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Essays on Agricultural Water Pollution and Human Health

Na Lu

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Na Lu

Candidate

Economics

Department

This dissertation is approved, and it is acceptable in quality and form for publication:

Approved by the Dissertation Committee:

Kira M. Villa, Co-chairperson

Janie M. Chermak, Co-chairperson

Jingjing Wang

Tim Bersak

ESSAYS ON AGRICULTURAL WATER POLLUTION AND HUMAN HEALTH

by

NA LU

B.Ec., Finance, Hunan University, 2011
M.A., Economics, Clemson University, 2013
M.A., Economics, University of New Mexico, 2016

DISSERTATION

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DEDICATION

To my family,

for their patience and support.

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ABSTRACT

This dissertation mainly focuses on agricultural policies, water pollution and human health. Chapter.2 examines the causal impact of agricultural water pollution on individual health outcomes. The findings suggest that agricultural water pollution worsens health outcomes and these adverse health effects appear to be largely due to contaminated drinking water. Chapter.3 explores both of the intended wealth effect and unintended pollution effect on human health caused by China's agricultural support polices. I find that although the income effect dominates on reducing the overall sickness, the pollution effect is more substantial on the diarrhea incidence and adult BMI. Income affects slightly higher than pollution on adults' overall health, while pollution has higher impacts on children's overall health. Chapter.4 builds a dynamic optimization model internalizing the health cost of agricultural water pollution. My simulation results suggest that policymakers should manage fertilizer application rates based on the initial nitrate concentration levels.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter 1: Introduction

Agriculture, beginning more than 10,000 years ago, plays an important role in the human history and is the foundation of modern civilization. Although industrialization and urbanization attenuate the impact of agriculture to the economy, the technological progress also brings rapid development in agricultural sector in the 20th century: chemical fertilizers provide necessary nutrients to crops pesticides control the risks of crop diseases, agricultural machines reduce the massive human labor needed for farming. While all these technological advancements improve the crop productivity and produce more food supply to human beings, they also bring damage to the environment including water, air and soil. Among them, water pollution from agriculture is most severe and has direct impact to human health (Thayalakumaran etal.,2008; Infascelli et al. 2009; Savci 2012).

Compared to the large-scale industrial agriculture in developed countries, most developing countries still use traditional household farming mode because of the limited farming land with relative huge farming population and cheap labor. The diseconomies of scale in agricultural sector cause the production cost to be higher and agricultural productivity to be lower than developed countries. Thus, maintaining food security is still one of the primary policy goals in developing countries. With 20% of world's population while only 10% of world's arable land, China's food insecurity issue has a long history. In addition to the continuing erosion of arable land and rural population due to the massive economy growth in the urban area, the income inequality between rural and urban area is also enlarging which makes agricultural activities less attractive to rural residents and further impede the rural development. To maintain the food security as well as to develop rural economy, Chinese government set the agricultural development as its primary policy goals in the 21st century starting with a series of agricultural tax abolition and agricultural support policies. These policies, on one hand, intended to increase rural resident's enthusiasm for farming and improve the agricultural production. On the other hand, it also intended to boost rural economy, reduce the income gap between rural and urban area, and improve the rural households' living standards. On the surface, the policies' intended goals seemed to be reached as both the agricultural production and income has been improved (Gale, 2013; Wang and Shen, 2014). However, the externalities caused by these policies is not clear and it is necessary to evaluate the economic efficiency of these policies by further exploring those unintended external impacts. For example, for the view of economics, subsidizing the usage of fertilizers and pesticides not only cause more deadweight loss to the economy, but also distort the farmer's behaviors by overusing them to pursue higher net revenue. From the view of environmental economist, the excessive usage of fertilizers and pesticides lead to higher environmental damage which is a negative externality brought by these polices.

Agricultural pollution has been overlooked in the history compared to the industrial pollution, not only because non-point pollution is harder to be monitored and controlled, but also because it has some conflicts with government's food security goal. Recently, governments and the public start to be aware of the severe issues of agricultural pollution when the industrial wastes have been well regulated and more negative health impact of nutrient and other agricultural pollutants have been found. In fact, in some countries, water pollutants from agriculture has exceeded those from industry. For example, in China, 67% of phosphorus and 57% of nitrogen pollution in water coming from agriculture (Chen et al., 2017a). Most of these agricultural pollutants are in fact from the chemical fertilizers and pesticides that Chinese government encouraged farmers to use to increase the crop yields.

