: What are the foregone benefits of lower pesticide use associated with Bt rice and its technology spill-overs on the price of international rice?

Regulatory delay has economic consequences. The suspension of the commercialization and cultivation of Bt rice in the past ten years has created postponement costs. To the best of my knowledge, this is the first study to quantify the foregone benefits of lower pesticide use associated with Bt rice and its technology spill-overs on the price of international rice. Chapter 4 determined the opportunity cost of postponing Bt rice commercialization in China between 2009 and 2019 to be 12 billion US dollars per year, including the external costs in the economic surplus model. I estimated the annual external costs of the uses of Chlorantraniliprole, Imidacloprid, and Cartap hydrochloride in China to be 1.8 million US dollars (0.06 dollars per hectare of agricultural land) using the pesticide environmental accounting tool. Considering China a large, open economy, the cost postponing the commercialization of Bt rice from 2009 to 2019 was 104 billion US dollars under a 3% discount rate and 94 billion US dollars under a 5% discount rate.

The results in Chapter 4 showed that the continuous postponement of Bt rice introduction in China has come at a substantial economic cost, including not only direct economic losses of efficiency due to higher prices of rice for consumers but also human health and environmental costs. These costs must be weighed against the concerns about Bt rice analyzed in Chapter 2. Consumers tend to ignore the environmental benefits of crop production in their purchasing behavior. The introduction of Bt rice in combination with information about its environmental benefits (Ando & Khanna, 2000; Wesseler et al., 2011) may overcome some of the potential consumer resistance.

The cost of postponing Bt rice over the past ten years can be considered a sunk cost due to the regulatory delay analyzed in Chapter 3. With the rapid development of genome-editing technology in plant breeding, potential changes in GM technology trends are of great interest to those working on genome editing for more accurate expectations. Genome-editing technology is, in many ways, even more precise and predictable than GM technology (Gao et al., 2018), so people expect that genome editing will be accepted by the public more easily. An ex ante analysis of crops based on genome editing is urgent to farmers, seed developers, and policymakers concerning the case of Bt rice.

Research question 4: What is the annual benefit of CRISPR rice adoption under the uncertainty of pest severity, and which factors are the most influential on the optimal planting share of CRISPR rice?

CRISPR rice has the trait of insect resistance, like GM rice, but like rice developed by traditional breeding techniques, no new gene is inserted, so CRISPR rice may not be considered a GM product in China. This advantage is evident since a slow approval process hampers the commercialization of new GM crops, as discussed in Chapter 3, and postponing its approval incurs a considerable opportunity cost, as discussed in Chapter 4. To the best of my knowledge, this is the first study to estimate the annual benefit of CRISPR rice adoption under the uncertainty of pest severity and determine ex ante the most influential factors on the optimal planting share.

Chapter 5 economically assessed the market potential of CRISPR rice considering the uncertainty of insect pest severity and providing a framework to assess the influence of its factors. I developed a microeconomic model of a representative rice farmer allocating her land into conventional and CRISPR rice under the uncertainty of insect pest severity considering the yields differential. For a given probability of pest outbreak, would the farmer be better off planting both types of rice or just sticking to conventional rice? Using my microeconomic model, I calculated that the representative farmer's expected profit in a counterfactual scenario with only conventional rice and the same probability of a severe pest outbreak as the baseline was 10.48 billion US dollars. The results showed that the farmer benefited from cultivating both types of rice at 1.84 billion US dollars annually. Based on profits per hectare, I expected the farmer to favor CRISPR rice, as it could bring almost 20% more profit per unit of land in a weak pest scenario and nearly seven times more in a severe pest scenario.

Converting the simulated dependent variable (optimal share) and independent variables (exogenous parameters) based on Monte Carlo simulations into logs, I used an ordinary least-squares regression on the converted variables to obtain coefficients, which by construction represented the elasticities of the optimal share with respect to the individual parameters. Three main groups of factors affect the optimal planting share of CRISPR rice in China: the regulatory environment, the market situation, and the state of the technology. Of these three groups, producers have direct control over only the state of the technology indicated by the potential yield.

The ex ante economic analysis of the market potential of CRISPR rice in Chapter 5 contributes to the literature since the future of CRISPR rice is still uncertain against the background of the controversial debate on genome-editing regulation in China. To fully benefit from the CRISPR revolution, we should focus on resolving its technical and regulatory uncertainties (Gao, 2018).

