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Assessment of policy and climate variability impacts on food, water and energy in the Asian monsoon region under diverse adaptation scenarios

Roger Cremades Rodeja

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Zusammenfassung

Anpassungsstrategien sind insbesondere für jene wirtschaftlichen Aktivitäten relevant, die in direktem Zusammenhang mit Klimavariablen stehen, so zum Beispiel landwirtschaftliche Aktivitäten. Die aktuellen Herausforderungen einer qualitativ als auch quantitativ beschränkten Ressourcenverfügbarkeit und die durch externe Faktoren hervorgerufenen Spannungen inklusive des Klimas könnten die Lebensmittelproduktionskapazitäten des Agrarsektors reduzieren. Im Agrarsektor beziehen sich Anpassungsstrategien im Wesentlichen auf das Wasser- und Landmanagement, wobei hierbei die verbesserten Anbaumethoden zur Ressourcenschonung besonders hervorzuheben sind. Diese Herausforderungen sind beispielsweise in den Entwicklungsprozessen in Asien zu beobachten, die unter dem Einfluss des Monsuns entstehen. Das asiatische Monsunsystem, welches etwa ein Drittel der Weltbevölkerung direkt betrifft, hat starken Einfluss auf zwei Länder von besonders hoher Relevanz: Indien und China, die sich rasch entwickeln und aufgrund ihrer Größe die umwelttechnischen und ökonomischen Veränderungen im gesamten Erdsystem maßgeblich beeinflussen. Hierbei gibt es viele unerforschte Lücken am Schnittpunkt von Politik, wirtschaftlicher Entwicklung, Umweltökonomie, Klimaeinfluss und globalem Wandel als Ganzes in den oben beschriebenen Zusammenhängen. Das Gesamtziel ist es, eine Zusammenfassung über jene Lösungsansätze bereitzustellen, welche in Asien zur Anpassung an den globalen Wandel benötigt werden. Um dieses Ziel zu erreichen nutzen wir eine Reihe von transdisziplinären Methoden, um Forschungsfragen mit einem spezifischen Fokus auf Politik, Technologie und Klimavariabilität zu untersuchen. In Kapitel 2 gebrauchen wir ein ökonometrisches Modell, um den Einfluss der chinesischen Politik auf die Anwendung von Bewässerungstechnologien im Bezug auf die allgemeine Anpassung an den globalen Wandel zu analysieren. Wir zeigen, dass staatliche Hilfen und wirtschaftliche Anreize sehr wichtig sind, um die Anwendung von modernen Bewässerungstechnologien bekannt zu machen. Unsere Studie zeigt zum ersten Mal, dass insbesondere der Wasserpreis einen Einfluss auf die Anwendung von Bewässerungstechnologien in China hat. In Kapitel 3 repräsentieren wir Wasser und Energie als Bindeglied der Bewässerung durch eine Reihe von Gleichungen, um die Auswirkungen der aktuellen politischen Pläne zur Entwicklung der Bewässerungstechnologien auf die Energieversorgung in China zu zeigen. Interessanterweise liegt unsere berechnete Bewässerungseffizienz für China (23,80%) unter den Werten anderer Studien. Wir finden heraus, dass der verbreitete Einsatz von Sprinklern und Mikro-

Bewässerung, wie sie im Fünfjahrplan (2011-2015) beschrieben wird, den Ausstoß von Treibhausgasen durch die agrartechnische Wassernutzung ansteigen ließe. Wir zeigen, dass die Anwendung der teuersten Technologien zu einem Ausgleich führen, während positive Nebeneffekte generell durch weniger kostspielige Technologien erreicht werden. In Kapitel 4 entwickeln wir ein integriertes Assessment-Modell, das sowohl die Saisonalität als auch die kleinen geographischen Skalen in Indien abbildet, um den Einfluss von ‚stay green' Hirse, einer innovativen Nutzpflanzenvarietät, auf den gesellschaftlichen Wollstand zu diskutieren. Wir zeigen, dass, obwohl diese Innovationen in der Landwirtschaft einen signifikanten Beitrag zur Steigerung des Wohlstands leisten, die Bereitstellung von Informationen einen größeren Beitrag zur Steigerung des Wohlstands leistet. Zu guter Letzt machen wir einige Vorschläge, wie Wissenschaft im Bereich des globalen Wandels verbessert werden könnte.

Assessment of policy and climate variability impacts on food, water and energy in the Asian monsoon region under diverse adaptation scenarios.

Abstract

Adaptation is especially relevant on those economic activities that have direct links with climate variables, like agriculture. Current challenges related to the constraints on resource availability, both on quality and quantity, and the stresses caused by external factors, including climate, might undermine the ability of the agricultural sector to produce food. In the agricultural sector, adaptation has to do mainly with water and land management, in particular with enhanced cropping techniques to improve the management of these resources. These challenges find very good examples in the developing processes occurring in Asia, under the influence of the monsoon. The Asian Monsoon system, which covers roughly one third of the global population, strongly influences two countries of special relevance: India and China, which are developing quickly and because of their relative sizes will significantly determine what will happen in the whole earth system, both environmentally and economically. There are many uncovered gaps in the intersection of policy, development economics, environmental economics, climate impacts and global change as a whole in the context described above. The overall aim is to provide an overview of the solutions needed for adaptation to global change in Asia. To achieve this aim, we use a variety of transdisciplinary methods to tackle research questions with a specific focus on policies, technologies and climate variability. In Chapter 2 we use an econometric model to analyse the impact of Chinese policies on the adoption of water technologies related to adaptation to global change. We show that governmental support and economic incentives are highly relevant to promote the adoption of modern irrigation technology. In particular water pricing is found for the first time to have an impact on the adoption of irrigation technology in China. In Chapter 3 we reproduce the water-energy nexus of irrigation in a system of equations, to show the energy implications of current policy plans of irrigation development in China. Interestingly, our calculated irrigation efficiency for China (23.80%) is lower than other estimates. We find that expansion of sprinklers and micro-irrigation as outlined in the 5YP would increase greenhouse gas emissions nationally from agricultural water use. We show that the most costly technologies relate to trade-offs, while co-benefits are generally achieved with less expensive technologies. In Chapter 4 we built and ad-hoc Integrated Assessment Model capturing seasonality and low geographical scales in India to calculate the welfare contribution of "stay-green" sorghum, an innovative crop variety. We show that although a significant amount of welfare is added by these innovations to the agricultural

sector, the provision of information has much larger welfare amounts to add. Finally, we make some suggestions to improve global change related science.

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List of Publications and Conference Presentations

Peer-reviewed publications published in scientific journals indexed in Scopus and/or Web of Science during the work on the thesis (last submission first):

Hasselmann, K., **Cremades**, R., Filatova, T., Hewitt, R., Jaeger, C., Kovalevsky, D., Voinov, A. & Winder, N. (2015). Free-riders to forerunners. [Electronic version]. Nature Geoscience, 8(12), 895-898.

Cremades, R., Rothausen, S. G., Conway, D., Zou, X., Wang, J., & Li, Y. (2016). Co-benefits and trade-offs in the water–energy nexus of irrigation modernization in china. [Electronic version]. Environmental Research Letters, 11(5), 054007. (See Chapter 2).

Li, X., Philp, J., **Cremades**, R., Roberts, A., He, L., Li, L. & Yu, Q. (2016). Agricultural vulnerability over the chinese loess plateau in response to climate change: Exposure, sensitivity, and adaptive capacity. [Electronic version]. Ambio, 45(3), 350-360.

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Zou, X., Li, Y., **Cremades**, R., Gao, Q., Wan, Y. & Qin, X. (2013). Cost-effectiveness analysis of water-saving irrigation technologies based on climate change response: A case study of china. *Agricultural Water Management*, 129(0), 9-20.

Books:

Froehlich, C., Gioli, G., Greco, F. and **Cremades**, R. (Eds).Water Security Across the Gender Divide. Springer Series "Water Security in a New World", Dordrecht: Springer. (Expected October 2016).

Contributions to conferences related to the work presented in the thesis:

2015: "Opportunities and challenges in China's irrigation water–energy nexus", joint research kindly presented by Prof. Declan Conway (London School of Economics) at the third Global Science Conference on Climate-Smart Agriculture (Montpellier). "Extreme events and the value of forecasting services for agricultural stakeholders in India" at European Climate Change Adaptation Conference (Copenhagen).

2014: Chaired poster session "Agriculture and Environment", at 5th World Congress of Environmental and Resource Economics (Istanbul). "Modeling the limits of adaptation", at 7th Annual Meeting of the Integrated Assessment Modeling Consortium (Washington). "Uncertainty and the impact of forecast information on food security and environmental externalities in India", at Global Land Project Open Science Meeting (Berlin).

2013: Chaired session "Agriculture II: Ecosystems and Water", at BIOECON Conference, Cambridge University (UK).

Chapter 1. Introduction

1.1 The Importance of Adaptation for Humankind

Adaptation can be defined as an adjustment to external stress, or as an improvement of the ability to cope with it. In the climatic scientific arena, it refers to adjustments to current or expected climatic impacts. Adaptation is a crucial concept in the human dimensions of global change, where risks, opportunities and stresses intersect with a myriad of complex processes and actions partly driven by policies and technological change (Smit and Wandel, 2006).

Adaptation is especially relevant on those economic activities that have direct links with climate variables. Adaptation in the agricultural sector is crucial. Agricultural productivity has significantly increased through the 20th century due to technological advances and policies that made them reach the fields. However, current challenges related to the constraints on resource availability, both on quality and quantity, and the stresses caused by external factors, including climate, might undermine the ability of the agricultural sector to produce food. However, agriculture is not a significant part of the gross domestic product of the developed world. Even so, it might be also noted by the reader that there is no other source of food that could substitute the output of the agricultural sector. Beyond the production of food, agriculture in developing countries has a major role in societal stability. For this reason agriculture has a value that, even if it can be quantified, goes beyond its economic dimension.

In the agricultural sector, adaptation has to do mainly with water and land management, in particular with enhanced cropping techniques to improve the management of these resources. Water is an essential factor, and there is a quest for searching technologies and for developing new plant varieties that can help to cope with current climate variability and with an increase of risks related to climate change.

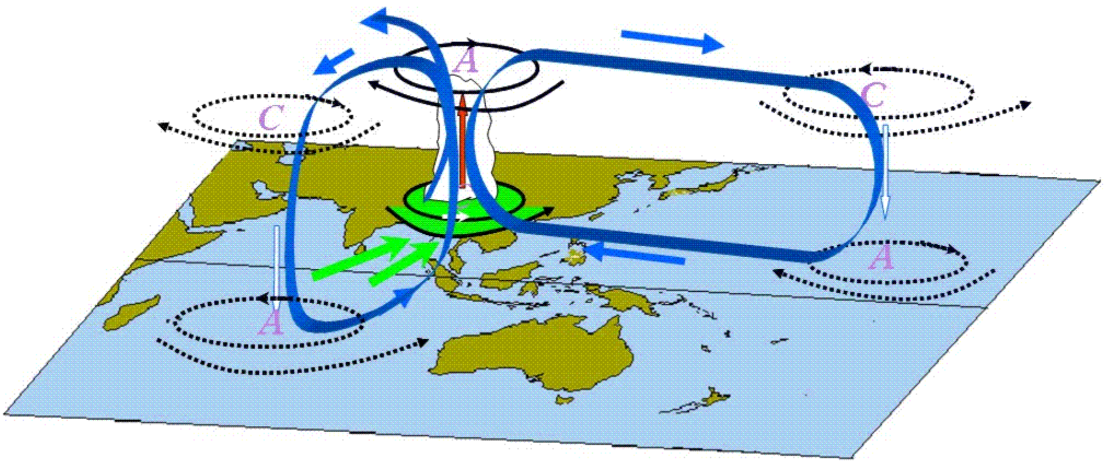

Figure 1-1 Boreal Summer broad scale circulation of the Asian Monsoon system; A stands for anticyclonic circulation (high pressure), whereas C stands for cyclonic circulation (low pressure) (Source: CLIVAR/GEWEX Monsoons Panel).

1.2 Motivation for the Selection of the Regions Covered

From the whole region covered by the Asian Monsoon system, which covers roughly one third of the global population, I[1] selected two countries of special relevance. India and China are developing quickly and many questions are raised over their ability to cope with increased demands of water and land, considering the limited amount available of these resources. It is indeed necessary for any global researcher to have at least a perspective on what is happening in these regions, because of their significance at the global level the outcome of their development processes will determine what will happen in the whole earth system, both environmentally and economically.

The Asian Monsoon system is a seasonal reversal of atmospheric circulation and associated precipitation, arising from reversal changes in temperature gradients between the land surface and the neighbour oceans. In Figure 1-1 we can observe the boreal summer circulation pattern with ascent over South East Asia that favours precipitation. This reversal phenomenon creates a climatic

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[1] I use the singular form “I” when referring to decisions or actions performed by myself. The plural form “we” is preferred when there is some degree of implications regarding the co-authors (cf. Acknowledgements section below).

characterization of wet and dry seasons that has massive implications for the human dimension of the earth system (Wang, 2006).

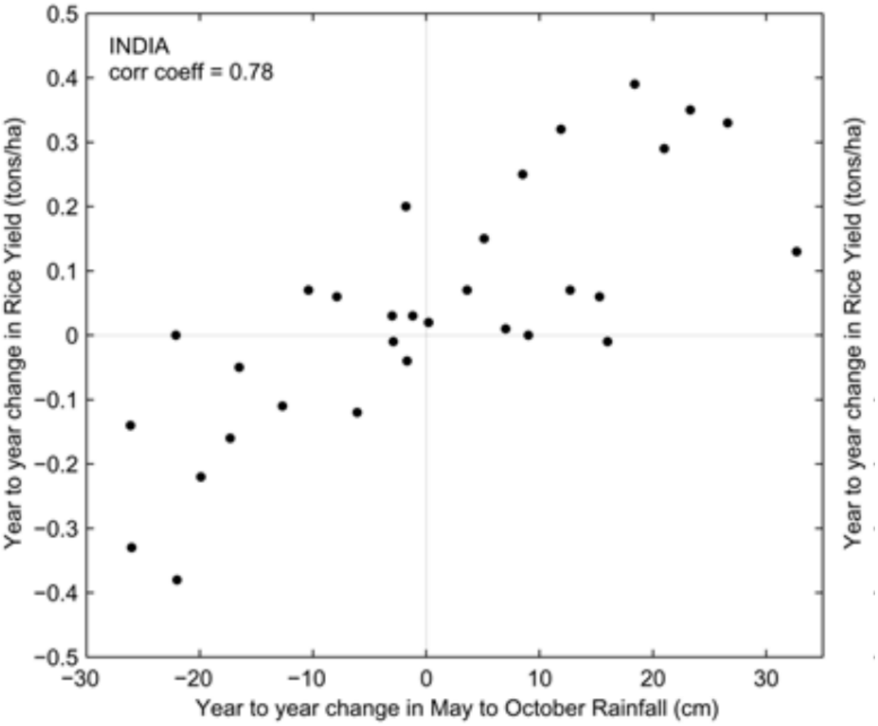


Figure 1-2 Correlation between rice yields and rain on the wet monsoon season, which constitutes the main agricultural season in India (Source: Wang, 2006).

Food security is a crucial issue on developing countries. Indeed, China and India have food security as a first order policy goal. The influence of the Asian Monsoon system in the economy of both countries is very large, particularly on the agricultural sector. The wet and dry seasons constitute the basis of a seasonal differentiation also in agricultural terms. The wet face of the reversal monsoon arrives to the Indian subcontinent in dates ranging from early June in the South-Eastern limit with the Indian ocean, to early August in the North-Western in the border between India and Pakistan. Figure 1-2 shows a clear correlation between precipitation on the wet face of the reversal monsoon system and the degree of success of the main agricultural season.

1.3 Development Challenges, Technology and Global Change

Policies might have unintended consequences. Linear thinking and lack of understanding of all the factors involved on processes have often led to wrong environmental policies. As an example, by willing to save water without considering the energetic consequences of the measures applied, it is possible that in many cases the outcome becomes contradictory in the nexus between water and energy: in some cases water might be saved, but at the cost of increased emissions, which constitutes a trade-off. The synergistic co-benefit of saving water and saving energy could be achieved in much more situations if the nexus linking resources is considered in the design of the policies.

In China, indeed it is happening that water is saved with a lot of technological effort in areas where the water availability is very limited, thus the amount of water saved is scarce, and the amount of emissions needed to save water is significant. Contrarily, in those places where water is abundant, like in the south of China, there are less efforts to save water. To complicate more the situation, societal changes related to the migration of the sons of farmers into the city and the unwillingness to continue farming, are a pending challenge to policy makers in this very moment (November 2015), especially because this transformation is more intense in the south of China, where water is more abundant, so it can be expected that more farms will remain in the north of the country, which agricultural areas are poorer and endowed with a lower amount of resources.

There is not an authoritative answer to the question whether 9 billion people can be fed in the Earth System in 2050 with a healthy diet and a sustainable production, and India is one of those places where much progress is needed to improve the supply side of the question, especially in those places under challenging environmental conditions, like arid or semi-arid contexts where lack of soil humidity is assumed in the dry post-rainy season. Under these conditions crop failure happens often and innovations are needed to improve production. Management innovations, such as varieties obtained with methods of accelerated breeding, have the potential of improving the living conditions of households under extreme socio-ecological conditions, such are low soil quality fields in drought-prone contexts with little opportunities for development.

1.4 Overall Aim of the Thesis and Brief Outlook

There are many uncovered gaps in the intersection of policy, development economics, environmental economics, climate impacts and global change as a whole in the context described above. My aim is to provide an overview of the solutions needed for adaptation to global change in Asia, with a specific focus on policies, technologies and climate variability. To achieve this aim, the following general research questions are approached in the next chapters:

- How good is the performance of policies promoting the adoption of agricultural technology related to water and adaptation to climate change?
- Does the adoption of these water-related technologies have unexpected negative impacts in terms of energy consumption?
- What is the full adoption potential of new agricultural varieties for improving welfare and food production under climate variability?

Each of the following three chapters relates to one of these research questions, in consecutive order, and in each chapter these general questions are disaggregated in a more specific set of research questions. However, the dispersion of the geographies covered, the size of the regions explored, and the disparities of the challenges and methods used might give the reader a certain sense of disconnection between the chapters. To produce scientifically relevant results, I focused on those cases for which it was possible to find relevant local collaboration in data collection and production of data from related experiments. From a diverse network of data providers I selected those cases that were most appropriate to the main challenges described above.

In this way, within an exclusive focus on the agricultural sector, we cover water, land and energy in China in Chapters 2 and 3, and land and food production in India in Chapter 4, and we introduce policy and technology scenarios for both regions. Then we introduced climatic variability and information scenarios for India. From the methodological perspective, in Chapter 4 we introduce significant innovations in the Integrated Assessment Modelling arena, improving spatial and temporal resolutions. I perceive these modelling exercises are relevant for adaptation to global change.

Our exercises produced novel contributions, and show some striking results of global relevance. Our main novel contributions, in relation to the stated above research questions, show that:

- water pricing has an impact on the adoption of modern irrigation technology;
- irrigation efficiency is much lower than previously estimated for China, and strikingly, it is cheaper to achieve co-benefits, between adaptation to and mitigation of climate change in irrigation planning, than to achieve trade-offs;
- innovative crop varieties have significant contributions to agricultural welfare and reduce the impact of climate variability on agricultural production, but the potential contribution of forecasting information provided to the user is much higher.

These findings have significant added value for policy making under global change in the Asian Monsoon region, because they clarify pending crucial issues on the understanding of policy and climate variability impacts on food, water and energy. In this way, I am immodest enough to believe we indeed covered a relevant subset, albeit certainly limited, of the challenges in the context described.