Even with the realization of the harmful agricultural pollution, it is painful to remove the pollutants as the pollutants are widely distributed, and some even accumulated in the deep groundwater. Nitrate, one of the nutrient pollutants, accumulated in the groundwater for more than 50 years, is known to be costly to remove. Because of the special features of agricultural pollution, it is wise and economic efficient for governments and the public to start preventing these pollutions before it getting worse.

Previous studies have connected different water pollutants with different negative health outcomes, such as diarrhea, cancer, and birth defects. However, the research on the combination of agriculture, water pollution and human health are rare in developing country context. Some studies only focused on the overall water pollution part (Ebenstein, 2012), while some utilized the usage of agricultural inputs as a proxy for agricultural pollution (Lai, 2017). My Chapter 2 provides a unique view to look at the impact of a composite of different water pollutants associated with the increasing agricultural activities and usage of fertilizers and pesticides on individual health in a developing country. To obtain exogenous variation in agricultural water pollution, we use a quasi-experimental design and exploit a series of agricultural support policies enacted in China. We further employ a difference-in-difference-in-differences (DDD) framework to examine the differential effect of agricultural water pollution on households with and without access to treated water. We find that the agricultural water pollution worsens health outcomes through increased incidence of sickness and diarrhea and lower body mass index (BMI) and height-for-age z-score. We further find these adverse health impacts appear to be primarily due to contaminated drinking water more than reduced food safety. Finally, our study indicates exposure to agricultural water pollution in utero and during early childhood results in lower height-for-age z-score.

Although we found negative pollution effect from agriculture in Chapter 2, it is unfair to ignore the facts that these agricultural support polices improve the farming household's income and living standards. This intended income improvement might also to invest more on the health, such as nutrient intakes, taking health supplements, and having preventive health services, which can have positive health effects as well. Therefore, to explore the effectiveness of such agricultural support policies, it's necessary to understand the magnitudes of both effects. Chapter 3 disentangles the pollution effect and income effect of agricultural support policies on human health based on a theoretical model of small farming household's profit maximization. I then employ a quasi-experimental design to explore both impacts on individual- and household- level health using longitudinal household data. Furthermore, I use the predicted health index from factor and principal component analysis which captures unobserved health conditions to replace the observed health indicators as a robustness check. I find that although the income effect dominates on reducing the sickness, the pollution effect is more substantial on the diarrhea incidence and adult BMI. Income affects slightly higher than pollution on adults' overall health, while pollution has higher impacts on children's overall health.

Given the negative health impacts caused by agriculture, policymakers should take these into account the potential environmental cost when making agricultural policies. Nitrate pollution, for example, is very costly to remove afterwards, one of the optimal ways to avoid high nitrate contamination in groundwater is to control fertilizer application rate during the crop production process. My Chapter 4 tries to find the optimal fertilizer application rate in agriculture by incorporating the health cost of nitrate pollution in groundwater. Chapter 4 examines the optimal fertilizer application rate in agriculture over time by incorporating the health cost from nitrate pollution in groundwater. Dynamic optimal control is used to establish the model and simulation is conducted in three scenarios of different initial levels of nitrate concentration in groundwater. The results indicate that optimal fertilizer application rates are increasing over time for all three cases, with the lowest initial fertilizer application rate and highest increasing speed in the case of highest nitrate concentration level. In addition, the nitrate concentration level is decreasing over time for cases of moderate or high initial nitrate concentration level, but increasing at a small rate for the cases of low initial nitrate concentration level. In the sensitivity analyses, I find the nitrate decay rate, population, and incidence rate all affect the optimal fertilizer application paths, while only decay rate actually affects the nitrate concentration levels.

Chapter 2: Agricultural Subsidies and Contaminated Spillovers: The Health Effects of Agricultural Water Pollution in China

2.1 Introduction

Water pollution from agriculture presents one of the most severe environmental hazards in China with 67% of phosphorus and 57% of nitrogen pollution in water coming from agriculture (Chen et al., 2017a). Yet with almost 20% of the world's population but only 10% of the world's arable land, in addition to urbanization continuing to erode its rural population, the Chinese government has addressed the country's food needs via policies that encourage the use of chemical fertilizers and pesticides in order to increase crop productivity. However, these policies come at a real cost to the environment and potentially human health as well. Currently, agricultural pollution exceeds industrial and is the country's largest source of water pollution. Fertilizer overuse and poor livestock waste management cause nitrate contamination and pesticides that leave toxic residues in water, which can subsequently harm human health (Thayalakumaran et al., 2008; Infascelli et al., 2009; Savci, 2012). Consequently, evidence demonstrates that rural areas in China face greater health risks. These risks appear to be especially salient for children (Chen et al., 2016; Su et al., 2013).