6.2 Policy Implications

Even though new rice biotechnology is available for and needed by many developing countries, such as China, various obstacles still hinder its immediate adoption. More science-based input is needed to provide policy makers with more information to weigh the pros and cons and make decisions while considering the inevitable opportunity costs of waiting for research outcomes. Timing under uncertainty is both a science and an art.

The public influence on Weibo from competing coalitions shows that the coalition opposing rice biotechnology has been much more active in the online debate in the past seven years. Their main reasons, which Chapter 2 covers, provide information to enhance the Chinese government's understanding of the concerns of citizens and its ability to target those concerns more specifically when promoting the commercialization of GM crops instead of merely repeating the potential benefits and safety of GM crops based on scientific evidence. One reason for opposition involves distrust of the government, so regaining public trust is vitally important for food policies related to controversial topics (e.g., GMOs and food labeling) as well as other more general societal issues. Mass media is an important way for the public to access GM-relevant information, so for companies with lobbying intentions, promoting GMOs through social media (e.g., Weibo) might be a feasible supplement to direct governmental lobbying, given that the MARA also considers socio-economic and political factors when making decisions (USDA, 2015). These implications also apply to other countries aiming to commercialize GM crops while facing strong public resistance.

China has a complex regulatory system and GMO approval process, as shown in Chapter 3. For imported GM crops, a foreign seed company is only entitled to apply for a biosafety certificate in China after the variety has been approved in its country of origin for the same use. The prohibition of simultaneous application in both the foreign country and China leads to asynchronous approval, which may significantly impair trade (Faria & Wieck, 2015). Therefore, the requirement of an asynchronous application is recommended to be removed to mitigate asynchronous approvals of the same GM crop variety in the world. Besides, technical assessments are required once again in China when applying for biosafety certificates. Possibilities for accelerating the Chinese approval process include immediate approval for the import and processing of GMOs that have received approval in their countries of origin to avoid needlessly replicating technical assessments in China. Although the issue is controversial, this may substantially reduce trade disruptions caused by asynchronous approval and increase the comparative advantage of food production in China.

The continuous postponement of Bt rice introduction in China has come at a substantial economic cost that includes not only the direct economic losses of efficiency at higher prices of rice for consumers but also human health and environmental costs. Besides addressing the potential benefits and safety of GM crops, an information campaign about its environmental and health benefits is recommended based on the reduced usage of pesticides and increased human health, which also applies to other insect-resistant GM crops worldwide. The immediate approval of Bt rice cultivation in China is also recommended from both economic and environmental perspectives. To address potential consumer concerns, its introduction may be accompanied by mandatory labeling of products derived from Bt rice.

The scope of biosafety processes must also broaden to involve genome editing. China’s decision about the approval and commercialization of CRISPR rice will be crucial for other main trading countries, as China is a large global producer and trader of rice. Inconsistent regulatory rules in different countries for CRISPR technology might affect international trade by allowing the coexistence of similar conventional products. Since there are already inconsistent regulations between the United States and the European Union, the issue of coexistence and segregation is inevitable for China as an important rice exporter and importer. Chapter 5’s ex ante economic analysis on the market potential of CRISPR rice found a higher probability of economic benefit from planting CRISPR rice together with conventional rice than from focusing on conventional rice alone, indicating the significant potential for CRISPR rice to enter the Chinese market. The regulatory environment (i.e., the strictness of segregation) is the most important factor affecting the optimal planting share of CRISPR rice in China. Therefore, a simplified approach to regulating genome editing (such as the US approach) is recommended based on safety assessments and economic considerations. Simplified regulations will shorten the approval time and reduce the cost of segregation, which will also positively influence the direction of research and development of plant-breeding companies and the development of CRISPR technology in general. Scientists are recommended to continue improving the technical performance of CRISPR crops to enable them to enter the market regardless of governmental regulations on the strictness of segregation.

6.3 Limitations and Recommendations for Future Research

In general, this study does not go into great detail about the international trade of GM crops, the most influential factors in the asynchronous approvals of different leading players in the international rice market, or the impact of asynchronous approvals. Further research is suggested to economically analyze biotechnology in China and worldwide regarding international trade and the impacts of asynchronous approvals.

Limitations of Chapter 2

The discourse network analysis in Chapter 2 is based on the heated debate topics on Weibo with more than 5,000 discussions, resulting in 781 statements of Weibo users with clear attitudes about GM crops between March 2013 and April 2020. Selection bias might lead us to consider only the most heated debate topics, however, so we should be careful in interpreting and generalizing the conclusions for a larger population not participating in online debate. Although the absolute number of statements from the government may seem small, Chinese government officials seldom engage in online debate, unlike government officials in other countries. More research is needed to check the robustness of these findings with a larger sample size over a longer period (e.g., using big-data analysis).