Chapter 2. Policies, Economic Incentives and the Adoption of Modern Irrigation Technology in China

Abstract

The challenges China faces in terms of water availability in the agricultural sector are exacerbated by the sector’s low irrigation efficiency.To increase irrigation efficiency, promoting modern irrigation technology has been emphasized by policy makers in the country. The overall goal of this paper is to understand the effect of governmental support and economic incentives on the adoption of modern irrigation technology in China, with a focus on household-based irrigation technology and community-based irrigation technology. Based on a unique dataset collected at household and village levels from seven provinces, the results indicated that household-based irrigation technology has become noticeable in almost every Chinese village. In contrast, only about half of Chinese villages have adopted community-based irrigation technology. Despite the relatively high adoption level of household-based irrigation technology at the village level, its actual adoption on crop-sown areas was not high, even lower for community-based irrigation technology. The econometric analyses results revealed that governmental support instruments like subsidies and extension services policies have played an important role in promoting the adoption of modern irrigation technology. Strikingly, the present irrigation pricing policy has played significant but contradictory roles in promoting the adoption of different types of modern irrigation technology. Irrigation pricing showed a positive impact on household-based irrigation technology, and a negative impact on community-based irrigation technology, possibly related to the substitution effect, that is, the higher rate of adoption of household-based irrigation technology leads to lower incentives for investment in community-based irrigation technology. The paper finally concludes and discusses some policy implications.

2.1 Introduction

Increasing industrial and urban demands for water are intensifying the pressure on agricultural water use in China. The water resources in the country are scarce and the annual per capita water availability is only approximately one-quarter of the world average (MWR, 2010). With increasing water demand from the industrial and domestic sectors, the share of water used in agriculture has declined from 97% in 1949 to 62% in 2013 (Wang, J. et al., 2005, MWR, 2013). In addition, there is concern about future water deficits in irrigated agricultural production areas due to climate change; such deficits are projected to cause an estimated 7 to 14% drop in rice production that would threaten food security (Xiong et al., 2010). Furthermore, agricultural production in China is concentrated in areas that are increasingly prone to water shortages (FAO, 2011; Wu, Z. et al., 2010; Wu, P. and Zhao, 2010). Some areas have also experienced environmental problems associated with water pollution and sea-water intrusion, thus limiting the availability of water for agricultural use (Mei and Dregne, 2001).

The challenges China faces in terms of water availability in the agricultural sector are exacerbated by the sector’s low irrigation efficiency (Cheng et al., 2009; Yang et al., 2003). In 2010, irrigation efficiency in China was estimated to be 48% on average; this figure is lower than that of some developed countries such as Israel (75%) (Wang, X. et al., 2010). Such low irrigation efficiency is one of the major reasons of increasing water scarcity in China. An improvement on irrigation efficiency is necessary to maintain the use of existing irrigation capacity in the face of increasing demand for water from other sectors (Cheng and Hu, 2011; Zhang, et al., 2005). Modern irrigation technology can make a substantial difference in efficiency and contribute to the successful adaptation of the agricultural sector to climate change in China (Belder, 2004; Erenstein et al., 2008; Zhao et al., 2010; Zou et al., 2013a; Zou et al., 2013b). However, the adoption level of modern irrigation technology is low in China (Blanke et al., 2007).

The Chinese Government stated that the promotion of modern irrigation technology is one of the priorities in its water conservancy reforms (CPC, 2010; USDA, 2011a). The rural and agriculture sections of the China’s 12th Five-Year Plan, issued in March 2011, highlight the importance of efficiency and technological innovation (CPC, 2011a; USDA, 2011b). In addition, the Chinese Government announced expenditures of over 600 billion USD on water conservation over 10 years starting in 2011 (CPC, 2011b) and a specific investment of 6.03 billion USD to support the adoption of modern irrigation technology on 2.53 million hectares (Xinhua, 2012).There is clearly a strong policy commitment to diffusing modern irrigation technology, but the likely impact of these interventions remains largely unknown.

2.1.1 **Scope**

For analytical convenience, Blanke et al. (2007) have divided irrigation technology into three groups: traditional, household-based and community-based. Traditional irrigation technology includes border irrigation, furrow irrigation and field levelling. These technologies are characterized by relatively low fixed costs and are divisible in the sense that one farm household can adopt the practice independently of its neighbors. Traditional irrigation technology is already widely adopted in China; they were used prior to the period of agricultural reform of the late 1970s and early 1980s. During the reform period, the adoption of traditional technologies grew slowly, in part due to the relatively high prevailing adoption level. When policy makers and scholars in China refer to the adoption of modern irrigation technology, they mainly emphasize the adoption of household-based and community-based irrigation technologies. Unlike traditional technology, these two categories of technology have been adopted mainly since the 1980s. Given this observation, we refer to them as modern irrigation technologies and focus on their adoption in our paper

As modern irrigation technology, household-based and community-based irrigation technologies have different characteristics. Household-based irrigation technology includes intermittent irrigation, surface pipes, plastic-film mulching, reduced or no tillage, retaining stubble, incorporation of crop residue and use of drought-resistant crop varieties. Household-based irrigation technology can be adopted separately by each household and have low fixed costs. Community-based irrigation technology includes sprinklers, drip irrigation, underground pipes and lined canals. These technologies are not typically adopted by single households; they normally require collective organization by farmer groups or village committees. In contrast to traditional and household-based irrigation technology, community-based irrigation technology has higher fixed costs. The adoption of sprinklers, drip irrigation and underground pipes is more recent (1990s) than the adoption of household-based technology, but lined canals were used earlier (Blanke et al., 2007).

The existing literature tells us that governmental support is an important factor in farmers' decisions whether to adopt modern irrigation technology. Policies promoting adoption of modern irrigation technology often aim to overcome farmers' economic and technical constraints. To overcome economic constraints, direct provision of subsidies is proven to be an important policy measure in increasing the adoption level of modern irrigation technology, especially when the prevailing adoption levels are low (Feder and Umali, 1993; Tiwari and Dinar, 2000). Liu et al. (2008) found a significant positive relationship between subsidies and adoption of some types of irrigation technology in rural China. In terms of technical constraints, providing knowledge and technical advice through extension service activities are effective ways to increase the adoption level of modern irrigation technology (Dong, 2008; Feder and Umali, 1993; Ommani et al., 2009).

In addition to governmental support, setting rational economic incentives for farmers is another important factor that influences farmers' technology adoption behaviour. International experience indicates that water price is a significant determinant of adoption of modern irrigation technology in the agricultural sector (Dinar and Yaron, 1992; Negri and Brooks, 1990; Zilberman and Caswell, 1985). Although Blanke et al. (2007) do not conduct a quantitative analysis, they argue that reforming water pricing in China will promote the adoption of modern irrigation technology. However most research concurs that in China's agricultural sector, the "price" of water in terms of actual water charges is low, which constrains its potential role in promoting the use of modern irrigation technology (Finlayson et al., 2008; Huang et al., 2010).

2.1.2 **Goal and Objectives**

To design more effective policies to foster the adoption of modern irrigation technology in China, it is essential to answer the following questions: What are the current levels of extent and intensity of adoption of modern irrigation technology in rural China? Have interventions such as subsidy and extension policies played a significant role in promoting the adoption of modern irrigation technology? Could economic incentives established through a water pricing policy play an important role in increasing the adoption level of modern irrigation technology? Despite a relatively rich international literature quantitatively analysing the determinants of adoption of modern irrigation technology (Webb et al., 2005; Zilberman and Caswell, 1985; Dinar and Yaron, 1992), such studies focused on China are very few. We only found a few quantitative analyses that explore the factors influencing the adoption of modern irrigation technology in China, such as those by Liu et al. (2008) and Zhou et al. (2008). More importantly, no study has assessed the effectiveness of economic incentives in promoting the adoption of modern irrigation technology in rural China.

The overall goal of this paper is to understand the effect of governmental support and economic incentive on the adoption of modern irrigation technology in China. With this goal in mind, the following objectives have been specified. First, we examine the extent of adoption of modern irrigation technology at households and village levels. Second, we quantitatively identify the policy drivers that have been most important in promoting the take up of modern irrigation technology. Third, we explore the influence of economic incentives (in terms of charges for irrigation water) on the adoption of modern irrigation technology.

The paper is organized as follows. The next section explains materials and methods, including sampling procedures, survey design and data collection, indicators for measuring the adoption of irrigation technology, and specification of the econometric model. Based on descriptive statistical analyses and econometric model estimation, section 3 presents analyses and results on the adoption status of modern irrigation technology (household-based and community-based technologies) and major factors influencing the adoption. Section 4 discusses the results and concludes.

2.2 Material and methods

2.2.1 Sampling Procedures

The data used in this study are collected from one large-scale household survey conducted in seven provinces in China, which allow for regional variation in geophysical conditions and levels of socioeconomic development. These seven provinces include Beijing and Hebei in the Haihe River Basin (RB), Jilin in the Songliao RB, Anhui in the Huaihe RB, Sichuan in the Yangtze RB, Yunnan in the Southwest RB and Zhejiang in the Southeast RB (Figure 2-1).

When selecting provinces for the field survey, we have accounted for the differences in climate and water resources between Northern and Southern regions; in addition, the pattern of diverse economic development has been considered. For example, the survey samples cover three river basins (Songliao, Haihe and Huaihe RBs) characterized by less precipitation, while the other three river basins (the Yangtze, Southwest and Southeast RBs) have more abundant precipitation and water resources. These regions also represent high (Zhejiang Province), middle (Jilin and Hebei Provinces) and low (Anhui, Sichuan and Yunnan Provinces) levels of economic development (NBSC, 2010).

Stratified random sampling was used in each province to select study areas. First, we divided all counties in each province into three quantiles by the per capita annual net income of rural residents in 2009. In each quantile, we randomly selected one county to be surveyed. After the counties were chosen, we randomly selected two townships in each county and three villages in each township for field surveys. In each village, we randomly selected 10 households with which to conduct the field survey. Therefore, the survey sample included a total of 20 counties, 40 townships, 123 villages and 1269 households. Because rainfed farmers do not need to pay irrigation fee —one of the key variables that we are interested, in the analysis we only focus on those farmers who replied on using irrigation for crop production. The final samples used in the analysis include 993 households in 118 villages in 20 counties.

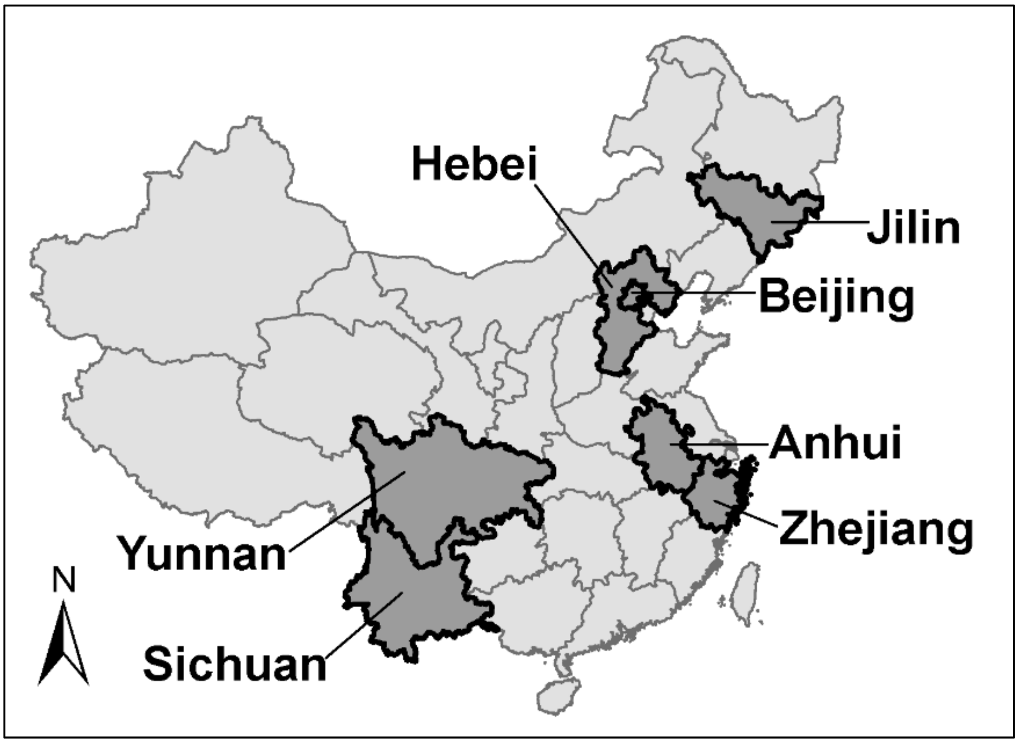


Figure 2-1 Map of China illustrating the surveyed provinces in bold. Source: Authors.

2.2.2 Survey Design and Data Collection

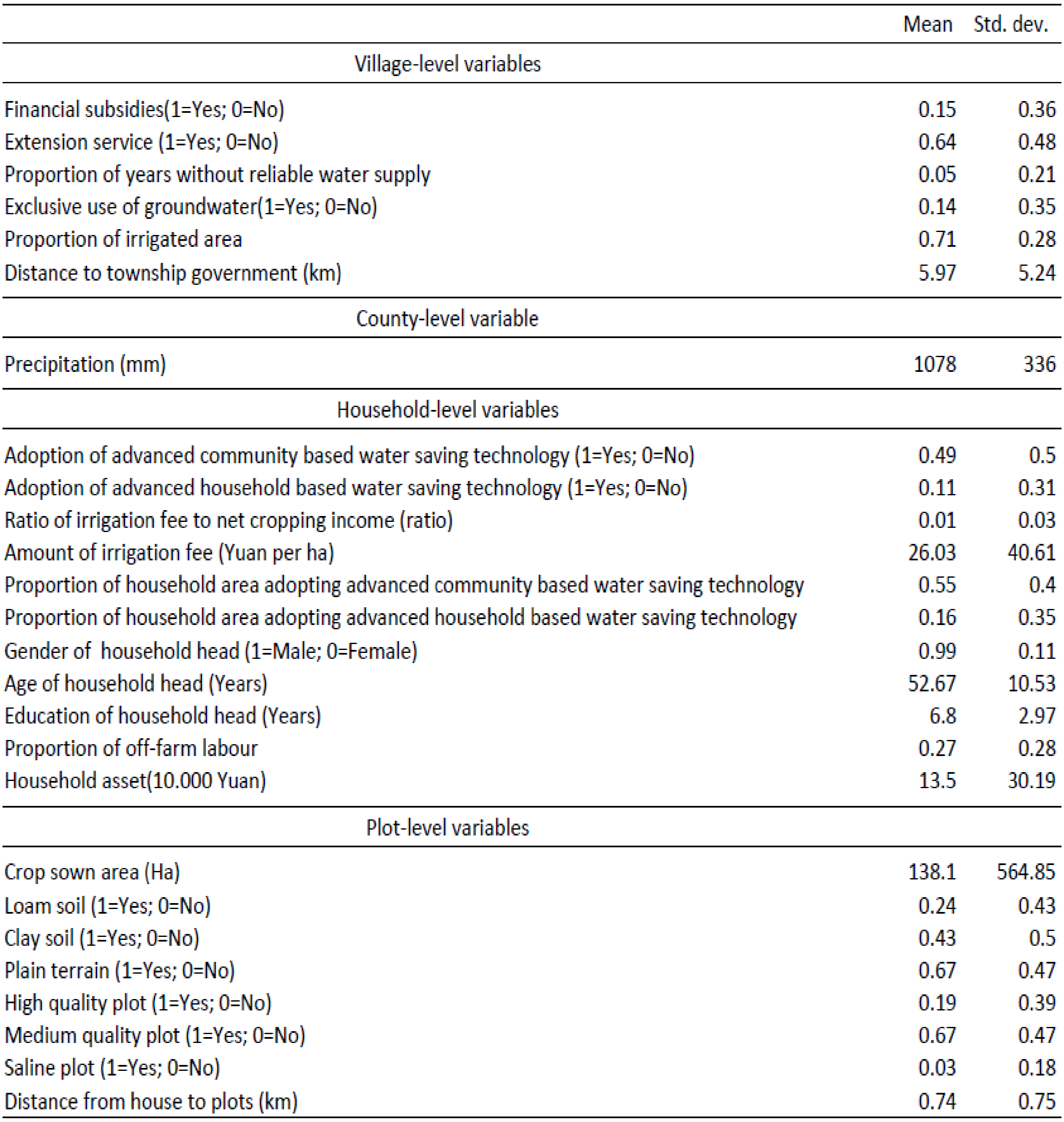
In each village, we conducted two surveys, the household and the village surveys. While the household and village level surveys cover a wide range of issues, our analysis only used data relevant to this study. From the household level surveys, we used the following data: i) whether any kind of modern irrigation technology was adopted in each plot, and areas adopting modern irrigation technology; ii) annual irrigation fee paid for each plot; iii) the household characteristics, including the gender, age, and education of household heads, hours of total labor and off-farm labor, household assets, and production inputs and outputs for each plot that can be used for calculating net cropping income; and iv) the plot characteristics, including crop sown area, soil type, soil quality, saline nature, topography and the distance from the households to the plot.

From the village level surveys, we used the following data: i) whether the households in the village adopted any kind of modern irrigation technology in their plots; ii) whether the village obtained the financial subsidy for the adoption of modern irrigation technology; iii) whether the village obtained extension service on adopting modern irrigation technology, such as extension experts coming to the villages to guide farmers, or the village being an experimental site for modern irrigation technology; iv) the proportion of irrigated area; v) the distance to township government; vi) whether using groundwater for irrigation, and groundwater reliability in the past 5 years. Finally, we obtained the annual precipitation data for each county from the Chinese National Meteorological Information Center. Table 1 provides the descriptive statistics for the data used in the study.

2.2.3 Indicators for Measuring the Adoption of Irrigation Technology

In the following discussion, we examine two dimensions of the adoption of modern irrigation technology: the extent of adoption, and its intensity. The extent of adoption measures how spatially pervasive modern irrigation technology has become. To measure the extent of adoption, we apply the information collected at the village, household and plot levels. At the village level, we intend to reveal the percentage of villages that are adopting modern irrigation technology. By our definition, if even a single household in the village adopts modern irrigation technology, the village is considered to have adopted the technology.

Table 2-1 Descriptive statistics for major variables included in the study.



	Mean	Std. dev.
Village-level variables		
Financial subsidies(1=Yes; 0=No)	0.15	0.36
Extension service (1=Yes; 0=No)	0.64	0.48
Proportion of years without reliable water supply	0.05	0.21
Exclusive use of groundwater(1=Yes; 0=No)	0.14	0.35
Proportion of irrigated area	0.71	0.28
Distance to township government (km)	5.97	5.24
County-level variable		
Precipitation (mm)	1078	336
Household-level variables		
Adoption of advanced community based water saving technology (1=Yes; 0=No)	0.49	0.5
Adoption of advanced household based water saving technology (1=Yes; 0=No)	0.11	0.31
Ratio of irrigation fee to net cropping income (ratio)	0.01	0.03
Amount of irrigation fee (Yuan per ha)	26.03	40.61
Proportion of household area adopting advanced community based water saving technology	0.55	0.4
Proportion of household area adopting advanced household based water saving technology	0.16	0.35
Gender of household head (1=Male; 0=Female)	0.99	0.11
Age of household head (Years)	52.67	10.53
Education of household head (Years)	6.8	2.97
Proportion of off-farm labour	0.27	0.28
Household asset(10.000 Yuan)	13.5	30.19
Plot-level variables		
Crop sown area (Ha)	138.1	564.85
Loam soil (1=Yes; 0=No)	0.24	0.43
Clay soil (1=Yes; 0=No)	0.43	0.5
Plain terrain (1=Yes; 0=No)	0.67	0.47
High quality plot (1=Yes; 0=No)	0.19	0.39
Medium quality plot (1=Yes; 0=No)	0.67	0.47
Saline plot (1=Yes; 0=No)	0.03	0.18
Distance from house to plots (km)	0.74	0.75

Data source: Authors' survey.