A challenge to estimating the health effects of agricultural water pollution is that there are likely systematic differences between agricultural and non-agricultural areas outside of water pollution levels that also affect health. Moreover, it can be difficult to capture variation in water pollution specifically due to agricultural activities. Consequently, much of the current evidence on the health impact of water pollution does not address causality nor does it specifically examine the impact of water pollution due to agricultural activities (Ebenstein, 2012; He and Perloff, 2016). Moreover, most current evidence on the relationship between water quality and health uses water access or water source as a proxy for exposure to water pollution but lacks actual water quality measurements (Mangyo, 2008; Zhang, 2012; Zhang and Xu, 2016). Lai (2017) improves on this evidence by giving a somewhat more refined measure of agricultural water pollution exposure by interacting household water source with province-level pesticide intensity. However, pesticide intensity does not capture the pollution caused by fertilizer application and animal waste. Furthermore, Lai (2017) focuses on the use of surface water for drinking as a proxy for pollution exposure. However, this may miss a significant portion of water pollution as 90% of China's shallow groundwater is also polluted (Zhang et al., 2015). Consequently, treated water access is a more appropriate control group to examine the impact of unsafe drinking water.

In this article, we explore the causal impact of agricultural water pollution on individual health by merging administrative data on observed county-level water pollution with a large longitudinal sample of Chinese households from the China Health and Nutrition Survey (CHNS). The CHNS covers 12 provinces for 9 waves during the years 1989-2011. Specifically, we look at the effect of agricultural water pollution on morbidity, diarrhea incidence, body mass index, and height-for-age z-score. We are also the first that we are aware of to explore the effect of in utero and infant exposure to agricultural water pollution on child health.

Our article contributes to this literature in three key ways. First, we provide a plausibly causal estimate of the health effect of water pollution due to agricultural activities. Second, we use observed data on water pollution and quality, rather than proxying for water quality with water source or agricultural input use. Finally, we examine the different channels through which the relationship between agricultural water pollution and health operates.

To obtain exogenous variation in agricultural water pollution, we use a quasi-experimental design and exploit a series of agricultural support policies enacted in China during the years 2004-2006.[1] These policies were nationwide and exogenous and led to dramatic increases in grain and livestock production (Wang and Shen, 2014; Lai, 2017; Gale, 2013). Our empirical approach identifies the effects of water pollution due to changes in agricultural activities as a result of these policies. This identification strategy relies on the assumption that pollution from other sources were not similarly affected during the policy period. We know of no other policies enacted in China during this time that would similarly affect water pollution from non-agricultural sources. Additionally, trends in health and water quality are improving throughout our study period, suggesting that the water degradation we identify off in the post-policy period is unlikely to be due economic activities outside of agriculture. In fact, our identification in this paper comes from a change in the composition of pollutants due to changes in agricultural activities rather than changes in levels overall water quality. Nonetheless, this violation is impossible to rule out, and we address this possibility through falsification tests and providing graphical evidence on trends in individual pollutants (i.e., one primarily associated with industrial pollution and on primarily associated with agricultural pollution). These checks can be found in the Results section.

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[1] Lai (2017) similarly used these policies to obtain exogenous variation in province level-pesticide use.

Finally, we examine the potential mechanisms through which agricultural water pollution affects human health. Individuals can be exposed to agricultural pollution through contaminated drinking water as well as through reduced food safety by using polluted water in the food production and processing. Households with access to water treated at a water treatment plant would have substantially less exposure to contaminated drinking water than those without that access. We therefore examine the differential impact of county-level agricultural water pollution on households with and without access to treated water to parse out the extent that contaminated drinking water drives the effects on human health.

We find that agricultural water pollution worsens health outcomes through increased incidence of sickness and diarrhea and reduced body mass index and height-for-age z-scores. Our results also indicate that in utero and infant exposure to agricultural water pollution can substantially reduce child-height-for-age z-scores. Finally, the adverse health effects of agricultural water pollution appear to be almost entirely driven by exposure to contaminated drinking water.