Limitations of Chapter 3

Due to the data limitations of the application dates of domestic GM crop varieties for biosafety certificates, Chapter 3 only focuses on investigating the trends of approving an imported GM crop in China, which is of great interest for foreign seed-developing companies and those working with genome-editing technologies in plant breeding for more accurate expectations. At this stage, only GM cotton and GM papayas are allowed for commercialization and cultivation in China, even though various GM crop varieties have biosafety certificates. Therefore, future research should focus on domestic GM crop varieties, such as investigating the trends of domestic GM crop varieties receiving biosafety certificates in China and the time between acquiring them and being approved for cultivation. Future research can also expand to crop varieties developed by other technologies for plant breeding in agriculture, such as genome editing.

Limitations of Chapter 4

The economic surplus model is one of the most parsimonious methods in terms of data requirements with a long history of ex ante analysis. However, it requires a set of assumptions (Alston et al., 1995). The limitations of Chapter 4, as with most research based on the economic surplus model, include assuming elasticities based on the literature and ignoring transaction costs, possibly resulting in an overestimation of benefits. It also ignores the effects of any relationships with other products and factors in the market, which is assumed by all partial equilibrium models. Although Chapter 4 includes the external costs of individual chemicals in rice production using the pesticides environmental accounting tool to quantify the environmental impact, expanding the model to include more sophisticated features, such as stochastic parameters, is left for future research.

Limitations of Chapter 5

Chapter 5 contributes to the literature by quantifying the value of including CRISPR rice in farmers' production compared to growing conventional rice alone. The theoretical framework I advanced enables simulating counterfactuals to evaluate the impacts of future actions of the Chinese government with respect to CRISPR rice. However, it makes assumptions. First, not all data are available, especially those related to the production of CRISPR rice. In that case, I adopted information for Bt rice, which, although similar, is different from CRISPR rice. Second, I modeled the optimal planting share of CRISPR rice solely from the perspective of a farmer who does not consider environmental externalities related to pesticide and fertilizer use, to mention but a few. These considerations might be important in the future if the Chinese government regulates these negative environmental externalities more strictly. The expectation is that the inclusion of these effects would increase the share of CRISPR rice. Third, I considered a representative farmer in China. However, the climatic and production conditions in China vary, as do the production costs of rice in different regions. Further research zooming into regional differences is undoubtedly needed.

SUMMARY

This study examines the approval process for GM crops and stakeholders' views on them, and it analyzes the economic impacts of adopting new rice biotechnology in China. The applied approaches can be adapted and extended to other products with similar concepts and backgrounds.

The main body of the study consists of four chapters (Chapters 2–5). In Chapter 2, I examine stakeholder participation in the online public debate on GMOs in China and how the debate influences the reactions of stakeholders over time. I analyze posts on Weibo, a Chinese microblog website, using discourse network analysis to identify coalitions and communities within each coalition. The findings reveal a strong opposition to GM crops and the existence of two competing coalitions of supporters and opponents. The number of supporting posts by anonymous individuals has risen in recent years, and the positions of stakeholders have changed over time.

The general GMO environment, as discussed in Chapter 2, is important for understanding the current GMO regulatory system in China. In Chapter 3, I review the complex Chinese regulatory system involving various departments and a host of regulatory documents for approving GM crops. I analyze the trend of the approval process of imported GM crops in China as well as the factors affecting their approval to better understand the complex underlying process. The results show that the average time to obtain approval for imported GM crops in China increased by around 16 months after ca. 2010 due to increased public concerns about GM crops. Worldwide, China approves GM crops, on average, around one year earlier than the European Union but lags, on average, 4.2 years behind the United States and 4.9 years behind Canada.

Like many other countries, China experiences regulatory delay, which Chapter 3 analyzes. This has economic consequences. In Chapter 4, I determine the opportunity cost of postponing Bt rice commercialization in China between 2009 and 2019 to be 12 billion US dollars per year considering the external costs of pesticide to be 1.8 million US dollars per year. The positive impacts of technology spill-over, the maximum adoption rate, and the diffusion rate on the cost of postponement are analyzed. The results show that the continuous postponement of Bt rice introduction in China has come at a substantial economic cost that includes not only the direct economic losses of efficiency at higher prices of rice for consumers but also human health and environmental costs.