Similarly, even if a household uses modern irrigation technology on only one plot, the household is considered as having adopted modern irrigation technology. The extent of adoption at the household level is measured by the percentage of households adopting modern irrigation technology. The extent of adoption at the plot level is measured by the percentage of plots adopting modern irrigation technology. To measure adoption intensity, we use the percentage of crop sown areas that adopt modern irrigation technology.

2.2.4 Specification of Econometric Methods on Analyzing Major Factors Influencing the Adoption of Modern Irrigation Technology

To identify the influence of policies, economic incentives and other factors on the adoption of modern irrigation technology (household and community-based irrigation technology), the following econometric methods have been specified:

$$A_{ijk} = \alpha + \beta S_{ijk} + \gamma E_{ijk} + \delta IFCI_{ijk} + \lambda C_{ijk} + \varepsilon_{ijk} \qquad (1)$$

$$I_{jk} = \alpha + \beta S_{jk} + \gamma E_{jk} + \delta IFCI_{jk} + \lambda C_{jk} + \varepsilon_{jk} \qquad (2)$$

In equation (1), A_{ijk} represents adoption of modern irrigation technology (household-based or community-based technology) for the *i*th plot of household *j* in village *k*. A_{ijk} is a dummy variable that equals 1 when the plot adopts irrigation technology and 0 otherwise. Among the explanatory variables, S_{ijk} , E_{ijk} and $IFCI_{ijk}$ are the variables of interest. S_{ijk} is a qualitative dummy variable that represents the availability of subsidies to households for investing in modern irrigation technology; it equals 1 when the subsidy is available and 0 otherwise. Similarly, E_{ijk} is a dummy variable capturing the availability of extension service activities that equals 1 when the activities are available and 0 otherwise. $IFCI_{ijk}$ is the ratio of the irrigation fee to net cropping income of the household; this variable expresses the importance of an annual per-area irrigation fee relative to the household's economic standing.

C_{ijk} is a set of control variables included to reduce omitted variable bias. It includes variables related to village, household and plot characteristics. Village variables include the proportion of irrigated area, the distance to the township government (km), the proportion of years without reliable groundwater supply in the last 5 years, a dummy variable reflecting the exclusive use of groundwater

(1=yes, 0=no) and precipitation at the county level (mm). Household variables include the proportion of off-farm labors in the household, household assets (10,000 Yuan), education (years), gender (1=male, 0=female) and age (years) of the head of household. Variables related to a particular plot include the distance from house to the plot (km) and six dummy variables (1=yes, 0=no) regarding various characteristics of the plot: loam soil, clay soil, plain terrain, high-quality, medium-quality and saline soil. β, γ, δ and λ are the parameters to be estimated. The error term, ε_{ijk}, is assumed to be uncorrelated with the independent variables.

In Equation (2), I_{jk} represents intensity of adoption of modern irrigation technology for the *j*th household in village *k*, measuring the proportion of crop-sown areas adopting modern irrigation technology. Similar to equation (1), equation (2) also includes explanatory variables such as the availability of subsidies, the availability of extension service and IFCI. In equation (2), the variables related to village and household characteristics are the same as those in equation (1). However, in equation (2) the variables related to the characteristics of the plots of the household are not the same. Instead, they are the average distance from the house to the various plots of the households (km), and six variables reflecting the proportion of the household's plots that exhibits a given characteristic. These six variables include the proportion of loam soil plots in the household (ratio), and five analogous variables describing the proportion of plots with the following characteristics: plain terrain, clay soil, high quality, medium quality and saline soil.

In equation (1), since the dependent variable is dummy variable, we used the Logit model to estimate it (Train, 1993). For the equation (2), considering some values of the dependent variable are zero since not all plots adopted the modern irrigation technology, in order to reduce the estimation biases, the Tobit model is used (Feder and Umali, 1993).

2.3 Analyses and Results

2.3.1 Adoption of Modern Irrigation Technology

Our data indicate that almost all villages in China adopted household-based modern irrigation technology. For example, 99% of sampled villages adopted household-based irrigation technology in 2010 (Table 2, column 1). It implies that household-based irrigation technology has become a pervasive practice for famers to increase irrigation efficiency of agricultural activities. However, only 47% of villages adopted community-based irrigation technology (column 2).

Consistent with the village scale data, at household and plot scales the levels of adoption of household-based irrigation technology are much higher than the levels of community-based irrigation technology. For example, 73% of all households reported that they adopted some types of household-based irrigation technology in 2010 (Table 2, column 1). On average, household-based irrigation technology was adopted in 54% of plots. Turning to community-based irrigation technology, we find that only 17% (Table 2, column 2) of households adopted this category of irrigation technology and the percentage of plots adopting was only 14% (column 2).

Table 2-2 The adoption extent and intensity of modern irrigation technology in China, 2010.

	Household-based technology	Community-based technology
Adoption extent		
Percentage of villages (%)	99	47
Percentage of households (%)	73	17
Percentage of plots (%)	54	14
Adoption intensity		
Percentage of crop sown areas (%)	32	4

Data source: Authors' survey.

Despite the relatively high adoption level of household-based irrigation technology at the village and household level, its actual adoption on crop-sown areas is not high: roughly one third of crop-sown areas are utilizing this technology. The level of intensity of adoption for community-based irrigation technology is even lower. Our data reveals that in the full sample, community-based irrigation technology is used on only 4% of crop-sown areas (Table 2, row 4). Our data are consistent with the findings of other researchers (such as Blanke et al., 2007; Liu et al., 2008) who also found that the intensity of adoption of modern irrigation technology is very limited.

2.3.2 Governmental Support, Economic Incentives and the Adoption of Modern Irrigation Technology in China

Consistently with other studies (Dinar and Yaron, 1992; Ommani et al., 2009), descriptive statistical analyses show a possible positive relationship between the adoption of modern irrigation technology and policies encouraging it. In our analysis, we use two variables to represent governmental support: a subsidy for investing in irrigation technology and extension services that assist farmers in becoming familiar with the application of irrigation technology. Based on our field survey, we found that 15% of households accessed to the subsidy policy. More importantly, when subsidies are available to farmers, they are more likely to adopt both household-based and community-based irrigation technology. For example, if the subsidy was available, 73% of plots adopted household-based irrigation technology; the adoption level was only 50% if the subsidy was not available (Table 3, column 1). Similarly, if farmers can obtain the subsidy when they invest in modern irrigation technology, the adoption level of plots for community-based irrigation technology (29%) was also considerably higher than without the subsidy (11%) (column2).

Table 2-3 Relationship between governmental support and adoption of modern irrigation technology in China, 2010.

	Adoption extent: share of plots adopting (%)		Adoption intensity: share of crop sown areas adopting (%)	
	Household-based technology	Community-based technology	Household-based technology	Community-based technology
Financial subsidy				
Available	73	29	77	24
Not available	50	11	45	6
Extension service				
Available	61	18	50	8
Not available	41	8	42	8

Data source: Authors' survey

When the subsidy policy is available, the percentage of crop-sown areas to which modern irrigation technology was applied was higher. Specifically, in households where the subsidy was available, the average intensity of adoption of household-based irrigation technology was 77% (Table 3, column 3), while the average intensity of adoption was lower (45%) in those households where the subsidy policy was not available. In the case of community-based irrigation technology, the availability of subsidies makes also a difference, although smaller. If the subsidy was available, the average intensity of adoption of community-based irrigation technology was 24% (column 4), while the figure was much lower (6%) if the subsidy policy was not available. This smaller difference most likely arises because community-based irrigation technology has higher fixed costs; thus, the subsidy policy plays a fundamental role in adoption.

Table 2-4 Relationship between economic incentives and adoption of modern irrigation technology in China, 2010.

	Adoption extent: share of plots adopting (%)		Adoption intensity: share of crop sown areas adopting (%)	
	Household-based technology	Community-based technology	Household-based technology	Community-based technology
Ratio of irrigation fee to net cropping income				
0	47	11	45	7
>0	59	16	49	8
Among samples[a]:				
>0~0.002	60	17	46	4
0.002~0.005	60	17	59	19
0.005~0.011	60	18	61	19
>0.011	56	15	58	19

Note: a) When the ratio of irrigation fee to net cropping income is larger than 0, we have divided the sample into four groups by their ratio of irrigation fee to net cropping income; each group has the same number of elements.
Data source: Authors' survey

Our data also show that when extension services were available, the likelihood that farmers will adopt modern irrigation technology was higher. According to our field survey, 64% of households had access to support activities from extension services. When extension services were available, 61% of plots adopted household-based irrigation technology, while the level of adoption was only 41% if these services were not available (Table 3, column 1, last two values). Similarly, the availability of extension services was associated with a higher adoption level of community-based irrigation technology (18% versus 8%, column 2). Likewise, the provision of extension services also appears to increase the adoption intensity of modern irrigation technology. If the extension service activities were implemented, the adoption intensity of household-based irrigation technology increased from 42% to 50% (column 3), but the adoption intensity of community-based irrigation technology remained at 8% (column 4). Although the availability of extension services seems to have an impact on the intensity of adoption of household-based irrigation technology, the differences of values in Table 3 imply that the availability of subsidies may have a larger impact on the adoption of modern irrigation technology.

Charges for irrigation water can provide an economic incentive to conserve water through the adoption of modern irrigation technology (Tiwari and Dinar, 2000). Among the surveyed households that irrigate, almost all farmers that use groundwater exclusively paid for water whereas only about half of the exclusive surface water users paid for water. Surface water users pay less often for water because they usually have optional sources from which to obtain water, some of which are free, such as using water directly from rivers, water cellars, ponds, small streams or springs. Payment for irrigation water is reflected here by the proportion irrigation fee to net cropping income of household (IFCI).

Our descriptive statistical analyses suggest the existence of a positive relationship between payment for water (IFCI) and the adoption of modern irrigation technology. When there was a water fee, farmers exhibited a positive increased difference in the extent of adoption of household-based and community-based irrigation technology. For example, Table 4 (column 1) displays that in plots from households with values of IFCI larger than 0, the adoption extent of household-based irrigation technology was 12% higher than among those plots without payment. A lower increase in the adoption level (5%) was evident in the extent of adoption of community-based irrigation technology (column 2), although less perceivable increases are apparent in the adoption intensity of modern irrigation technologies (columns 3 and 4).

2.3.3 **Estimation Results of Econometric Models**

The estimated results of the four models show that they all perform well (Tables 5 and 6). The models passed the Chi-square test, and the PseudoR2 values of the four models range from 0.072 to 0.288. These values are sufficiently high enough for regression analyses based on large-scale cross-sectional data. Moreover, many village, household and plot control variables have signs that agree with our expectations and are statistically significant. For instance, in the four models, the sign of the coefficient of exclusive use of groundwater is positive and statistically significant (Tables 5 and 6). This outcome implies that after keeping all other factors constant, farmers using groundwater exclusively are more likely to adopt modern irrigation technology. This result is in agreement with findings of other researchers (Yang et al., 2003; Caswell and Zilberman, 1985).

The results also indicate that farmers with a higher education level are more likely to adopt community-based irrigation technology with more extent and intensity, as expected. In the same way, adoption is positive and significantly related to plain terrain and plots with saline conditions. This relationship implies that modern irrigation technology is more likely to be adopted in plots with no slope conditions and can minimize the effects of soil salinity, which is consistent with previous findings (Castilla, 1999).

More importantly, the results show that when the subsidy policy is available to farmers, the farmers adopt modern irrigation technology with greater extent (Table 5), and with greater intensity in the case of household based technology (Table 6). If a subsidy policy is applied, the probability of adopting modern irrigation technology will increase by 11.7% for household-based irrigation technology and by 2% for community-based irrigation technology. Similarly, the probabilities of an increase in crop-sown areas using household-based irrigation technology are 10.6%.

Table 2-5 Estimates of determinants of the adoption decision of modern irrigation technology in China (Logit model).

	Whether the plot adopts (1=Yes; 0=No)	
	Household-based irrigation technology	Community-based irrigation technology
Policy support		
Financial subsidies (1=Yes; 0=No)	0.117^{***}	0.020^{**}
	(4.71)	(2.11)
Extension service (1=Yes; 0=No)	0.106^{***}	0.008
	(5.43)	(0.98)
Economic incentives		
Ratio of irrigation fee to net cropping income	1.346^{***}	-0.822^{***}
	(3.77)	(3.74)
Village characteristics		
Proportion of irrigated area	0.276^{***}	0.093^{***}
	(7.79)	(6.19)
Distance to township government (km)	0.001	-0.000
	(0.40)	(0.59)
Proportion of years without reliable water supply	0.015	0.003
	(0.31)	(0.23)
Exclusive Use of groundwater (1=Yes; 0=No)	0.100^{***}	0.080^{***}
	(2.94)	(6.68)
Annual total precipitation (mm)	-0.0001^{**}	-0.0001^{***}
	(2.01)	(5.05)
Household characteristics		
Gender of household head (1= Male; 0=Female)	-0.141^{*}	-0.018
	(1.84)	(0.71)
Age of household head (Years)	-0.002^{**}	-0.000
	(2.18)	(0.01)
Education of household head (Years)	0.005	0.005^{***}
	(1.54)	(4.09)
Proportion of off-farm labour	-0.017	0.057^{***}
	(0.56)	(5.25)
Household asset (10.000 Yuan)	0.001^{***}	0.0001^{***}
	(2.65)	(2.78)
Plot characteristics		
Loam soil (1=Yes; 0=No)	-0.046^{**}	0.010
	(1.98)	(1.12)
Clay soil (1=Yes; 0=No)	-0.056^{***}	-0.015^{*}
	(2.86)	(1.96)
Plain terrain (1=Yes; 0=No)	0.002	0.040^{***}
	(0.12)	(4.21)
High quality plot (1=Yes; 0=No)	0.044	0.026^{**}
	(1.48)	(2.25)
Medium quality plot (1=Yes; 0=No)	0.059^{**}	0.020^{**}
	(2.44)	(2.02)
Saline plot (1=Yes 0=No)	0.092^{**}	0.050^{***}
	(2.00)	(4.06)
Distance from house to plots (km)	0.039^{***}	-0.011^{**}
	(3.42)	(2.01)
Observations	4172	4172
Prob> chi^2	0	0
Pseudo R^2	0.0720	0.2880

Notes: Estimates are marginal effects. Absolut value of zstatistics in the parenthesis.
***p<0.01, ** p<0.05, * p<0.1
Data source: Authors' survey.

Table 2-6 Estimates of determinants of the adoption intensity of modern irrigation technology in China (Tobit model).

	Proportion of crop sown areas adopting	
	Household-based irrigation technology	Community-based irrigation technology
Policy support		
Financial subsidies (1=Yes; 0=No)	0.106***	0.130
	(2.69)	(1.47)
Extension service (1=Yes; 0=No)	0.102***	0.043
	(3.12)	(0.49)
Economic incentives		
Ratio of irrigation fee to net cropping income	-0.003	-1.223
	(0.01)	(0.94)
Village characteristics		
Proportion of irrigated area	0.247***	0.867***
	(4.33)	(5.18)
Distance to township government (km)	-0.002	0.009
	(0.67)	(1.17)
Proportion of years without reliable water supply	0.028	0.056
	(0.47)	(0.40)
Exclusive use of groundwater (1=Yes; 0=No)	0.175***	0.411***
	(3.29)	(3.67)
Annual total precipitation (mm)	-0.0001***	-0.001***
	(5.52)	(7.32)
Household characteristics		
Gender of household head (1= Male; 0=Female)	0.036	0.080
	(0.41)	(0.41)
Age of household head (Years)	-0.001	0.002
	(0.72)	(0.52)
Education of household head (Years)	0.005	0.035**
	(0.88)	(2.40)
Proportion of off-farm labour	-0.021	0.199
	(0.40)	(1.48)
Household asset (10.000 Yuan)	0.000	0.002**
	(0.56)	(2.40)
Plot characteristics		
Proportion of loam soil plots	0.060	0.317***
	(1.33)	(2.68)
Proportion of clay soil plots	0.103***	0.085
	(2.86)	(0.90)
Proportion of plain terrain plots	0.112***	0.254**
	(2.93)	(2.31)
Proportion of high quality plots	0.004	0.226
	(0.07)	(1.45)
Proportion of medium quality plots	-0.013	0.210
	(0.26)	(1.57)
Proportion of saline plots	0.074	0.305*
	(0.97)	(1.89)
Distance from house to plots (km)	-0.018	-0.036
	(0.89)	(0.57)
Observations	993	993
Prob> chi^2	0	0
Pseudo R^2	0.1686	0.2644

Notes: Estimates are marginal effects. Absolut value of z statistics in the parenthesis.
***p<0.01, ** p<0.05, * p<0.1
Data source: Authors' survey.

Similarly, in both logit and Tobit regressions, the coefficient of the extension service activities variable is positive and statistically significant for household-based irrigation technology. This result suggests that when extension service activities are accessible to farmers, the probability that farmers adopt household-based irrigation technology significantly increases. If extension service activities are available, the possibility of adopting household-based irrigation technology increases by 10.6%, and the probability of increase in crop-sown areas is 10.2%.

Having a stronger economic incentive significantly facilitated farmers adopting household-based irrigation technology, but hindered the adoption of community-based technology. The estimated coefficient of the IFCI is positive and statistically significant in the model of household-based irrigation technology (Table 5, column 1). It implies that when farmers need to pay higher irrigation fees in relation to their limited net cropping income, they are more concerned about the adoption of household-based irrigation technology, which is expected to reduce the application of irrigation and relevant production inputs for irrigation. However, an interesting finding is that the coefficient of IFCI in the model of community-based irrigation technology (column 2) is negative and also significant. This result indicates that having higher irrigation fee ratio will hinder the adoption of community-based irrigation technology. Finally, our results also have not indicated the significant role of economic incentives on increasing adoption intensity of irrigation technology (Table 6).

2.4 Discussion and Conclusions

In this paper, we have sought to explore the importance of governmental support measures and economic incentives on the adoption of modern irrigation technology in China. Descriptive statistical analyses show that household-based irrigation technology has become noticeable in almost every Chinese village. In contrast, only about half of Chinese villages have adopted community-based irrigation technology. Adoption levels are lower at the household and plot scales. Amongst those households adopting modern irrigation technology, there are very few adopters that use it in all their crop-sown areas; this observation especially applies to community-based irrigation technology.

Overall, our descriptive and econometric analyses reveal that governmental support has played an important role in promoting the adoption of modern irrigation technology. Descriptive statistical analyses show positive differences in adoption levels of modern irrigation technology when subsidies available (Table 3). Moreover, econometric results demonstrate that the availability of subsidies has a positive and significant impact on adoption extent of both described types of modern irrigation technology (Table 5), and on adoption intensity of household-based technology (Table 6). These results are consistent with results from previous research (Bjornlund et al., 2009; Dinar and Yaron, 1992; Feder and Umali, 1993) and confirm the relevance of subsidies in encouraging adoption of agricultural innovations. In fact, subsidies appear as the most influential and comprehensive policy for encouraging the adoption of household-based and community-based irrigation technology. However, only 10% of villages are currently eligible for such support. Consideration should be given to extend the subsidy to include more farmers in the future. Since these subsidies are a public expenditure that also provides private benefits, they should be made available until the advantages of the technology are known to farmers and they adopt the technology by themselves.