2.2 Agricultural Pollution and Health in China

China has undergone rapid agricultural development to meet its food needs resulting in high demand for agricultural inputs and a correspondingly high environmental cost. The economic cost of environmental damage from agriculture is 7-10% of total agricultural GDP (Norse and Ju, 2015). The three primary areas of environmental damage from agriculture are water pollution, soil pollution, and greenhouse gas emissions (Chen et al., 2017b). Among them, water pollution is the most severe and has direct negative health impacts.

Water pollutants from agriculture come from chemical fertilizers, pesticides, and livestock waste. Fertilizers added to soil increase essential nutrients for plant growth. However, these nutrients include nitrates and phosphates which can flood surface water and groundwater causing nutrient pollution. Moreover, the overuse of fertilizers can decrease soil fertility and reduce future plant yields. China uses nearly 550 kg of chemical fertilizers per hectare of land on average, which is much more than the average 100 kg used in the rest of the world. The excessive fertilizer use in China is mainly caused by input subsidies, low inputs prices, small-scale farming, risk-averse farms, and structural changes in farm labor (Smith and Siciliano, 2015). Furthermore, the growing number of concentrated animal feeding operations (CAFOs) substantially adds to nutrient pollution levels due to livestock waste (Norse and Ju, 2015). Nutrient pollution from phosphorus and nitrogen are a major source of water pollution that affects not only surface water quality through eutrophication, but also groundwater quality and soil acidification (Smith and Siciliano, 2015).

In addition to fertilizers, a substantial amount of agricultural water pollutions results from pesticide use. Pesticides are toxic substances used to kill weeds and insects that threaten high plant yields. However, pesticides contain toxic components and are not well-regulated in China. Consequently, excessive pesticide residues can be left on the agricultural products and cause considerable food safety concerns in China. These toxins can stay in the soil and continue to pollute crops as well as flow into the water systems to contaminate drinking water.

2.2.1 Health Impact Channels of Agricultural Pollution

Agricultural water pollution affects human health through two channels: contaminated drinking water and food safety issues. Approximately, 300 million rural residents in China lack access to safe drinking water (Smith and Siciliano, 2015). Drinking water pollutants include bacteria from unsanitary conditions and animal waste, nutrient pollution from nitrogen and phosphorus accumulation, and toxins and heavy metals from pesticides and wastewater discharge. Food safety issues occur when chemical residues left on food exceeds the safety standard as a result of polluted water and excessive pesticide application during the production or processing stage.

Bacteria in drinking water is the leading cause of waterborne diseases such as diarrhea and Hepatitis A (Lam et al., 2013). However, this health risk can be easily avoided by boiling water, a practice which has been widely adopted in China.

Nutrient pollution associated with algal blooms and nitrate contamination poses multiple hazards to human health, including cancer and blue baby syndrome (Thayalakumaran et al., 2008; Infascelli et al., 2009; Savci, 2012). Chen et al. (2016) find children tend to face more significant health risks from this kind of pollution than adults. Nutrient pollution accumulates in the groundwater and is more severe in rural areas with agricultural production (Su et al., 2013). Unlike bacterial pollution, nutrient pollution, especially nitrate, is very hard to remove from drinking water and is not reduced through boiling water.

Pesticides can also accumulate in the water system and damage ecosystems through soil microorganisms and harmful insect species (van der Werf, 1996). Toxic pesticides left in drinking water and on food pose a health risk for both adults and children (Gilden et al., 2010; Weiss et al., 2004). Lu et al. (2010) conclude that the frequent consumption of food with pesticide residue can cause developmental and neurological defects in young children. Lai (2017) also finds evidence that pesticides adversely impact health of the elderly. Since pesticides can affect health through drinking water and food, it is necessary to consider both channels when examining the relationship between agricultural water pollution and health.

2.2.2 China's Agricultural Support Policies

Quasi-experimental design, such as an event study, is a common way to control for the unobserved confounders and explore causal relationships (e.g., Lai (2017)). Agricultural support policies in China are utilized in this study to examine the causal impact of water pollution from agricultural activities on health outcomes. Between 2004 and 2006, China implemented a series of agricultural support policies including abolishing agricultural taxes and providing agricultural subsidies.