The current blockage of cultivating GM crops resulting from public debate, together with the complex regulatory process in China, have implications for the potential regulation of crops derived by genome editing. In Chapter 5, I economically assess the market potential of CRISPR rice considering the uncertainty of insect pest severity and provide a framework to assess the influence of its factors ex ante. CRISPR rice has the trait of insect resistance, like GM rice, but like rice developed by traditional plant-breeding techniques, no new gene was inserted. I develop a microeconomic model of a representative rice farmer who allocates her land into conventional and CRISPR rice under the uncertainty of insect pest severity considering the yields differential. The results show that the representative farmer benefits from cultivating both types of rice by 1.84 billion US dollars annually. Based on profits per hectare, I expect the farmer to favor CRISPR rice because it can bring almost 20% more profit per unit of land in a weak pest scenario and nearly seven times more in a severe pest scenario. Monte Carlo simulations show three main groups of factors that affect the optimal planting share of CRISPR rice in China: the regulatory environment, the market situation, and the state of the technology. The ex ante economic assessment of CRISPR rice contributes to the current heated discussion on how to regulate genome editing in China.

Biography

Yan Jin was born in Shanghai, China, on December 23, 1991. She studied finance at Sichuan University in China from 2010 to 2014 and received her B.Sc. degree. During her bachelor's studies, she studied at the University of Turku in Finland as an Erasmus Mundus scholar for half a year. From 2014 to 2016, Yan studied Economics, Management, and Consumer Studies at Wageningen University in the Netherlands and graduated with an M.Sc. degree. In November 2016, Yan started her Ph.D. studies in the Agricultural Economics and Rural Policy Group at Wageningen University under the supervision of Prof. Dr. Justus Wesseler, Dr. Dušan Drabik, and Prof. Dr. Nico Heerink. During this period, she spent six months at Heidelberg University in Germany as a visiting researcher. After finishing her contract in Wageningen, Yan started as a post-doctoral research fellow at Teagasc – Agriculture and Food Development Authority in Ireland. Her research focuses on the impact of regulating the cultivation and marketing of crops derived from genetically modified organisms, new plant-breeding techniques, and organic farming systems. Her research interests include the welfare impacts of public policies and regulation, risk and uncertainty, stochastic modeling, technology adoption, and social network analysis.

Yan Jin

Wageningen School of Social Sciences (WASS)

Completed Training and Supervision Plan

Name of the learning activity	Department/Institute	Year	ECTS*
A) Project related competences			
Proposal Writing	WUR	2016	6
Advanced Microeconomics, ECH51806	WUR	2017	6
Advanced Macroeconomics, ENR51306	WUR	2017	6
B) General research related competences			
WASS introduction course	WASS	2020	1
Scientific Writing	Wageningen in'to Languages	2017	1.8
Presentation with Impact	WGS	2017	1
'Getting an Imported GM Crop Approved in China'	22nd International Consortium on Applied Bioeconomy Research, Washington DC, the USA	2018	1
'The CRISPR Dilemma of a Chinese Rice Farmer'	8th European Association of Agricultural Economists Workshop, Uppsala, Sweden	2019	1
	23rd International Consortium on Applied Bioeconomy Research, Ravello, Italy	2019	
'Does Modern Biotechnology Make a Difference? A Comparison of the Impact of GMOs on Owner Operator Income between the EU and the USA'	2020 Agricultural & Applied Economic Association Annual Meeting, Kansas City, the USA (virtual conference)	2020	1
	24th International Consortium on Applied Bioeconomy Research, Córdoba City, Argentina (virtual conference)	2020	
'A Paradox of Genetically Modified Crops in China: A Discourse Network Analysis of Public Mobilization on Weibo'	3rd International Bioeconomy Congress, Stuttgart, Germany (virtual conference)	2020	1
Introduction to Programming in R for Social Sciences	WASS	2019	5
Assessing Economics and Policies Using the Real Options Methodology	WASS	2019	3

Risk Analysis and Risk Management in Agriculture: Updates on Modelling and Applications	WASS	2019	3
C) Career related competences/ personal development			
Interpersonal Communication for PhD Candidates	WGS	2017	0.6
Project and Time Management	WGS	2017	1.5
Member of WASS PhD Council	WASS	2017-2019	3
Teaching Assistant for Econometrics, Advanced Econometrics, Theories and Models in Economics, Economics of Agribusiness	WUR	2018-2020	3
Total			44.9

* One credit according to ECTA is on average equivalent to 28 hours of study load

Colophon

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