Subsidies to motivate adoption should be combined with actions to promote knowledge of the benefits of advanced irrigation technologies amongst farmers. Statistical analyses show positive differences in adoption levels of household-based irrigation technology when extension service activities are accessible to farmers. This is corroborated by the econometric results, showing that the probability that farmers adopt household-based irrigation technology significantly increases when extension service activities are accessible to farmers. This is in agreement with previous findings in the literature (Dong, 2008; Feder and Umali, 1993; Ommani et al., 2009). Conversely, the descriptive statistical analysis for the levels of adoption intensity of community-based irrigation technology do not show differences when extension service activities are accessible to farmers (Table 3). Similarly, the econometric results show that there is no impact of extension service activities on the adoption of community-based irrigation technology. This lack of impact might be because the decision to adopt community-based technology are highly influenced by local leaders —village, township and even county leaders. Nevertheless, the provision of extension services makes valuable contribution by spreading information about the beneficial aspects of the technology. Consideration should be given to expanding extension effort in those technologies and in areas of high potential benefit, but current low adoption because of limited awareness or knowledge. Overall, it seems clear that there is scope to strengthen the extent and integration of targeted subsidies and extension support for irrigation technology where there is most potential benefit.

Compared with governmental support, the present irrigation pricing policy has played a very important role in promoting the adoption of household-based irrigation technology. Descriptive statistical analyses show higher levels of adoption of modern irrigation technology when irrigation charges are levied and IFCI is greater than 0, but these differences are large only for adoption extent of household-based irrigation technology. Our econometric results confirm that the payment for water and the adoption level of household-based irrigation technology are positively and significantly related. Our result implies adoption of household-based irrigation technology is influenced by irrigation price policy. Irrigation pricing can play an important role in inducing farmers to change their irrigation behavior. This result is consistent with previous studies from Caswell et al. (1990), and Dinar and Yaron (1992).

Interestingly, the impact of irrigation pricing on the extent of adoption of community-based irrigation technology shows significant and negative values. An explanation for this is that there is some substitution effect between household and community-based irrigation technology. If farmers have higher incentives to adopt household-based irrigation technology, there may be fewer incentives to invest in community-based irrigation technology, which has an added barrier for adoption due to high costs. In fact, such relationship further indicates the significant role of irrigation pricing policy on promoting the adoption of modern irrigation technology. Compared with community-based irrigation technology, household-based irrigation technology is cheaper and easier to adopt by small and individual farmers, which is more consistent with the present production environment in China. Therefore, instead of investing in expensive community-based irrigation technology, the government should consider putting more effort into encouraging farmers to adopt household-based irrigation technology through appropriate and targeted irrigation pricing and extension policies.

Within the limits of available data, the econometric models used here have been applied to groups of irrigation technologies together rather than at the detail of individual irrigation technologies. The limitations could be overcome with further work through collecting more data for the individual technology, and combining both quantitative and qualitative methods. If possible, we can conduct follow-up surveys to create panel data with multiple time points to further improve econometric estimates. In addition, although policies and incentive mechanism can play role on promoting the adoption of modern irrigation technology, the significance for their role maybe differ by farmers' characteristics, such as their different degree of wealth. Such interesting issue also can be further explored in the future studies.

Chapter 3. Co-benefits and trade-offs in China's irrigation water–energy nexus

Abstract

There are strong interdependencies between water use in agriculture and energy consumption as water saving technologies can require increased pumping and pressurizing. The Chinese Government includes water efficiency improvement and carbon intensity reduction targets in the 12th Five-Year Plan (5YP. 2011-2015), yet the links between energy use and irrigation modernization are not always addressed in policy targets. Here we develop linked resource analysis to assess policy targets for deployment of irrigation technologies, which contribute to reduce water application and adapt Chinese agriculture to climate change. The consequences of policy targets involve co-beneficial outcomes that achieve water and energy savings, or trade-offs in which reduced water application leads to increasing greenhouse gas emissions. We analyze irrigation efficiency and energy use using scenarios based on targets in the 12th 5YP nationally and in four significative provinces. Interestingly, our calculated irrigation efficiency for China (23.80%) is lower than other estimates. We find that expansion of sprinklers and micro-irrigation as outlined in the 5YP would increase greenhouse gas emissions nationally from agricultural water use. We show that the most costly technologies relate to trade-offs, while co-benefits are generally achieved with less expensive technologies. Overall, the results show that water sources largely determine whether energy savings occur with reduced water application.

3.1 Introduction

China faces its own 'perfect storm' as rapid economic transition drives increasing per capita demand for water, energy and food. National food production increased substantially in recent decades but in doing so the agricultural sector has become responsible for nearly two-thirds of total water use and 17%-20% of China's greenhouse gas (GHG) emissions (Wang et al 2012). Groundwater use in China increased from around 10km^3 during the 1950s to more than 110 km3 in 2010 (Shah 2009) causing increases in pumping-related emissions of GHGs (Wang et al 2012). The interdependencies between water and energy are increasingly recognised (e.g. Hoff 2012). One example is the potential for co-benefits or trade-offs to occur when reducing water application in agriculture due to the need for energy consumption for increased pumping, pressurizing and conveyance. For instance, situations of groundwater use for irrigation might provide co-benefits via savings on the energy pumped when reducing water application (Zou et al 2013a), while areas irrigated with surface water can result in trade-offs between reductions in water application and increases in emissions when energy-intensive irrigation technology is deployed. Outcomes can be explored using a nexus approach (Finley and Seiber 2014; WEF 2011). Irrigation comprises the second largest contribution (22%) to the total carbon footprint of crop production in China (Cheng et al 2011). Jackson et al (2010) reported emissions savings of 12% to 44% could be achieved through the adoption of irrigation technology in groundwater fed conditions. Optimal management measures such as dynamic regulation of pressure may also lead to additional energy savings of 20% (Díaz et al 2009). Irrigation technologies can reduce the non-productive consumption (Perry 2011) of water in different ways; they can minimize leaching and evaporation and improve control of application to optimize water uptake in plants. Canal lining and pipelines are measures to avoid non-productive evaporation and leaching of water during conveyance; sprinkler and drip systems limit the application of water to fields/crops. By reducing applied water and potentially helping to cope with climate change (e.g. precipitation variability and more intense droughts), irrigation technology can contribute to adaptation and, in some contexts, irrigation technology might simultaneously contribute to carbon intensity reduction and mitigation of climate change.

The Chinese Government included water efficiency, farming modernisation and improved risk management in agriculture as priorities in the 12th Five-Year Plan (5YP, 2011-2015) (CPC 2011) and the No. 1 Central Document in 2011 (CPC 2010). The 12th 5YP was the first to set targets for carbon intensity reduction. Water pumping is a major input for Chinese agriculture, yet the links between energy use and irrigation modernization are not addressed directly in these policy plans. In fact, vertical planning processes often fail to integrate water-energy considerations (Yu 2011). The 12th 5YP targets increases in irrigation efficiency of 3% and includes objectives for increasing the area under four irrigation technologies which are the focus of this study; sprinkler irrigation. micro/drip irrigation, canal lining for seepage control and low pressure pipelines. The policy targets are intended to be realised by incentivizing and supporting farmers to adopt irrigation technology through extension activities, subsidies, discount loans for equipment and water pricing (Cremades et al 2015; NEA 2012). At the provincial level the current 5YP aims for increases in the area using irrigation technology of 26% in Hebei, 54% in Heilongjiang, 33% in Shandong and 53% in Xinjiang (detailed figures of baseline and scenarios in tables 2 and 3, respectively; CPC, 2011).

We examine how to decrease energy consumption linked to irrigation, whilst reducing irrigation water application and maintaining food security. This challenge is exacerbated by the diversity of situations in which outcomes of similar policies can be either trade-offs or co-benefits. We apply linked resource analysis by assessing the consequences of sectoral policy targets that intersect the irrigation water-energy nexus (Scott et al 2011): focussing on co-benefits; to identify win-win outcomes which achieve reductions of water applied and energy savings, and on trade-offs; in which reductions of water applied lead to increasing GHG emissions from energy use. The study uses data from government sources and develops a method based on the estimation of changes on water use efficiency and energy use emissions, applied to analyse policy scenarios based on the targets of China's 12thFYP. The analysis is done nationally and in four provinces with contrasting water-energy endowments. To achieve this we first seek to understand which factors determine different outcomes in terms of emissions from irrigation technology, and derive estimates of energy use and economic cost for key irrigation technology from the literature. Second, we assess the possible trade-offs and co-benefits in different cases of the nexus to understand the consequences of sectoral policy goals. We conclude by suggesting policy recommendations for improved management of the irrigation water-energy nexus.

3.2 Methodology

We apply a methodology for assessing water use efficiency and energy use emissions in irrigation schemes, comprising all processes from extraction and conveyance of water to its application in the field (Figure 3-1). These processes may require energy (e.g. for pumping, pressurising) and will unavoidably involve some consumption of non-productive agricultural water use through evaporation, runoff and seepage. Using provincial and national level averages from a range of official sources we calculate the scheme irrigation efficiency and energy use emissions for the year 2010 and use these as a baseline.

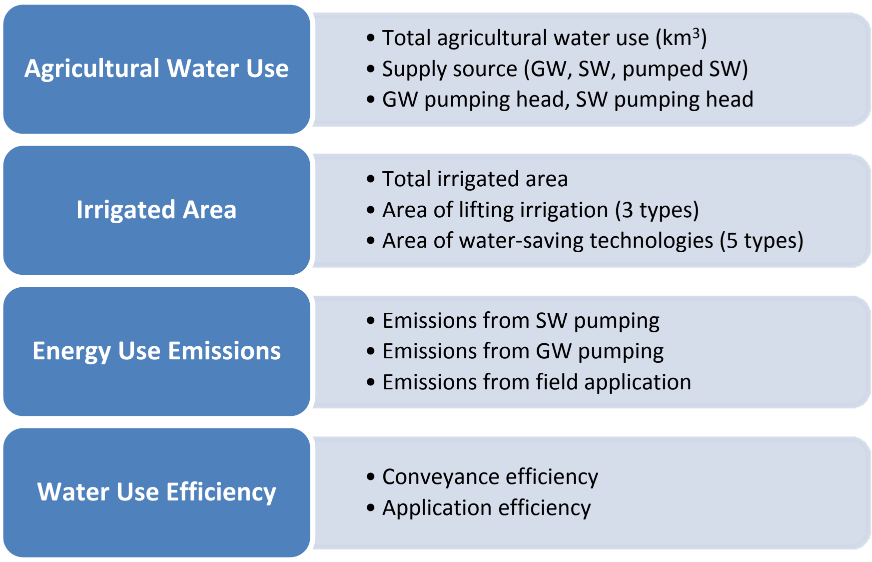


Figure 3-1 Main data sources used in the water-energy assessment (full details in Supplementary Section 2).

The scheme irrigation efficiency, defined as the fraction of water “pumped or diverted through the scheme inlet which is used effectively by the plants” (FAO 1989), is the combined efficiency of the conveyance and the application (see Equation 1). Conveyance efficiency represents the efficiency of water transport in canals and field application efficiency represents the efficiency of water application in the field.

$$\boldsymbol{\eta} = \frac{\eta c \times \eta a}{100} \tag{1}$$

$$\boldsymbol{\eta c} = \sum_i A_i \, \eta c_i \tag{2}$$

$$\boldsymbol{\eta a} = \sum_j B_j \, \eta a_j \tag{3}$$

Where:

η: scheme irrigation efficiency (%)

ηc: conveyance efficiency (%)

ηci: conveyance efficiency for ith kind of delivery facility, being i a set that includes the following delivery facilities: unlined canal, lined canal and low pressure pipeline

Ai: percentage of irrigated areas using the ith kind of delivery facility

ηa: field application efficiency (%)

ηaj: field application efficiency for jth kind of irrigation technologies in the field, being j a set that includes flood, sprinkler, micro-irrigation and other kinds of irrigation technologies

Bj: percentage of irrigated areas using the jth kind of irrigation technologies in the field

According to the Food and Agriculture Organization of the United Nations (FAO 1989) a scheme irrigation efficiency of 50-60% is good. 40% is reasonable, whereas 20-30% is poor. The combined irrigation scheme efficiency depends on the type of conveyance and application system all of which have different water use efficiencies (see supplementary table S4 in Appendix A1). If well maintained, long, sandy soil canals have maximum conveyance efficiencies of 60%. Taking into account poor maintenance of canals the conveyance efficiency of earthen canals is set to 30%, and the conveyance efficiency of canals with seepage control is set to 75% (FAO 1989). For low pressure pipelines, we assume a conveyance efficiency of 90%. For application efficiencies we adopt a mid-value of 50% for flood systems, 75% for sprinkler, 90% for drip and 70% for other field practices that enhance efficiency.

To calculate the scheme irrigation efficiencies (equation 1), we use national statistics for irrigated areas by province (sources detailed in Suppl. Section 2). For conveyance efficiency, the total irrigated area is divided according to the areas supplied by seepage controlled canals, low pressure pipelines and the remaining area is assumed to be supplied by traditional non-lined canals (see equation 2). For field application efficiency, the total irrigated area is divided according to areas of sprinkler, micro and other field measures; the remaining is classified as flood (see equation 3). Flood irrigation comprises all types of surface water irrigation (basin, furrow, border). It is important to note that Chinese government metrics for irrigation efficiency do not consider conveyance and application practices separately. While areas supplied by water through lined canals and pipelines are counted as irrigation technologies, water might still be applied through flooding practices. Hence, we argue it is important to acknowledge that water can leave the irrigation scheme through non-productive evaporation and seepage both during conveyance and application and therefore both steps should be accounted for.

For the energy use emissions, we divide the energy used for an irrigation scheme into pumping and conveyance (equation 4), and pressurising water for application to fields (equation 5). For both calculations we consider the two main types of engines used for water pumping in China: the proportion of engines used is set to 76% for electric and 24% for diesel, and pump engine efficiencies of electric and diesel driven systems are set to is set at 0.75 and 0.15, respectively (equation 6) (Wang et al 2012).

Table 3-1 Pressure ranges of irrigation systems.

	kPa	**Head (m)**	**Irrigation system**
Low pressure	0- 179.25	0-17	most surface and some drip/micro systems
Medium pressure	179.26-413.68	18-41	some drip/micro and some sprinkler systems
High pressure	≥413.69	≥42	some sprinkler systems

Source: USDA (2012)

Pump head is the most crucial factor, noting that efficiency of the power generation and supply and the pump and pipeline system also influence energy use. To calculate the energy used in the pumping and conveyance of groundwater and surface water we use equation 4 (Rothausen and Conway 2011). Conveyance consumes energy in the case of low pressure pipes. Even so, results from a large-scale field survey (see Cremades et al 2015) show low pressure pipes are used in 91% of cases in areas irrigated exclusively with groundwater, while only a 2% of cases in areas irrigated exclusively with surface water and the remaining 7% in areas with a mix of both. We therefore assume that the expansion of low pressure pipelines will occur in areas irrigated exclusively with groundwater. Then, since the adoption of low pressure pipes implies lower extraction of groundwater, the final effect is less water pumped and less energy consumed, which is according to findings from Zou et al (2013b).

$$\mathrm{EPC\ (kgCO_2e)} = \sum\nolimits_{k,m} \frac{9.8\left(\frac{\mathrm{m}}{\mathrm{s}^2}\right) \times \mathrm{Pump\ head}_k(\mathrm{m}) \times \mathrm{Mass(Kg)}}{3.6\times10^6 \times \mathrm{Pump\ Efficiency}_m} \times \mathrm{CF}\left(\frac{\mathrm{kgCO_2e}}{\mathrm{kWh}}\right) - \mathrm{A}_{en(i)}(\mathrm{ha}) \times \mathrm{LPR}\left(\frac{\mathrm{kgCO_2e}}{\mathrm{ha}}\right) \quad (4)$$

Where:

EPC: emissions for pumping and conveyance, comprising emissions caused by energy-intensive water sources and decrease of emissions related to conveyance using low pressure pipes.

K: set of energy intensive water sources, comprising pumping of groundwater and pumping of surface water.

Pump head: vertical distance over which water is raised, or the combined effect on pressure of elevation and/or distance over which water is pumped prior to application; also referred as “lift”.

Mass: weight of the water pumped.

Pump Efficiency: performance of the pump in terms of conversion to mechanical energy, being m a set including diesel and electric engines.

CF = conversion factor, as calculated in Equation (6) below.

Aen(i): area with conveyance through low pressure pipes; the subset en(i) includes the elements of i that consume energy for conveyance, referring only to low pressure pipeline.

LPR: reduction of emissions due to adoption of low pressure pipelines. According to a literature review by Zou et al (2013b) low pressure pipes reduce 177 kgCO2e per hectare of application.

The energy used to pressurize water for its application in the field with sprinklers and micro-irrigation is calculated according to Equation 5. Based on information in table 1 we set the pressure of the pump head at 45 m for sprinklers and 20 m for drip. We apply standard flow rates for sprinkler and drip systems at 40 l/s and 20 l/s. respectively.

$$\mathrm{EA(kgCO_2e)} = \sum_{en(j),m} \frac{9.8\left(\frac{\mathrm{m}}{\mathrm{s}^2}\right)\times \text{Pump head}_{en(j)}(\mathrm{m})\times \text{Mass(Kg)}}{3.6\times10^{6}\times \text{Pump Efficiency}_{m}} \times \mathrm{CF}_m\left(\frac{\mathrm{kgCO_2e}}{\mathrm{kWh}}\right) \qquad (5)$$

Wherein:

EA: emissions due to pressurizing water for its application in the fields, using the energy-intensive elements of the set j —sprinkler and micro-irrigation, that constitute the sub-set en(j)

In Equation 6 we use GHG conversion factors for diesel and electricity produced in China to derive the emissions for these two main types of energy use for water pumping in China (DEFRA and DECC 2010).

$$\mathrm{CF}_m\left(\frac{\mathrm{kgCO_2e}}{\mathrm{kWh}}\right) = \mathrm{DEU}_m \times \mathrm{CONV}_m\left(\frac{\mathrm{kgCO_2e}}{\mathrm{kWh}}\right) \quad (6)$$

Where:

DEU: distribution of engines used. 76% for electric and 24% for diesel.

CONV: conversion factors for diesel (0.32021kgCO2e/kWh) and electricity produced in China (0.94773kgCO2e/kWh).

The nexus between water use and emissions is captured for pressurized application and for pressurized conveyance. First, the emissions caused by irrigation in areas adopting pressurized conveyance are represented in Equation 4; when these areas vary, the change is also reflected in Equations 2 and 1. Second, the emissions caused by irrigation in areas adopting pressurized application technologies are represented in Equation 5; when these areas change, it is also reflected in Equations 3 and 1. Therefore, our method captures the implications in terms of irrigation efficiency and in terms of emissions.

Using this procedure, we calculate a baseline and simulate the water and energy use associated with increasing the area that adopts irrigation technology as described in the 12th 5YP targets. Then, by distributing the reductions of water applied from the estimated increases in irrigation efficiency, according to the supply sources in each province, we evaluate the potential GHG emission savings. Finally, we quantify the sensitivity of key parameters in the formulae above to understand their impact on irrigation efficiency and energy use. Figure 3-1 shows the main data sets used in the methodology.

This approach is used to analyse the outcome of the 12th 5YP targets in four Chinese provinces: Hebei. Heilongjiang. Shandong and Xinjiang. The provinces are chosen because they had the highest planned increases in area under irrigation technology according to the 12th 5YP and they present very different conditions of water supply sources and use of irrigation technology. The main characteristics of the four provinces are listed in the Supplementary Section 1 (table S1, Appendix A1). A full, detailed description of the data sources and additional methodological details can be found in the Supplementary Section 2 of Appendix A1.

3.3 Results and discussion

3.3.1 Baseline situation

Overall. GHG emissions from China's irrigation for a baseline scenario of 2010 are estimated to be 46.11 MtCO2e (table 2). This result comprises energy use from groundwater pumping and pumped surface water, including conveyance and application in irrigation systems. This result is similar to previous findings by Zou et al (2013b), however, our estimate for groundwater pumping on its own (24.59 MtCO2e) is lower than previous estimates of 28.65MtCO2e by Zou et al (2013b), and of 33.1 Mt CO2e by Wang et al (2012). The contrasting results are likely due to minor differences in methods between the studies and because we have used more recent data, made available from the Ministry of Water Resources in 2012.