China has a long history of implementing agricultural taxes, dating back 2600 years. In the last century, the agricultural tax was one of the most important fiscal income sources for the Chinese government. In 1949, the agricultural tax accounted for 40% of government revenue. However, this share decreased to 2.6% by 2002 after the rapid economic growth following China's Economic Reform in 1978 (Wang and Shen, 2014). As the importance of agricultural tax revenue declined, income inequality between rural and urban households substantially increased. Consequently, during the mid-2000s, the Chinese government began to implement policies designed to improve agricultural productivity and income in rural areas such as abolishing the agricultural tax and providing agricultural input subsidies.

Agricultural taxes and related fees are significant in China. The largest of these is a proportional tax on perennial production called the agricultural tax. Perennial production is different from actual production in that it estimated based on land acreage and average historical production accounting for soil quality, crop types, regional climate, and landscapes. Perennial production per acre for a household, once determined, stays constant each year for an extended period no matter what the actual yields and profits are in a given year. The most recent taxable perennial production was calculated as the average production of the five years before 1999. Therefore, this agricultural tax effectively operates as a fixed land tax. Other taxes on agriculture include taxes on special products that were taxed based on sales income and the agricultural surtax that was taxed based on the agricultural tax. In addition to taxes related to agricultural activities, fees like the township and township education fees also added to the financial burden of rural households. Unlike urban households, rural households are not tax exempt. Although the income of 90% of rural households falls below the tax exemption line, they still have to pay taxes, making the agricultural tax system regressive.

Between 2000 and 2003, the Chinese government began experimenting with agricultural tax reform. It first eliminated all taxes and fees except the primary agricultural tax. Then in 2005, the government started to abolish the agricultural tax as well. By the beginning of 2006, all agricultural taxes were abolished in China (Gale, 2013). These tax abolition policies made almost no difference to those who live in coastal provinces as the taxes were relatively low compared to their annual income. However, to farmers who live in poor areas, these tax policies made significant improvements to their lives.

Additionally, during the period 2004-2006, the Chinese government implemented a series of agricultural support policies including direct payment to grain producers, rice and wheat price supports, and subsidies for agricultural inputs such as chemical fertilizers and pesticides. In 2007, subsidies were also provided for pork production. These policies resulted in substantial increases in grain production and the use of chemical fertilizers and pesticides (Gale, 2013). Figure 2.1 plots rice and livestock production during the survey period. We clearly see a sharp increase in production during the 2004-2006 period and after.

These policies were largely effective in promoting the Chinese government's objective of improving rural well-being. The post policy period experienced improvements in multiple measures of well-being including rural health and income. However, the post-2006 period also saw increased water pollution from agricultural activities which may mitigate some of the positive effects resulting from these policies. In this article, we use longitudinal water quality and household data and exploit these changes in agricultural policies from 2004 to 2006 to obtain exogenous variation in water pollution due to agricultural activities in a quasi-experimental framework.

2.3 Data

To explore the relationship between agricultural water pollution and health, we exploit unique longitudinal household data and merge it with two sources of longitudinal data on water quality. We are thus able to connect variation in observed levels of agricultural water pollution to individual-level health outcomes. This allows us to improve upon previous research which proxies for water pollution exposure with water source type (Mangyo, 2008; Zhang, 2012; Zhang and Xu, 2016) or with the interaction of water source type and regional-level pesticide use Lai (2017).

2.3.1 China Health and Nutrition Survey (CHNS)

Our household data come from the China Health and Nutrition Survey (CHNS). The CHNS is a rich longitudinal data set that follows approximately 4,400 households with around 19,000 individuals over nine survey waves in the years 1989, 1993, 1997, 2000, 2004, 2006, 2009, and 2011[2]. The surveys cover both rural and urban areas in nine Chinese provinces from 1989 to 2009 with three additional provinces included in the 2011 wave. Our primary water quality data began in 2004. Therefore, we focus on CHNS data collected in the 2004, 2006, 2009 and 2011 survey waves.

We only include the 8 provinces highlighted in Figure 2.4. We exclude the 3 newly added provinces in the 2011 survey in order to exploit the panel. We also exclude Guizhou province because there are no water quality monitoring sites there during the study period. The 8 provinces in our study are located in the Northeast, East, Middle and Southwest parts of China. These provinces are representative of China and are diverse in terms of geographic location, economic development, population, urban to rural ratio, agricultural intensity, and water availability.