The irrigation efficiency value calculated for the baseline is 23.80% (table 2) lower than the FAO estimate for East Asia (33%; FAO 2002), and much lower than the Chinese official irrigation efficiency figure for 2010 (50%; MWR 2010). It should be noted that estimates of irrigation efficiency are notoriously uncertain at all scales and they are subject to strong debate. Differences in the definition and/or calculation method can strongly influence results. Our definition of irrigation efficiency is the fraction of water "pumped or diverted through the scheme inlet which is used effectively by the plants" (FAO 1989), while the Chinese government definition is the ratio between water available for crops and water extracted (MWR 2009; Han et al 2009).

Table 3-2 Estimates of irrigation efficiency and emissions from irrigation and their main parameters for the baseline scenario (values based on data for 2011).

	Units	**National**	**Hebei**	**Heilong-jiang**	**Shandong**	**Xinjiang**
Agricultural Water						
Total agricultural water	km^3	383.16	15.43	25.65	22.19	50.49
Groundwater	%	17	77	52	29	16
Surface Water	%	83	23	48	71	84
Pumped surface water	%	13	2	16	9	1
Average groundwater pump head	m	27.2	47.9	17.9	23.2	34.9
Average surface water pump head	m	32.2	43.8	14.6	30.5	50.0
Irrigated Area						
Total irrigated area	Mha	66.35	4.97	3.88	5.55	5.39
Groundwater irrigated area	Mha	17.81	3.79	1.81	2.37	0.76
Irrigation technology area	Mha	27.31	2.70	2.66	2.26	2.89
Conveyance						
Surface water canal*	Mha	48.09	2.69	3.75	3.82	4.15
Canal lining	Mha	11.58	0.28	0.12	0.57	1.17
Low pressure pipes	Mha	6.68	2.00	0.01	1.16	0.07
Application						
Flood/Surface*	Mha	57.29	4.51	1.34	5.01	3.64
Sprinkler	Mha	3.03	0.24	0.92	0.15	0.09
Micro-irrigation	Mha	2.12	0.03	0.13	0.06	1.60
Other field measures	Mha	3.91	0.19	1.49	0.33	0.06
Irrigation Efficiency						
Conveyance	%	44.40	58.69	31.56	48.21	40.61
Application	%	53.60	52.21	64.95	52.30	62.51
TOTAL	**%**	23.80	30.65	20.50	25.21	25.39

	Units	**National**	**Hebei**	**Heilong-jiang**	**Shandong**	**Xinjiang**
Energy Emissions						
Groundwater pumping	$MtCO_2e$	24.59	6.16	3.99	2.15	3.37
Surface Water pumping	$MtCO_2e$	12.92	0.10	0.47	0.51	0.16
Pressurising water for conveyance (low pressure pipes)	$MtCO_2e$	-1.18	-0.35	0.00	-0.21	-0.01
Pressurising water for application (micro-irrigation)	$MtCO_2e$	2.32	0.02	0.16	0.05	2.84
Pressurising water for application (sprinkler)	$MtCO_2e$	7.46	0.32	2.59	0.26	0.36
Total emissions	**$MtCO_2e$**	46.11	6.25	7.22	2.75	6.72

* Calculated. based on official data on areas adopting irrigation technology and groundwater irrigation

The definition we use includes conveyance efficiency, which is absent in the official Chinese definition (i.e. we include water abstracted from source to crop. whereas the governmental definition only includes water from irrigation scheme source to crop). Hence, the two irrigation efficiencies are not directly comparable.

The socio-ecological contexts of the four provinces are reflected in contrasting relative distributions of water supply sources and adoption levels of different irrigation technologies and therefore show considerable differences in both the overall efficiency and between conveyance and application types (table 2). Hebei has a very efficient conveyance system partly attributed to widespread use of low pressure pipelines but predominantly to the high proportion of groundwater use for irrigation (77%).

CO2e emission rates show even larger differences as rates vary considerably between groundwater and surface water pumping, depending on the pump head. Hebei has high total emissions from irrigation because of its large proportion of groundwater use. The relatively extensive use of sprinkler systems in Heilongjiang leads to a much higher emissions than the other provinces, whereas the high pump head in Xinjiang is behind its high emissions.

3.3.2 Scenario results

Table 3-3 lists the effect of expanding the area under irrigation technology according to the recent 12th 5YP plan. The results show an increase in irrigation efficiency from 23.80 to 26.76% which seems consistent with the 3% increase targeted by the national 12th 5YP. Hebei and Heilongjiang show higher increases in irrigation efficiency than the increase targeted in the 12th 5YP (Hebei 3%. Heilongjiang 3%. Shandong 4%. Xinjiang 6%). Other things being equal, these changes would provide reductions of applied water of nearly 11 km3 that, if realised, could be used to intensify or expand irrigated cropping to help meet the 5YP target of increased grain production. However, the changes also lead to increases in GHG emissions of 10.35% (4.77 MtCO2e) due to the expansion of pressurised irrigation systems. The effects on emissions from energy use vary substantially among the provinces with Heilongjiang and Xinjiang experiencing increases of nearly 50%. Hebei and Shandong, on the other hand, show narrow decreases due to their adoption of low pressure pipes and proportionally lower increases in sprinkler and micro irrigation systems. We now consider the potential reductions in water application (table 3). The national average reduction in applied water is 170.93 m3/ha and the provinces range from 139.40-502.09 m3/ha. Hebei, with the highest irrigation efficiency, has the lowest rate of reduction in water application (m3/ha), whereas Xinjiang, with an irrigation efficiency slightly above the national value, has the highest rate of reduction in water application. These differences highlight the importance of increasing efficiency in areas with high water use and low efficiency. Energy savings directly related to irrigation technology are primarily due to reductions in water use, hence energy is only saved if less water is pumped and/or pressurised.

Table 3-3 Increase in the area adopting irrigation technology as targeted in the 12th 5YP for 2015 and the effects on scheme irrigation efficiency and GHG emissions.

	Units	**National**	**Hebei**	**Heilongjiang**	**Shandong**	**Xinjiang**

Targeted expansion of irrigation technology						
Sprinkler	1000 ha	2001	19	1115	33	90
Microirrigation	1000 ha	2011	19	87	33	1297
Low pressure pipes	1000 ha	2453	559	1	522	27
Canal lining	1000 ha	3535	108	242	162	172
Total	1000 ha	10000	705	1445	750	1586
Irrigation Efficiency achieved with the targeted areas under advanced irrigation technology						
Conveyance	%	48.37	66.98	34.39	55.63	42.38
Application	%	55.32	52.46	73.03	52.69	72.56
TOTAL	**%**	26.76	35.14	25.11	29.31	30.75
% total increase	%	12.45	14.67	22.53	16.27	21.11
Absolute figure of total increase	%	2.96	4.49	4.62	4.10	5.36
Energy Emission						
GW pumping	$MtCO_2e$	24.05	6.16	3.99	2.15	3.37
SW pumping	$MtCO_2e$	12.63	0.10	0.47	0.51	0.16
Pressurising water for conveyance (low pressure pipes)	$MtCO_2e$	-1.62	-0.45	0.00	-0.30	-0.02
Pressurising water for application (micro irrigation)	$MtCO_2e$	4.23	0.03	0.27	0.07	5.14
Pressurising water for application (sprinkler)	$MtCO_2e$	11.59	0.34	5.74	0.31	0.72
TOTAL	**$MtCO_2e$**	50.88	6.18	10.47	2.74	9.38
% total increase	%	10.35	-1.00	45.06	-0.38	39.54
Effects of irrigation technology, compared with baseline irrigation system						
Reduction in water application per area	m^3/ha	170.93	139.40	305.42	163.93	502.09
Emissions change	$MtCO_2e$	4.77	-0.06	3.25	-0.01	2.66
Investment per area	CNY/ha	7311.64	4284.29	9108.23	4612.30	12950.39
Reduction in water application per unit of investment	L/CNY	23.38	32.54	33.53	35.54	38.77

Therefore Hebei is the only province to show a (modest) co-benefit, with lower emissions compared to the baseline, which can be explained by the characteristics of its water supply system. A high proportion of groundwater and deep groundwater pump lift make Hebei’s water supply is highly energy intensive, so that reductions in applied water tend to reduce emissions. This finding is consistent with the potential for energy savings in Hebei presented by Q Zhang et al (2013).

Then in Shandong the increase in areas adopting low pressure pipes compensates the increase of emissions due to larger areas adopting micro-irrigation and sprinklers. Both Heilongjiang and Xinjiang exhibit increases in emissions. For instance, despite the relatively large reductions in water application in Xinjiang, emissions show a significant trade-off, increasing by 40%. Co-benefits are lacking as the main water supply in Xinjiang is gravity-fed surface water. The characteristics of the water supply systems strongly determine the potential for energy savings from reductions in water application. In terms of GHG emissions, pressurized irrigation technology such as sprinklers and micro-irrigation is best implemented in areas with energy-intensive water supply. Where this is not the case, it is important to recognize the energy trade-offs associated with implementing energy-intensive irrigation technology, as seen in the case of Heilongjiang where emissions increase by 45%, despite reductions in water application.

The economic dimension of the irrigation water-energy nexus is now considered. A review of the investment costs of different irrigation technologies in 13 Chinese studies (see supplementary table S6, Appendix A1) allows an estimate of average cost (CNY/ha) for each of the four irrigation technologies that can be used to calculate the reduction in water application per unit cost. Improving conveyance by canal lining costs roughly 4,300 CNY/ha, low pressure pipes cost roughly 3,750 CNY/ha, sprinklers 9,700 and micro-irrigation is the most expensive at CNY 14,500 per ha. The results show that on a national level the average investment return is 23 litre of reduced water application per CNY (table 3) which is lower than any of the detailed provinces. The investment cost per area has no direct implications for the outcome, but both are related because the most expensive technologies listed above use more energy. Prioritizing low pressure pipes in contexts dominated by groundwater sources, like Hebei, is cheaper and leads to co-benefits. A similar result can be expected from canal lining; although it is not a technology strongly targeted in the analysed provinces, it could play a significant role. In contrast, prioritizing more expensive technologies like sprinklers and micro-irrigation leads to costly trade-offs, due to increased energy consumption when using surface water and/or increasing the pressure for sprinkler devices.

3.3.3 **Sensitivity analysis**

Finally we examine the sensitivity of some key parameters on the national scale. Increases in the area of low pressure pipelines for conveyance and micro-irrigation for application produce the highest proportional effect on raising irrigation efficiency (Figure 3-2).

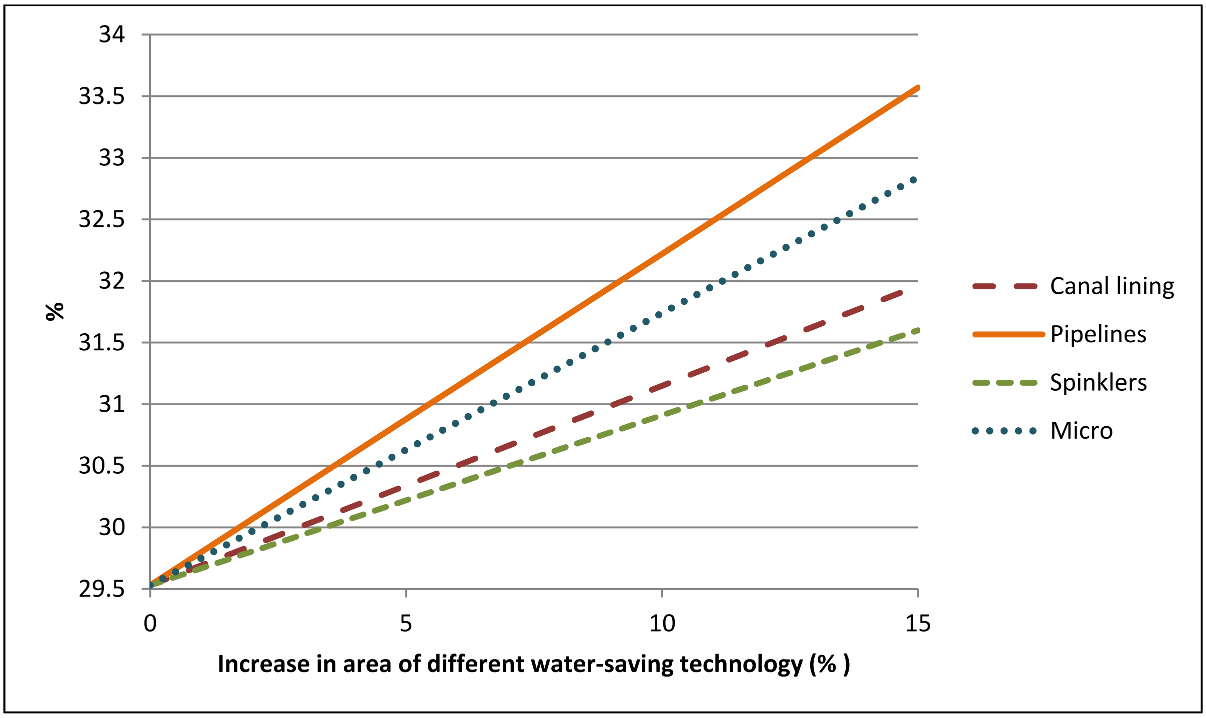


Figure 3-2 Sensitivity of irrigation efficiency to incremental per cent changes in the area using irrigation technology.

Sensitivity analysis of emissions to irrigation technology and water and energy sources shows that expansion of sprinkler systems strongly increases the emission rates (Figure 3-3); this is not the case, however, in areas where the groundwater pump head is greater than the critical energy saving head (Zou et al 2012). Pumping water is clearly the most energy intensive process. With the current configuration, changing the distribution of energy sources towards more electric pumps has little impact on the emissions.

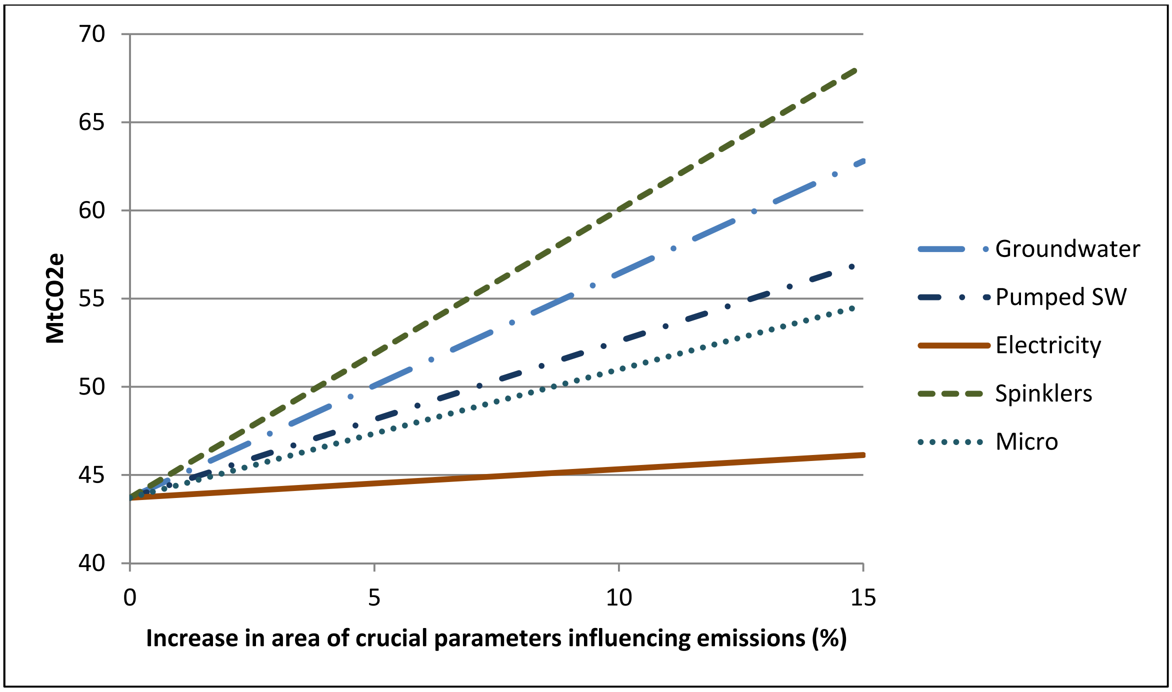


Figure 3-3 Sensitivity of energy use emissions to incremental per cent changes in key influencing factors.

The predominant use of surface water and traditional unlined canals is the main reason for the relatively low irrigation efficiency in China. Consequently, improving conveyance efficiency through canal lining and pipelines may be the most effective way of achieving the co-benefit of reducing water application with a low carbon footprint. Only in groundwater fed areas is micro-irrigation a suitable irrigation technology for both improving irrigation efficiency and decreasing GHG emissions, in situations where the pumping head value allows it (Zou et al 2012).

3.4 Conclusions and policy implications

Quantifying the trade-offs and co-benefits is just part of the nexus story; to successfully manage the water-energy nexus in China, a critical set of socio-economic and policy issues also need to be addressed. These include; improving communication amongst ministries with responsibility for different aspects of the water-energy nexus, creating clear incentives to decrease water application and adopt irrigation technology, establishing reliable water rights, and improving groundwater governance and use (Shiferaw et al 2009; Yu 2011; J Wang et al 2009, J Zhang, 2007, L Zhang et al

2008; Calow et al 2009). This study enhances our understanding of co-benefits and trade-offs in the irrigation water-energy nexus, across a set of diverse provincial cases in China using targets defined in the 12th 5YP. The approach applies a suite of assumptions about water use efficiency for various stages and technologies in the process of irrigation. Whilst such aggregate estimates of efficiency are widely used, they are subject to high levels of uncertainty and site-specific factors will lead to considerable variability.

We find that expansion of sprinklers and micro-irrigation as outlined in the 12th 5YP could increase GHG emissions from agricultural water use by roughly 45% at provincial level and 10% at national level. Where pressurized irrigation technology is used in surface water irrigated areas (Xinjiang) or where the energy consumption to pressurize water (Heilongjiang) is high, emissions increase dramatically. The results show that water supply configuration largely determines the potential energy savings from reductions in water application. An implication of this is that co-benefits of irrigation technology for energy saving only appear in areas irrigated with energy intensive supply (Hebei). Trade-offs appear in surface water irrigated areas (Xinjiang), where emissions due to expansion plans for pressurized irrigation technology could increase by one third. Taken together, these results suggest that in situations where policy makers seek to optimize both water and energy use they should encourage the adoption of low pressure conveyance pipes in groundwater irrigated areas, and canal lining in surface water areas, since these increase efficiency with lower emissions than other methods. Another important implication is that sprinklers and micro-irrigation appear as a suitable means to increase efficiency only in groundwater irrigated areas. Regarding the costs, the most expensive technologies appear linked to trade-offs, while co-benefits result from lower-priced technologies. These insights are relevant to make adaptation policies consistent with mitigation goals in the irrigation sector.

Chapter 4. Integrated Economic Assessment of “Stay-green” Technology in Sorghum under Current Climate Variability

Abstract

Sorghum is the 4th most important crop by cultivated area at the world level. In India, around 5 million households plant it to support their dietary requirements. There sorghum is planted in drought-prone conditions in the post-rainy season with frequent occurrence of crop failure. An emergent technology utilizing knowledge of "stay-green" phenotype in sorghum has been shown to increase the probability for obtaining higher production of grain for human food and stover for cattle feed in drought-prone areas. The purpose of this article is to conduct an integrated economic evaluation of the potential of the "stay-green" technology innovation. To do so, we have introduced methodological innovations to improve spatial and temporal resolutions in an Integrated Assessment Model. Our results estimate in which areas appear the desired effects, which are increase in mean production and decrease of standard deviation of grain and biomass yields, for a set of stochastic climatic scenarios. We show that new crop varieties, obtained with techniques such as accelerated breeding, significantly contribute to adaptation to climate variability, producing in many cases more food and also more biomass, which has implications for mitigation of climate change. We also show that, although a significant amount of welfare is added by these innovations to the agricultural sector, the provision of information has much larger welfare amounts to add. However, it remains unclear whether crop varieties alone can solve the expected pressures due to increased demand for a higher population in the mid XXI century.

4.1 Introduction

Sorghum [*Sorghum bicolor* (L.) Moench] ranks 4th cereal globally and in India by cultivated area (Faostat, 2015; Yadav et al 2011); worldwide it covers roughly 250 Mha located mostly in the semi-arid tropics. In India around 5 million small-holders plant sorghum in post-rainy season (rabi) to support their basic dietary requirements (Kholová et al., 2013). Post-rainy sorghum is planted in 6.2 Mha in India mainly due to lack of better alternatives suitable to withstand the challenging environmental conditions, mainly drought. Sorghum yields in India are 4 times lower than in the developed countries using technologies of precision agriculture, such as United States or Australia (Faostat, 2015). In India sorghum is a staple crop, particularly in poorly resource-endowed areas with low soil fertility and a limited amount of soil water holding capacity. Increasingly, its fodder residues after harvest are used to feed cattle and the fodder value now reaches about half of the sorghum value chain. Despite sorghum is considered a drought adapted crop per se its production often fails to produce grain and in this case the crop value correspond to fodder production, which is also a desired product because during the post-rainy season there is not much of other alternatives to obtain fodder for livestock. The mentioned reasoning of the lack of better alternatives is supported by the fact that post-rainy sorghum production and area had not suffered the severe decrease that sorghum crop areas have shown the previous years during rainy season in favour of economically better cropping alternatives (Nagaraj et al. 2013).

With this challenging socio-ecological context in mind, considerable progress in understanding the mechanistics of promising "stay-green" technology for sorghum has been made (Vadez et al. 2011, Kholova 2013, 2014, Borrell 2014, 2015). The "stay-green" phenotype has been shown to link to several key genetic parameters influencing plant water management, e.g. tillering; canopy development rate, limited transpiration under high vapor pressure deficit, improved water extraction and sensitivity of canopy expansion to soil water content. These genetic traits enable the conservation of soil water during vegetative growth phase and increases the proportion of water that is used during the reproduction phase, and this has been shown to be a feature of critical importance in the increase of crop productivity under limited water. The genetic markers have been established to enable accelerated introgression of "stay-green" traits into desired genetic background. Overall, the "stay-green" phenotype can be provided as a public good with the seed price in the range of other mainstream sorghum traditional planting varieties, so it emerges as a relevant management alternative due to the improved performance on the parameters described below.

Although the effects on grain and stover yield of the different genetic trait that lead to "stay-green" have been tested in experimental fields and in-silico with a crop simulation model (Kholova et al., 2014), this technology innovation has not been analysed from an economic perspective yet, so its contribution to the welfare of the agricultural sector of India is unknown. We aim to perform such analysis with an Integrated Assessment Model (IAM), and to the best of our knowledge there is no similar analysis published for such an innovation, possibly because the crop models used in the IAM arena lack the sensitiveness required to mechanistically capture such variation of phenotype. Others studied the farm scale returns of sorghum (Enciso et al., 2015) and evaluated its diverse economic potentials (Chagwiza, and Fraser, 2014). More to the point, Sassi (2013) have shown that the interaction of sorghum with climate variability has notable economic consequences for traditional varieties or sorghum.

There are approaches to assess and understand the contribution of an agricultural management innovation under global change, mainly based in Agricultural Sector Models (McCarl and Schneider, 2001; Schneider et al., 2011). In our case, we will significantly depart from these approaches on three points. First, we use a crucial stochastic feature for the decision variable depicting land use. Using a stochastic configuration, a single solution for the variable representing the land use captures the variation existing in the whole data input of states of nature representing climate variability, in this way the whole range of options is depicted and the results capture the impact of climate variability. The rest of the variables are configured to have one solution for each state of nature. Summarizing, a single solution will capture the inherent variability to which the socio-ecological context is subject. Second, we analyse crop land use at the districts level, a unit of resolution much lower than in other models. And third, we go into details also in temporal terms, modelling only the dry season.

The aim of this study is to understand the overall economic impact of the "stay-green" sorghum phenotype planted in the post-rainy season on the Indian agricultural sector. With this in mind, we will answer the following research questions:

- How are the positive treats of "stay-green" Sorghum distributed in space?
- Are there co-benefits between adaptation to climate variability and mitigation of emissions through biomass production for fodder?
- What is the economic value of the “stay-green” sorghum variety?
- How much can farmers adapt to climate variability adopting the cultivation of "stay-green" Sorghum?

The paper is structured as follows: next section describes the data and methods used. Section 3 presents and discusses the results, and finally, section 4 concludes with some policy recommendations.

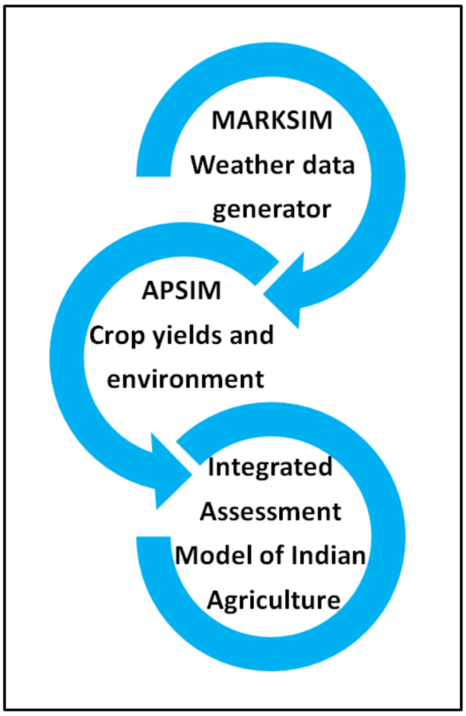


Figure 4-1 Modelling chain used to investigate the economics of Sorghum innovative varieties.

4.2 Materials and methods

Overall our study follows the classic impact model chain (Figure 4-1), starting with climate variability data, following with an impact model for crops, and introducing the yields resulting from the crop model into an IAM.

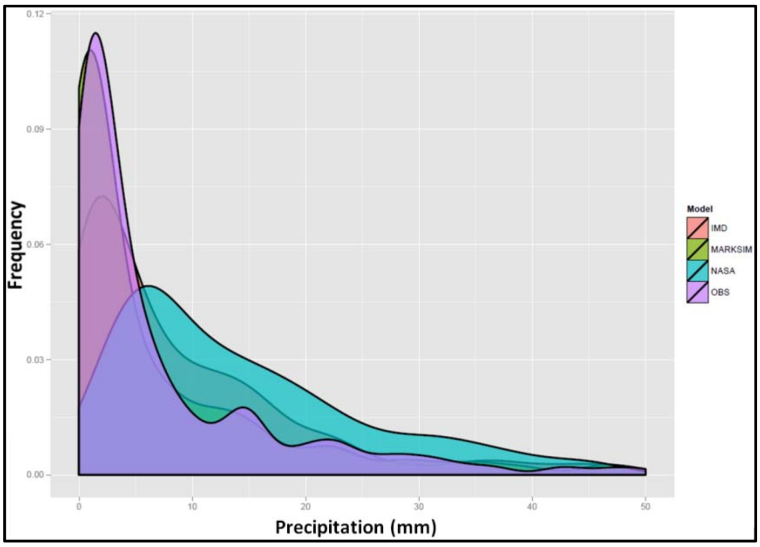


Figure 4-2 Comparison of weather generator models for wet day rainfall intensity in Pune in October. (Source: Suresh et al., unpublished).

4.2.1 Climate variability

Climate variability is modelled with MARKSIM, a stochastic weather generator arranged to reproduce the current climatic conditions. The observed weather data used comes from the Indian Meteorological Department, which gathers observations from weather stations spread out in the country. MARKSIM has been used all around the world for more than 30 years and has been identified as a reliable weather generator. Here it is being used to provide weather input to a crop simulation model (APSIM). In Figure 4-2 it is shown an example of how MARKSIM reproduced observed data better than other similar models (NASA, IMD). Several experiments have been conducted before for the same crop and trait. Overall, in these experiments the response to observed weather and generated weather data with Marksim provided higher levels of agreement than other weather generator models.

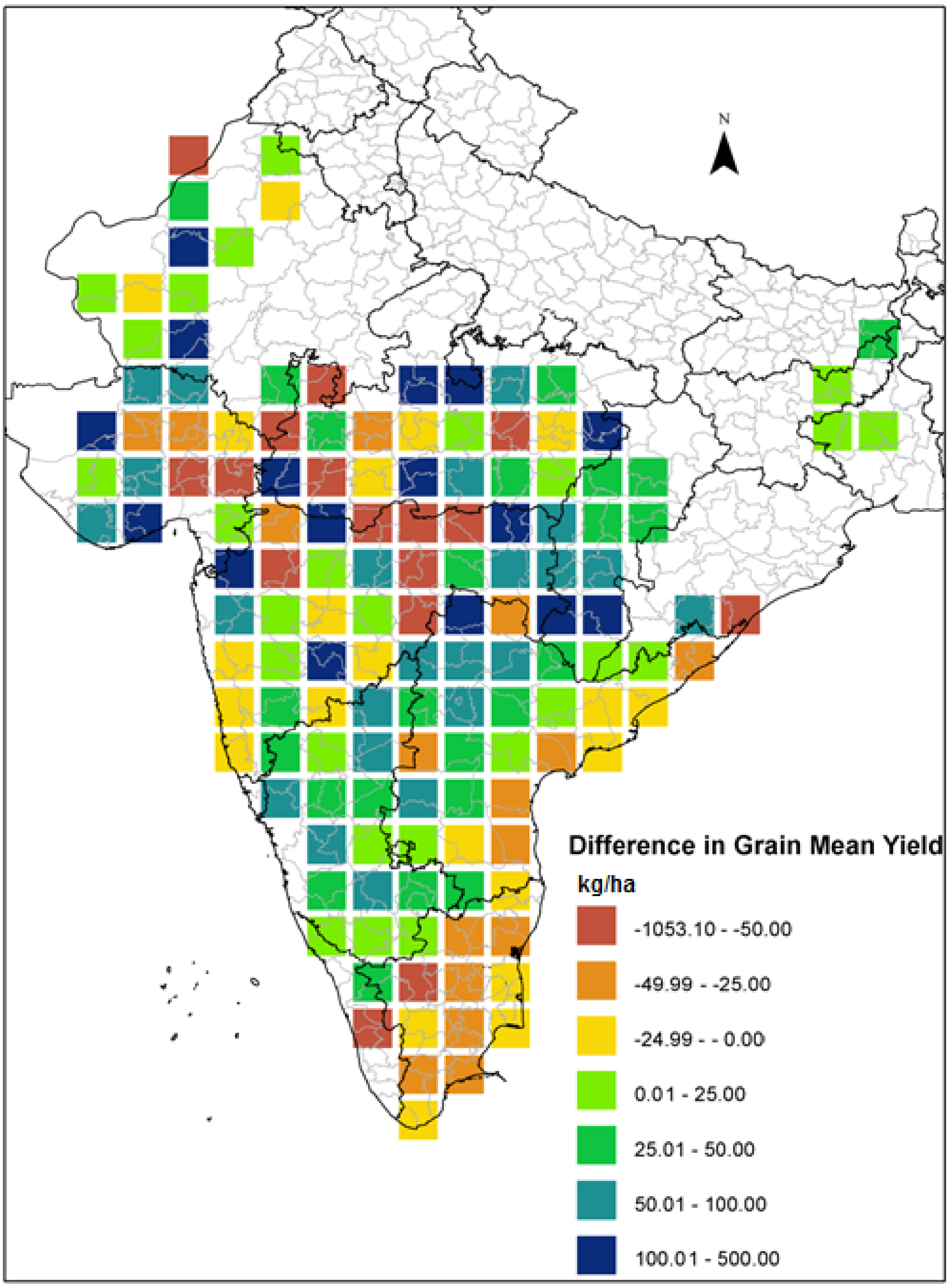


Figure 4-3 Simulated areas of crop modelling results, showing differences in mean grain yield from Sorghum (Stray-green minus Traditional) in India.

4.2.2 Crop modelling

Amongst all possible options for assessing the potential of a "stay-green" phenotype, APSIM (Agricultural Production Systems sIMulator) has being selected due to its mechanistic nature. APSIM has been proven relevant to reproduce "stay-green" traits and its putative production benefits. In earlier studies, the APSIM model reproduced the variation of Sorghum yields across the study region with a reliable correlation value of 73% (cf. Kholova et al 2014). Climate data to feed the APSIM model is generated by MARKSIM, and soil data comes from FAO soil data base.

4.2.3 Stochastic Integrated Assessment Model of the Indian Agricultural Sector (ASMIN)

This section describes the IAM, which is a stochastic partial equilibrium optimization model of the agricultural sector of India (ASMIN) programmed in General Algebraic Modeling System (GAMS). ASMIN is an IAM that summarizes bio-physical and socio-economic information related to climate change to assess policy recommendations. Methodologically, in this exercise we innovate by going into the details of the temporal and geographical dimensions. Geographically, we take the Indian districts as the resolution of our crop variable, instead of the Indian states or the whole country, as it happens often in other similar models. Temporally, we model only the dry season, instead of packing both seasons and assuming they are only one, as it happens so far in other IAM. In our particular application, these methodological innovations have implications on further aspects of the model: India is only an exporter of sorghum, trade records show no imports in the last 10 years and previous amounts are not relevant, therefore traded quantities are related to the much more productive rainy season. For this reason we finally excluded trade of the model for this particular application.

ASMIN mimics decision making of the Indian agriculture by portraying the agricultural sector of the 74 Indian districts involved in Sorghum production, together with its impacts on the national market. Amongst other features, ASMIN can provide a measure of the welfare of the sector. ASMIN is an optimization mathematical program written in GAMS, with roughly 80,400 individual variables and

6,100 single equations, introduced as blocks via the use of indices in GAMS. ASMIN consists on an objective function that maximizes the welfare of the sector. The objective function is constrained by several equations. These constraints define the feasibility of the optimal level for the endogenous variables and the maximum welfare. The maximum welfare is calculated as the sum of producer’s surplus and consumer’s surplus, at this level of welfare the market finds the equilibrium in perfect competition, as described in McCarl and Spreen (1980). In this market equilibrium, the optimal levels of the variables are considered equilibrium levels for the agricultural sector.

Before we start a detailed description of ASMIN’s equations, its variables and parameters will be depicted. The levels of economic activities are represented by endogenous variable blocks, written in capital letters in the equations below. Specifically, CROP stands for the amount of land (ha) allocated for different cropping activities, DEMD (Tones) represents demand of commodities, RESR (diverse units) symbolizes resources consumption and CMIX (ha) appears for historical crop mixes. The parameters given to the model as data input, namely coefficients of the variables and the right hand side values of the equations, appear in small letters. In particular, *b* stands for the available resources and *h* for the historical data on crop mixes. Similarly, *ic* represents variable undetermined costs coming from a calibration that depend upon the activity level. Then, *yi* represents the crop yields, that come from APSIM, an agricultural productivity biophysical model, and *a* represents production factors. Finally, *prob* is the probability of each of the involved states of nature representing climate variability.

The equations described below actually depict blocks of equations that are reproduced through indices. The indices are indicated via subscripts: *f* stands for resources and production factors, *c* for crops, *m* for management technology option, *w* for climate variability states of nature, *x* for historical alternatives of crop land uses, *y* for commodities and *r* for regions. Equation block (1) express the supply-demand balance of commodities, which links production with markets.

$$-\sum_{c,m} yi_{r,c,m,y,w} \cdot CROP_{r,c,m,w} + DEMD_{r,y,w} \leq 0 \quad \forall r, y, \mathrm{w} \qquad (1)$$

Equation (2) reproduces the constraint in natural resources, which is related to exogenous parameters in equation (3), in which the variable RESR is limited to the exogenous amount of available resources for every region.

$$-RESR_{r,f,w} + \sum_{\mathrm{c},m} a_{r,c,m,f,w} \cdot CROP_{r,c,m,w} \le 0 \quad \forall r, w, f \tag{2}$$

$$RESR_{r,f,w} \le b_{r,f} \quad \forall r, f, w \tag{3}$$

The crop mix is imitated from reality through equation block (4). This equation avoids extreme specialization in the model by reproducing historical crop mixes.

$$\sum_{m} CROP_{r,c,m,w} - \sum_{x} h_{r,c,x} \cdot CMIX_{r,x,w} = 0 \quad \forall r, c, w \tag{4}$$

Finally, equation block (5) represents the objective function, which contains an inverse demand function for commodities and an inverse supply function for resources.

$$Max\ \ WELF = \sum_{w} \left[\left(\begin{array}{l} \displaystyle\sum_{r,y} \left[\int \varphi_{r,y}^{demd} \cdot \left(DEMD_{r,\mathrm{y},w} \right) d\left(\cdot\right) \right] \\ \displaystyle -\sum_{r,f} \left[\int \varphi_{r,f}^{resr} \left(RESR_{r,f,w} \right) d\left(\cdot\right) \right] \\ \displaystyle -\sum_{r,c} (ic_{r,c} \cdot \sum_{m} CROP_{r,c,m,w}) \end{array} \right) \cdot prob_{w} \right] \tag{5}$$

For the purpose of this article, ASMIN is run in a stochastic framework, over a discrete equally probable set of 50 possible states of nature. These states of nature depart from 50 different yield outcomes calculated with APSIM, using the corresponding 50 different sets of weather data stochastically generated with MARKSIM to reproduce current climate variability. A welfare value is obtained for each state of nature, however, the variable CROP is optimized in a single solution mode, that captures the best solution taking into account the variability of the current climate.

4.3 Results and Discussions

We present the results of our IAM, starting with a comparison of the yields and risks for both varieties analysed and their products. It follows an overall view of the increased welfare due to the "stay-green" sorghum. Then we present the positive effects of adaptation and a comparison with improved climatic information.

4.3.1 Assessment of Agricultural Output: Quantity and Associated Risk

Next we consider changes in mean grain yield comparing traditional sorghum with “stay-green” sorghum, and account for decreased risk observing the decrease in the standard deviation of the grain and fodder yields across the 50 climate variability scenarios produced. First we will compare grain yields, then fodder yields, and finally both. Overall, with “stay-green” sorghum the mean grain yield increases in 60.14% of the productive areas (Figure 4-3), and the standard deviation decrease in 60.81% of the productive areas (Figure 4-4). Seeking for both outcomes at the same time we find that in 42.57% of the productive areas the mean grain yield increases and the standard deviation decreases, and that only a 15.54% has the double negative outcome of decrease in mean grain yields and increased standard deviation and therefore increased risk. There is a 18.24% of the area in which lower grain yields are obtained with “stay-green” sorghum while the standard deviation is reduced, i.e. the production offers less risks; in these 18.24% of area there is a trade-off between grain yield and risk, meaning that the yield security improves, but yield is reduced in amount.