The CHNS collects extensive information at the individual- and household-level, particularly with regards to health and nutrition. In every survey round, information on morbidity and anthropometric measurements were collected for all sample individuals making these data uniquely suited towards examining health in China. The specific health

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[2] The number of observed households and individuals vary across survey waves as the project also follows households formed out of sample households.

measures we examine are whether or not the respondent reported being sick or having diarrhea in the last four weeks, adult body mass index (BMI), child BMI-for-age z-scores (BMIZ), and child height-for-age z-scores (HAZ).

Table 2.1 reports the descriptive statistics from our study sample across age groups. 19% of individuals in our sample reported being sick in the last 4 weeks, while only 2% of them had diarrhea during that time. Individuals aged 55 years and above report higher rates of sickness and diarrhea than other age groups while children younger than 18 years have the lowest sickness and diarrhea rate. Children and elderly are usually considered to be more vulnerable with respect to their health. The low sickness rate among children may indicate the high value placed on children in China due to its one-child policy, evidenced by the fact that children received the highest rate of preventive health care use among all age groups reported in table 2.1.

There is a large sample of households engaged in agriculture in our data. Approximately 20% own at least one agricultural machine and 30% raise livestock. While 78% have tap water, only 55.4% of our sample have access to treated water. Health outcomes by survey wave are summarized in table 2.2. Sickness and diarrhea incidence is much higher in the post-2000 waves than in the 2000 wave, but both measures fluctuate across waves. The anthropometric measurements BMI, BMI z-scores and height-for-age z-scores exhibit an increasing trend over time, indicating that, on average, health is increasing over the sample period.

2.3.2 Water Quality Data

Our water quality data come from two sources. The primary data we use in our main analysis is measured from water monitoring sites throughout the country by China's

Ministry of Environmental Protection. Figure 2.4 illustrates the geographic distribution of these sites. At each of these sites, water pollutants were recorded weekly including surface water levels of chemical oxygen demand (COD), dissolved oxygen (DO), and ammonia nitrogen (NH3-N). These measurements were then used to generate a water quality grade index ranging from 1 to 6. This index increases with pollution level, thus a higher grade represents lower water quality. An index higher than 3 means the water cannot be used for drinking. From this point forward, we will refer to the water quality index as the water pollution index for clarity.

At the county level, we calculate the annual mean value of the water pollution index. We then assign each county in the sample provinces the annual mean water pollution index measured at the monitoring sites nearest to the county centroid. These measures were then linked with the CHNS data at the county-level. County is a level 3 administrative division in China, which is smaller than province and prefecture. Figure 2.4 overlays our sample county polygons in our study provinces with water monitoring sites. While it would be ideal to connect each county with its nearest upstream water monitoring site, our data do not allow this due to privacy restrictions. However, most of our sample counties are small and therefore the nearest monitoring site is likely a reasonable proxy for average water pollution exposure in the county.

In addition to the water quality data, we also recorded the province-level drinkable water percentage as reported in each province's water resource bulletin. This measure is the percent of the total river length in each province that meets the drinking water standard based on the water quality data collected by the Water Resource Bureau.[3]

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[3] Water is safe to drink if the water pollution index is 3 and lower.

We use this measure to check the robustness of our findings to an alternative measure of water quality.

Table 2.2 also reports the mean and standard deviation of our water quality measures in the sample provinces. Figure 2.2 similarly plots the water pollution index (Panel a) and drinkable water percentage (Panel b) over the survey period. The left plots of Panels a and b show water quality over time, while the right plots illustrate the same measures but de-trended by year. During the survey period, particularly since 2000/2004, average water quality appears to be improving over time. The water pollution index exhibits a decreasing trend over time. Drinkable water percentage fluctuates a bit more but is overall improving, especially after 2006. Nonetheless, the average water pollution index hovers around 3 for the duration of the sample period indicating that much of the water in our sample area is unsafe to drink. Moreover, when looking at the de-trended plots on the right-hand-side of Figure 2.2, we clearly see reductions in water quality during the period 2003/2004 to 2006, when the agricultural policies were being implemented. In particular, the water pollution index peaks in 2006 when the input subsidies were introduced.