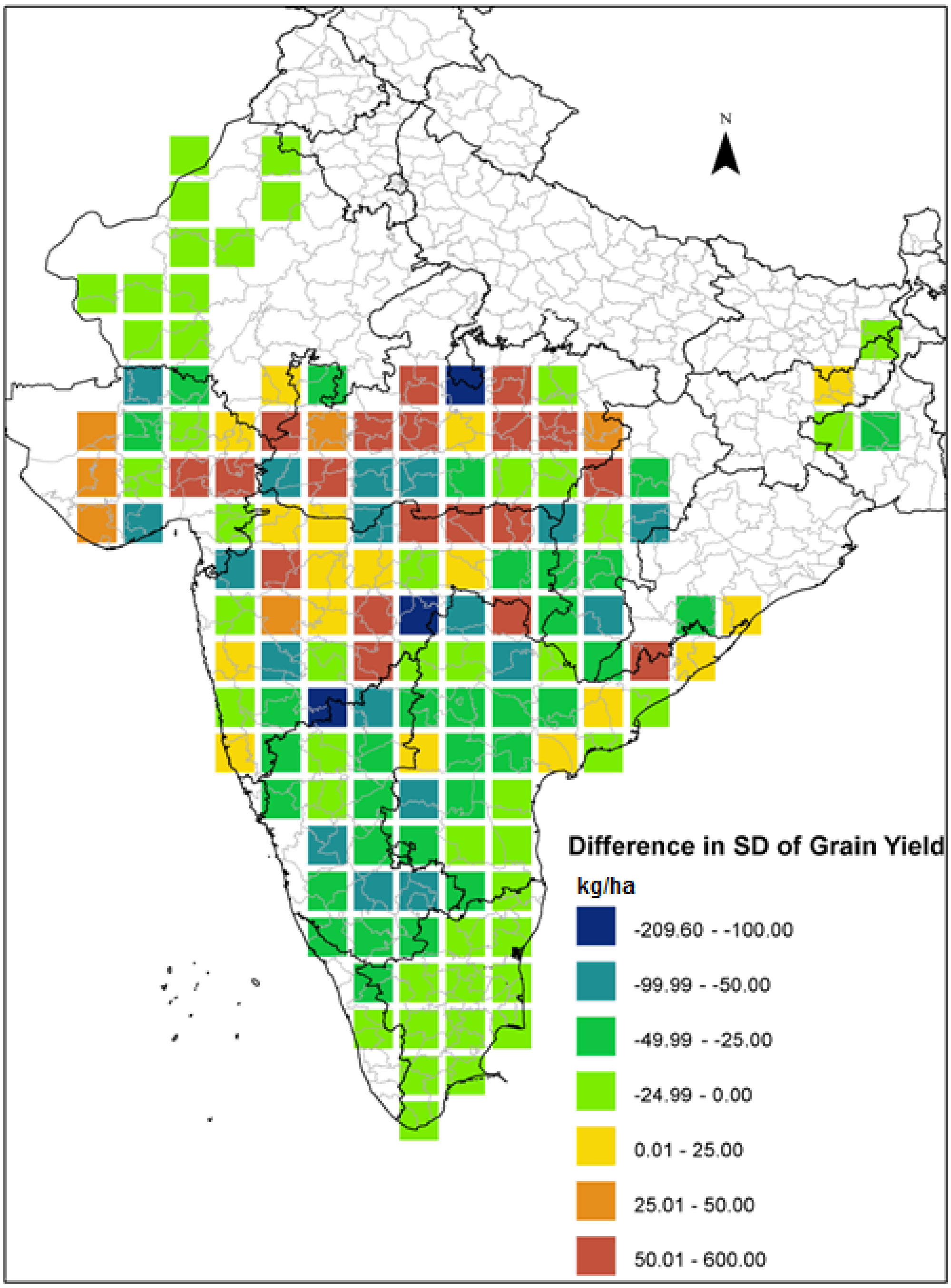


Figure 4-4 Simulated areas of crop modelling results, showing differences in standard deviation of grain yield from Sorghum (Stray-green minus Traditional) in India; please note that the desired effect is a decrease in yield variation.

In general, the increase in grain yield seems to come with a cost in terms of fodder yield, because in 63.51% of the productive areas the fodder mean decreases (Figure 4-5). While there is no striking effect in the changes in the standard deviation for fodder, still a 50% of the areas experiment a decrease in the standard deviation of the fodder yield (Figure 4-6), therefore only in half of the cases fodder security is increased, while decreased in the other half.

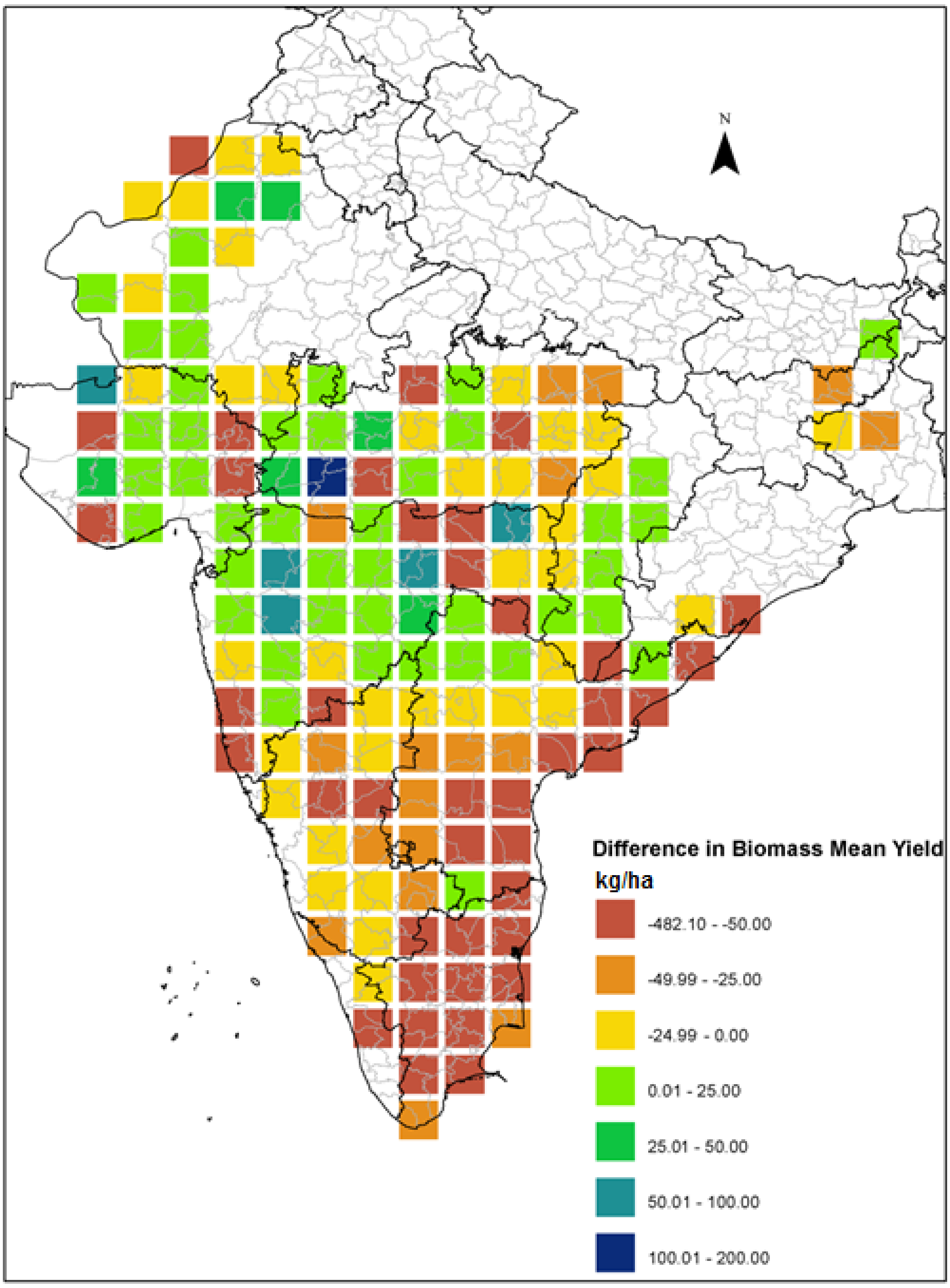


Figure 4-5 Simulated areas of crop modelling results, showing differences in mean biomass (fodder) yield from Sorghum (Stray-green minus Traditional) in India.

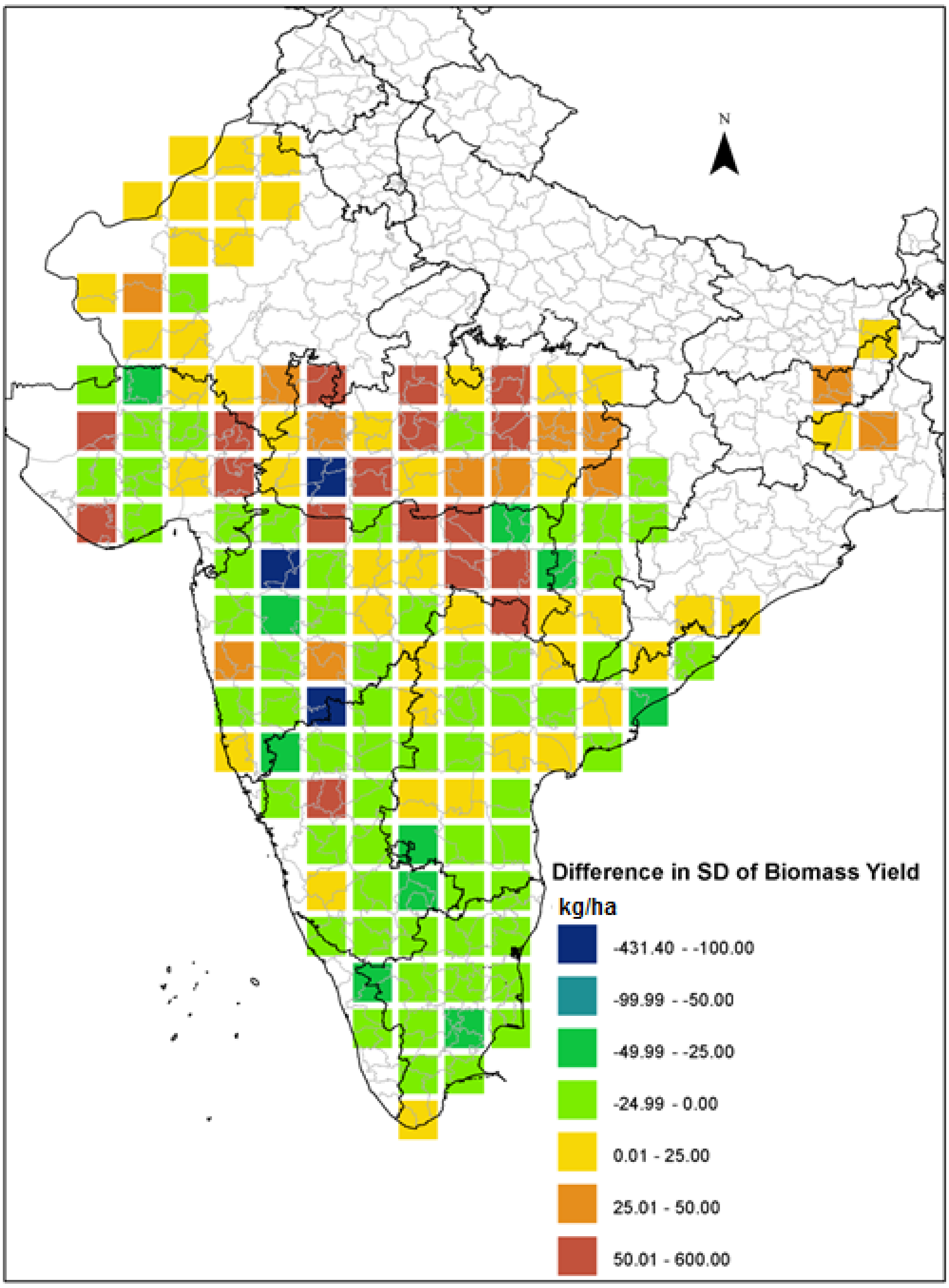


Figure 4-6 Simulated areas of crop modelling results, showing differences in standard deviation of biomass (fodder) from Sorghum (Stray-green minus Traditional) in India.

Looking at conjoint effects, we see that only in 20.27% of the productive areas there is a positive combined effect of increased mean fodder production and decreased standard deviation and therefore risk, while in a 33.78% the opposite happens, decreased mean production and increased risk.

When analyzing together grain and fodder yields, they both increase in 20.27% of the production areas, while in 35.14% of the areas grain yield increase and fodder decrease. The results shows a considerable contribution of “stay-green” sorghum in terms of security and resilience under current climate variability, because in 40.54% of the cases the standard deviation decreases for both products, while in 31.08% of the productive areas there is an increase in risk both for fodder and grain.

4.3.2 Economic Impact of "Stay-Green" Sorghum Under Current Climate Variability

The results of our IAM reproduce the production baseline of grain (Figure 4-7) and biomass (Figure 4-8) for fodder taking into account the 50 states of nature stochastically generated with MARKSIM and the derived Sorghum yields calculated with APSIM for both traditional Sorghum and "stay-green" Sorghum.

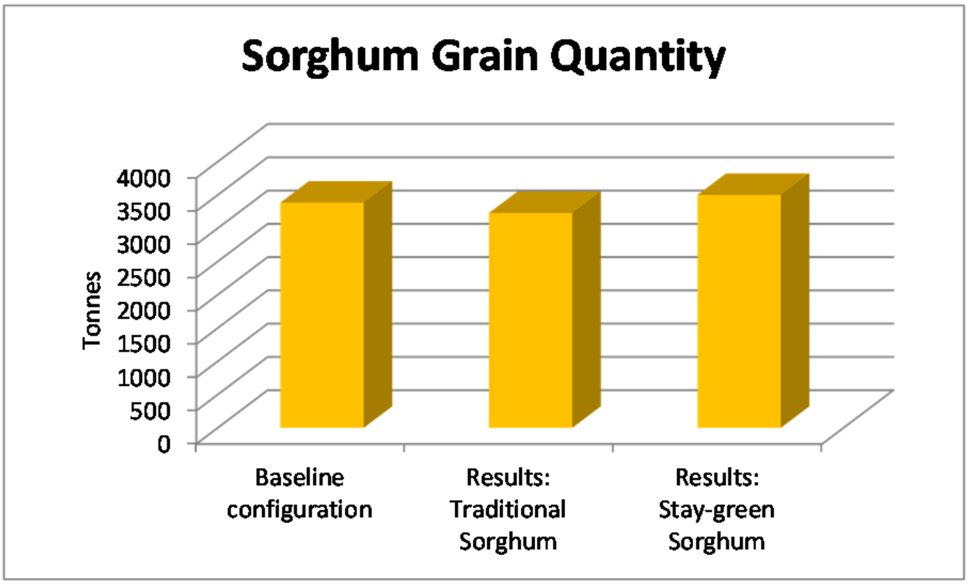


Figure 4-7. Comparison of results with baseline for production of grain from post-rainy sorghum.

Taking into account climate variability we calculate agricultural welfare for two scenarios: traditional sorghum and full adoption of "stay-green" sorghum. Due to the generally higher yields of "stay-green" Sorghum under a variety of conditions, the full adoption of "stay-green"sorghum would have an overall positive economic impact of roughly 55 M$ per year in the welfare of the Indian agricultural sector.

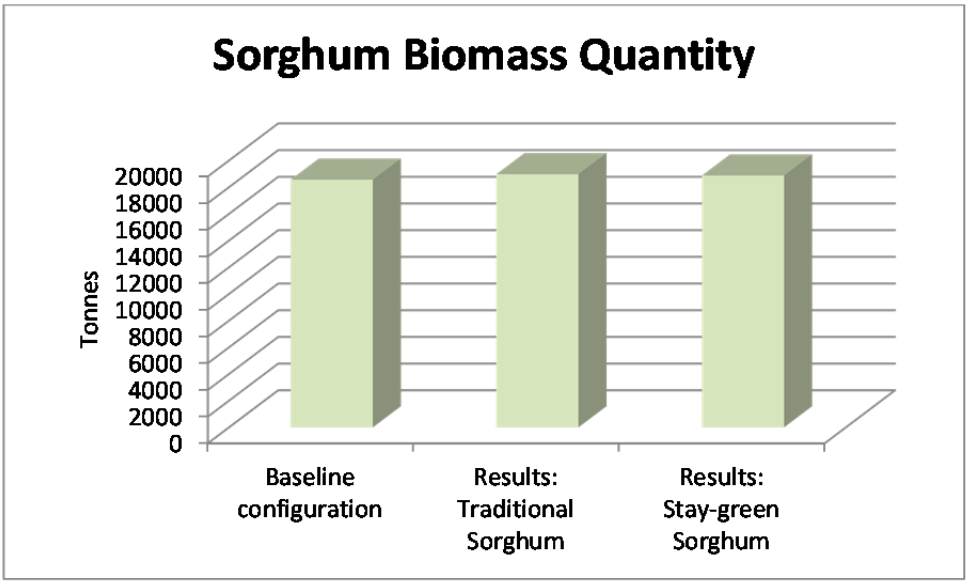


Figure 4-8 Comparison of results with baseline for production of biomass (fodder) from post-rainy sorghum.

This value (54.98M$) can be considered the social value of the "stay-green" trait, since it is the contribution of "stay-green" Sorghum to the welfare of consumers and producers of Sorghum in India. This value represents a 0.016% of the contribution of the agricultural sector to the Indian Gross Domestic Product; it appears as a significant fraction for a single innovation. If we go beyond the difference value above and analyse the economic impact of all considered states of nature for both scenarios (Figure 4-9), "stay-green" Sorghum visibly contributes to the improvement of the welfare of the sector. We see its probability density function is drawn a bit more to the right side in the X axis, meaning it takes higher welfare values. Even if the values are higher, Figure 4-9 conveys another message, the probability density function of "stay-green" sorghum has a lower spike around its mean value, i.e. the centre of the bell, and there is smaller area below it, meaning there is less probability than the contribution of "stay-green" sorghum to the welfare of the agricultural sector is around its mean. We interpret this as the effect of the increase of quantities produced on prices, which fall in some cases creating larger variations.

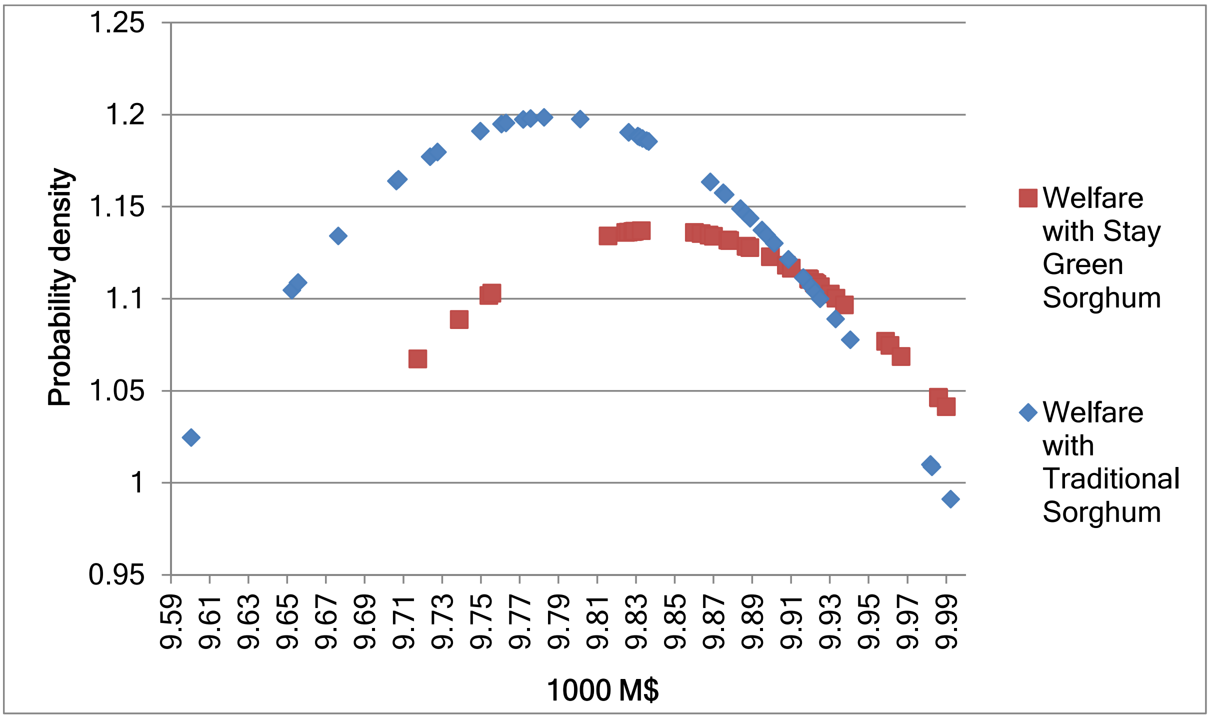


Figure 4-9 Detail of the probability density function of the values of the Welfare (a variable with a value for each state of nature representing climate variability) contribution of post-rainy Sorghum to the Indian Agricultural Sector.

4.3.3 Adaptation Potential of "Stay-Green" Sorghum Under Current Climate Variability

Overall, above we have seen "stay-green" sorghum improves the resilience against climate variability in biophysical terms, since it decrease the variation of the grain yield in most of the productive areas. This increase in mean grain yield comes with a decrease in the standard deviation of the grain yield all across the states of weather generated stochastically to reproduce climate variability. After this introductory verification for the input of our economic model, we will account what is the contribution of "stay-green" sorghum from the solution of the model.

At the quasi-local geographical scale of the Indian districts, our model provides a unique sorghum land use solution for all the states of nature. This solution, coherently to our preliminary analyses presented above, shows an increase in production of grain, but partially counterfactual results for fodder biomass. Fully adopting "stay-green" Sorghum would contribute to an average yield increase of 4.76 tonnes on each Indian district. The full contribution of "stay-green" Sorghum in terms of quantity would be of 266.2 tonnes of grain per year for the whole geographical area covered, which represents an increase of grain production of 7.86%. Given the administrative difficulties and significant economic expenditures of the Indian government on maintaining the Public Distribution System (PDS) derived from the National Food Security Act (2013), we argue whether it would not be a better option to invest on the diffusion of "stay-green" Sorghum instead of including sorghum in the PDS, contrarily to the arguments of Bali and Rao (2012).

4.3.4 The Potential Value of Information, compared with the Impact of New Cropping Varieties

The weight and the relevance of the numbers can be better understood by comparison of measures. We next compare the results of comparing crop varieties with an additional related adaptation scenario in which the farmers are assumed to have perfect knowledge about the weather in the planting season. First we shall explore these scenarios and discuss the validity of the assumptions behind them. On the one hand, it is unlikely that "stay-green" Sorghum will be fully adopted. On the other hand, it is unlikely that climate information coming from current generation of General Circulation Models will perfectly reproduce the future climate system. Furthermore, considering the basic pillars of Information Theory (cf. Shannon and Weaver, 1949), it cannot be accepted that the information will be perfectly transmitted and understood, and many behavioural science insights provide grounds to doubt that information will be used for the absolute maximum economic convenience. For all these reasons we find appropriate to introduce the term of “Potential Value of Information”, and disregard other terms such as “Expected Value of Information” as termed possibly by Dantzig (1963) and “Value of Information” as used by Chen and McCarl (2000).

Despite the caution expressed, we find informative the comparison of both scenarios, on one hand with and without perfect information for Traditional sorghum, and in the other hand with and without full adoption of "stay-green" sorghum with no additional information, to see which is the greatest contribution to welfare in the sector. Our results show that, if there would be such thing like perfect information, its actually related Potential Value of Information, i.e. in our case the welfare added by the information into the agricultural sector of India, would be of the order of 14.5 times higher than the contribution of "stay-green" sorghum fully adopted. This shows the high potential of information for adaptation, but arguably there are many unrealistic matters involved that will act as a barrier when trying to achieve such value.

4.3.5 **Concluding Remarks**

The contribution to human food security is precious and we wonder whether improvements in food security with even more modest GDP contributions capture the total welfare or economic value from a broader valuation economic perspective, similarly as it occurs with the valuation of non-marketed services from ecosystems, it might be that there are many other societal non-marketed values that have a strong weight when discussing food security. There is an important open question left in this study: whether different crop and technology improvements can overcome the needs of the Indian population in the mid XXI century.

It appears highly advisable for governments to invest in the development of more breeding technologies, for which I explored an example and provided estimations that show a substantial positive contribution to agricultural welfare, especially for those crops in the environmental productive frontier of the semi-arid areas of the tropics, even more when the involved populations might suffer of some degree of relative deprivation in some of the weather conditions that can be expected.

Chapter 5. Summary and Outlook

In this thesis, I explored transdisciplinary issues on diverse interfaces between policy making, the adoption of technology related to adaptation to climate change, and their environmental and economic consequences. We offered an overview of the solutions to the challenges posed by global change in the Asian Monsoon region.

5.1 Main Findings and Next Steps

The first results presented in this thesis (Chapter 2. Policies, Economic Incentives and the Adoption of Modern Irrigation Technology in China) provide statistical evidence and estimations of the impact of policies and economic mechanisms on the adoption of agricultural innovations, chiefly irrigation related-measures, which decrease water losses during transportation, decrease water application and/or decrease water evaporation from the field. The overall message from our descriptive statistics and econometric models is that governmental support and economic incentives are highly relevant to promote the adoption of modern irrigation technology. Our novel contribution shows that water pricing has an impact on the adoption of irrigation technology in China. Panel data series spanning over different 5 year plans would give a much more comprehensive picture. Besides, integrating the analysis of our results, and other results of the same nature, into cellular automata mimicking the adoption behavior amongst farmers, and introducing the output of the cellular automata into larger scale Integrated Assessment Models could potentially be a way to overcome the barrier between scales of analysis and to improve the depiction of reality into Integrated Assessment Models.

In the second set of results presented in this thesis (Chapter 3. Co-benefits and trade-offs in China’s irrigation water–energy nexus), we demonstrate the importance of understanding the full range of potential outcomes and implications of development policies related to technology adoption. Our linked resource analyses of water and energy estimated that an additional 10% of emissions would be produced just to reduce the application of water in the agricultural sector so that the current policy targets are achieved. The most striking novelty shown was that co-benefits are normally the result of lower-priced technologies, while the most expensive technology normally appears related to trade-offs. In the future, it would be beautiful to have detailed data of piezometric heads from all the areas using groundwater, and to know precisely where the technology investments where done, but this is currently impossible. Once we understood the water-energy nexus of irrigation, what can be done is a reformulation of the model mimicking the water energy nexus to calculate the cheapest and least environmentally damaging way of achieving the policy targets of the next (13th) 5 Year Plan of the Chinese Government.

In the third set of results presented in this thesis (Chapter 4. Integrated economic assessment of “stay-green” technology in sorghum under current climate variability), we have introduced methodological innovations related to spatial and temporal resolutions and we have shown that new crop varieties obtained with techniques such as accelerated breeding might contribute to adaptation to climate variability, producing more food and in many cases also more biomass, which has implications for mitigation of climate change. Our novel contribution is to show that although a significant amount of welfare is added by these innovations to the agricultural sector, the provision of information has much larger welfare amounts to add. However, it remains unclear whether crop varieties alone can solve the expected pressures due to increased demand for a higher population in the mid XXI century. It remains also the question whether these innovations extend the margin of human societies into challenging environmental conditions, and help humans overcome the limits to adaptation to global change. This question shall be tackled with a mix of qualitative and quantitative methods, complementing the numerical economic exercise with consistent narratives of the context as experienced by local farmers, which would imply combining field work interviews and observation with global change modelling.

The geographical and methodological diversity approached in this thesis, together with the transdisciplinary approach, provides a set of conclusions that might help the reader to have an overview of the challenges and options needed to cope with the resource constraints under global change in the Asian Monsoon region.

5.2 Self-Reflection about the Thesis and the Future of Global Change Related Science

The thought that an invention equivalent to infinitesimal calculus was going to make economics less ignorant than they still now are is attributed to John von Neumann. This can be interpreted in different ways, but in any case nowadays there is no consensus about how to go beyond equilibrium theory based approximations of the complex interactions between agents in the economic arena. Better approximations would reproduce how different emerging outcomes occur. These emerging outcomes are the complex systems science equivalent to the so called invisible hand proposed by Adam Smith to describe how the equilibrium between supply and demand was achieved. It seems quite fair to wonder why so many scholars still believe in such invisible construct proposed by Adam Smith 240 years ago; this fact gives little trust to the economic profession. Studying the complex dynamics and reactions of multiple agents involved could enlighten science and society about unexpected responses and non-linearities in the human side of the Earth system. However speculative this might sound, recent results with side contributions from the author of the thesis show that the complex dynamics inherent in any society cannot be missed anymore in Integrated Assessment Models, because then relevant policy options are equally ignored (Hasselman et al., 2015). I believe complexity is the next way to go with the problems presented and partly solved here, but lack of data is a barrier that in most of the cases should be overcome first.

A. Appendix

A.1. Supplementary Materials from Chapter 3

Supplementary Section 1. Characterization of the Chinese provinces used as case studies.

Supplementary Table S1. Summary characteristics of the four provinces detailed in the study. Diverse sources (see Supplementary Section 2).

		Heilongjiang	**Shandong**	**Hebei**	**Xinjiang**
Location		north latitude: 43°25′-53°33′ east longitude: 121°11′-135°05′	north latitude: 34°25′-38°23′, east longitude: 112°43′-114°36′	north latitude: 36°05′-42°37′, east longitude: 113°11′-119°45′	north latitude: 32°22′-49°33′, east longitude: 73°21′-96°21′
Climate		Continental monsoon climate	Warm temperate continental monsoon climate	Continental monsoon climate	Temperate continental dry and half dry climate
Acreage (sq km)		473,000	157,000	187,700	1,664,900
Annual average temperatures (°C)		from-5 to 3	from -14 to 11	From 5 to 13	10 to13 in southern region, below 10 in northern region
Annual precipitation (mm)		400 to 700	550 to 950	400 to 800	165.6
Annual average water resources quantity (Gm^3)		77.58	33.5	23.69	88.28
	Groundwater	26.93	26.4	16.7	79.3
	Surface water	64.7	15.42	14.58	57.95
	Repeated amount	14.05	8.32	7.59	48.97
GDP (billion CNY)		1023.5	3941.62	2019.71	541.88
	GDP	130.2	358.83	256.28	107.86

		Heilongjiang	Shandong	Hebei	Xinjiang
	contributed by agriculture				
Sown area of crops (Mhm2)		12.16	10.82	8.72	4.76
	Sown area of food crop	11.45	7.08	6.28	2.03
Grain yield (Mt)		50.13	43.36	29.76	11.71
	Rice	18.44	1.06	0.54	0.59
	Maize	23.24	19.32	15.09	4.22
	Wheat	0.92	20.59	12.31	6.24
	Soybeans	5.85	0.41	0.34	0.28

Supplementary Table S2: Characteristics of the studied irrigation systems. Diverse sources (see Supplementary Section 2).

		Heilongjiang	**Shandong**	**Hebei**	**Xinjiang**
Investment for irrigation (billion CNY)		1.78	2.09	0.27	4.15
Effective irrigated area (Mhm2)		3.87	4.96	4.55	3.72
Irrigation rate		31.82%	45.84%	52.18%	78.15%
Water-saving irrigation area (Mhm2)		2.66	2.26	2.7	2.98
	Sprinkler	0.92	0.15	0.24	0.091
	Micro-irrigation	0.13	0.06	0.03	1.6
	Low pressure pipe	0.01	1.16	1.95	0.066
	Canal lining	0.12	0.57	0.28	
	Others	1.48	0.33	0.19	1.17
Irrigated area by groundwater (Mhm2)		1.82	2.37	3.79	0.76
Efficiency of irrigative water utilization		0.52	0.59	0.71	0.47
Total amount of water resources (Bm3)		85.35	30.91	13.89	111.31
Water use for irrigation (Bm3)		25.65	22.19	15.43	50.49
	Supplied by storage works	3.14	2.01	1.39	9.03
	Supplied by diversion facilities	5.15	11.75	1.83	33.08
	Supplied by pumping stations	4.1	2.09	0.29	0.41

		Heilongjiang	Shandong	Hebei	Xinjiang
	Supplied by mechanical and electrical wells (groundwater)	13.26	6.34	11.92	7.97

Supplementary Table S3. Targets related to irrigation and agriculture included in the 12th Five-Year provincial Development Plans. Source: Provincial level 12th Five-Year Development Plans.

		Heilongjiang	**Shandong**	**Hebei**	**Xinjiang**
Sown area of crops (Mhm2)		12	7.3	6.42	5.12
Grain yield (Mt)		55	50	n.a.	n.a.
Increase effective irrigation area (Mhm2)		1.89	n.a.	n.a.	n.a.
Increase water saving irrigation area (Mhm2)		2.27	0.39	n.a.	1
Efficiency of irrigative water utilization		0.55	0.63	0.74	0.53
Total investment for water resource development (billion CNY)		150	n.a.	n.a.	n.a.
Increased water saving irrigation area (Mhm2)		1.45	0.75	0.71	1.2
	sprinkler	1.12	0.03	0.019	0.073
	Micro-irrigation	0.089	0.03	0.019	0.96
	Low pressure pipe	0.0013	0.52	0.56	0.027
	Canal lining	0.24	0.16	0.11	0.15

Supplementary Section 2. Data and Methodology.

The four selected Chinese provinces (Hebei, Heilongjiang, Shandong and Xinjiang) differ substantially in key parameters like agricultural water use, sources of water, irrigated area, use of irrigation technology, area under irrigation technology, and conveyance and/or application type. These differences in key variables lead to very different values of fundamental aspects of the water-energy nexus such as energy emission rate, total emissions, irrigation efficiency, water savings and the costs of the related investments.

The definition of irrigation scheme efficiency and the applied conveyance/application standards are both calculated according to guidelines by the Food and Agriculture Organization of the United Nations (FAO). We further calculate the energy use (electricity and diesel) for pumping of groundwater and surface water and pressurising water for application to fields. The UK Department of Environment, Food and Rural Affairs and Department of Energy and Climate Change greenhouse gas (GHG) conversion factors are applied to calculate the emissions.

Data inputs and calculations are based on provincial and national level data:

- Statistical Yearbook of China’s Water Resources (Ministry of Water Resources, 2010).
- Groundwater Level Yearbook of China, GEO-Environmental Monitoring Institute (year 2006).
- Extensive survey data collected by the Center for Chinese Agricultural Policy (2004–2014).
- Additional data from the Ministry of Water Resources.

Supplementary Section 3. Irrigation technology and the water-energy nexus in China.

Supplementary Table S4. Review of water savings from water saving technologies in China.

Author / Province	Old system	New irrigation technology	Savings / Unit	
Yuan & Wang, 2008 Shaanxi	Flood irrigation 8400 m^3/ha	Semi-fixed sprinkler	3900	m^3/ha
		Giant sprinkler	3150	m^3/ha
		Drip	6150	m^3/ha
Lin, 2003 Xinjiang	Furrow irrigation 10500 m^3/ha	Drip	5376	m^3/ha
Guo et al, 2004 Xinjiang	Flood irrigation 6699m^3/ha	Drip	2940	m^3/ha
		Buried drip	3870	m^3/ha
		Soft pipeline	1500	m^3/ha
Dang et al, 2006 Liaoning	Flood irrigation 4431m^3/ha	Drip	3810	m^3/ha
		Micro irrigation	1620	m^3/ha
		Infiltrating	1890	m^3/ha
		Under-film	1785	m^3/ha
Chai, 2000 Gansu	Flood irrigation 2699 m^3/ha	Sprinkler	1161.5	m^3/ha
Liu L, 2006 Gansu	Canal 6877 m^3/ha	Low pressure pipe	2352	m^3/ha
Guan, 2004 Gansu	Canal	Low pressure pipe	2700	m^3/ha
Li et al, 2007 Shandong	Flood irrigation	Pipe	750-1500	m^3/ha

Supplementary Table S5. Review of energy savings of pressurised water saving technologies in China.

Author / Province	Old system	New irrigation technology	Savings / Unit	
Dang et al., 2006 Liaoning	Flood irrigation	Drip Subsurface drip Drip under plastic film mulching Micro sprinkler	1530 1035 405 1425	$kWh \cdot hm^{-2}$ $kWh \cdot hm^{-2}$ $kWh \cdot hm^{-2}$ $kWh \cdot hm^{-2}$
Han et al, 1995 Gansu province	Flood irrigation	Low pressure pipe	777	$kWh \cdot hm^{-2}$
Guan, 2004 Gansu province	Flood irrigation 1650 $kWh \cdot hm^{-2}$	Drip	525 - 675	$kWh \cdot hm^{-2}$
Guo, 1996 Hebei province	Flood irrigation	Sprinkler	611	$kWh \cdot hm^{-2}$
Yuan & Wang, 2008 Shaanxi Province	Flood irrigation 1780 $kWh \cdot hm^{-2}$	Semi-fixed sprinkler Drip	115 1300	$kWh \cdot hm^{-2}$ $kWh \cdot hm^{-2}$

Supplementary Table S6. Review of investment costs per area of irrigation technologies in China.

Technology	Province	Investment	Unit	resource
Canal lining	Shaanxi	3000	Yuan/ha	Chen, 2008
	Inner Mongolia	4225	Yuan/ha	Dong et al, 2000
	Gansu	3881-8525	Yuan/ha	Li & Liu, 2008
		5651	Yuan/ha	Ba et al, 2005
	Jiangsu	4050	Yuan/ha	Wang & Wu, 2002
	Liaoning	3000-4500	Yuan/ha	Hai, 2006
	Shandong	2349	Yuan/ha	Yan & Li, 2008
	Gansu	2827-7879	Yuan/ha	Li & Liu, 2008
Low pressure pipes	Jiangsu	3860	Yuan/ha	Wang & Wu, 2002
	Liaoning	4500-6000	Yuan/ha	Hai, 2006
	Gansu	3442	Yuan/ha	Guan, 2004
	Shandong	2775-2812	Yuan/ha	Yan & Li, 2008
	Beijing	3000-3750	Yuan/ha	Li &Fu, 1998
sprinkler	Heilongjiang	1500-3000	Yuan/ha	Li &Fu, 1998
		4500-6500	Yuan/ha	Li &Fu, 1998
	Gansu	7819-14074	Yuan/ha	Li & Liu, 2008
	Jiangsu	19500	Yuan/ha	Wang & Wu, 2002
	Liaoning	13945	Yuan/ha	Hai, 2006
	Shandong	12390	Yuan/ha	Yan & Li, 2008
	Shaanxi	10000-14250	Yuan/ha	Yi & Wang, 2008
	Beijing	3416	Yuan/ha	Buck et al, 2005

	Shandong	6350-7100	Yuan/ha	Wang, 2006
		7500-13500	Yuan/ha	Li &Fu, 1998
Micro-irrigation	Xinjiang	6279-6690	Yuan/ha	Zhang et al, 2004
	Inner Mongolia	8512.8	Yuan/ha	Dong et al, 2000
	Gansu	14483-27447	Yuan/ha	Li & Liu, 2008
	Jiangsu	16500	Yuan/ha	Wang & Wu, 2002
	Liaoning	14390-16140	Yuan/ha	Hai, 2006
	Shandong	20640-20700	Yuan/ha	Yan & Li, 2008
	Liaoning	11580-16680	Yuan/ha	Dang et al., 2006
	Beijing	13583	Yuan/ha	Buck et al, 2005

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Eidesstattliche Versicherung

Declaration on oath

Hiermit erkläre ich an Eides Statt, dass ich die vorliegende Dissertationsschrift selbst verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe.

I hereby declare, on oath, that I have written the present dissertation by my own and have not used other than the acknowledged resources and aids.

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