2.4 Empirical Model

2.4.1 Health Impact from Agricultural Water Pollution

We are interested in the causal effect of agricultural water pollution on health. However, this presents a couple of empirical challenges. First, water pollution caused by agriculture cannot be observed directly as the monitors also capture water degradation from other sources, such as industrial pollution and residential discharge. Second, changes in agricultural activities may also systematically vary with other determinants of health such as income, food prices, and disease environment (related to temperature and precipitation). Employing a quasi-experimental design with individual fixed effects, we use changes in water quality that result from the full implementation of the agricultural support policies in 2006. These policies were nationwide, exogenous and targeted agricultural activities. Therefore, we assume that changes in water quality observed around 2006 and after can be associated with exogenous changes in agricultural activities. This assumption, of course, would be violated if other policies and/or conditions in China simultaneously caused increased water pollution from non-agricultural sources. While we cannot test for this directly, we address this concern in the Results section. We thus use the year 2006 (when the input subsidies were implemented and agricultural taxes were fully abolished) in a quasi-experimental, event study approach as follows:

$$\begin{aligned} Health_{it} = \beta_0^1 + \beta_1^1 Post2006_{it} \times Water_{it} + \beta_2^2 Water_{it} \\ + \beta_3^1 Post2006_{it} + \beta_4^1 X_{it} + \lambda_t + \mu_i + \varepsilon_{it} \end{aligned} \tag{1}$$

Equation (1) models the health outcome of individual i at survey wave t. The health outcomes we examine, $\text{Health}_{\text{it}}$, include: a dummy variable indicating whether the individual was sick in the last 4 weeks, had diarrhea in the last 4 weeks, adult BMI (for individuals aged 18 and above), child BMI-for-age z-score (for individuals aged below 18), and child height-for-age z-score (for individuals aged below 18). County-level water pollution exposure for individual i at survey wave t is captured by Water_{it}. We use the annual average water pollution index, calculated as the mean value at the nearest monitoring site to individual i at year t, to measure water quality - the higher the value the worse the water quality. As an alternative measure, we also use drinkable water percentage, measured as the percent of the surface water that is drinkable in province p at year t as a proxy for water quality - the higher the value the better the water quality. However, this latter measure is less preferable as it is only available at the province level, which will miss local spatial variation. X_{it} includes household and individual controls, such as log household income, individual daily calorie intake, unhealthy diet (=1 if diet is not healthy[4]), whether the individual uses preventive health care, household sanitation conditions, age, gender, and ethnic group (=1 if belong to ethnic minorities). λ_t is a vector of year fixed effects and μ_i is a vector of individual fixed effects.

Equation (1) allows us to compare the different impact of water quality on health before and after the agricultural subsidy policy starting from 2006. The differential impact may be due to changes in the composition of pollutants caused by changes in agricultural activities rather than changes in the level of water pollution as a whole. $Post2006_{it}$ is a policy indicator that equal to 1 if the survey was conducted after 2006, thus β_3^1 captures the average health difference in the sample in the post- versus pre-policy period. β_1^1 from Equation (1) captures the average difference in the effect of water pollution on health in the post-policy period. Since we account for trends in health and pollution by controlling for year fixed effects, we interpret the differential variation in water pollution in the post-period as primarily coming from agriculture, and thus interpret β_1^1 as the the effect of agricultural water pollution on health.

We also examine the effect of agricultural water pollution due to these policies on early childhood health proxied by child HAZ and BMIZ for children aged 6 years old and

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[4] According to the US recommendations on dietary reference intake for total energy (Institute of Medicine, 2005), we define unhealthy diet as having at least one of three macronutrients out of the US dietary reference intake range.

under. Early childhood is marked by rapid physical growth. Therefore, health inputs (such as pollution) often have a larger effect on child growth during this childhood period than in others. Consequently, we surmised that there might be a difference in the HAZ of children who spent their early childhood before and after the policy. We replace the $Post2006_{it}$ with $Bornafter2006_{it}$ which equal to 1 if the child i was born after 2006. The model is specified as:

$$\begin{aligned} Health_{it} = \beta_0^2 + \beta_1^2 Bornafter2006_{it} \times Water_{it} + \beta_2^2 Water_{it} \\ + \beta_3^2 Bornafter2006_{it} + \beta_4^2 X_{it} + \lambda_t + \mu_i + \varepsilon_{it} \end{aligned} \tag{2}$$

In Equation (2), we use community instead of individual fixed effects as each individual were only observed once at this age range.

By interacting with water quality with the 2006 agricultural supporting policies, this quasi-experimental framework teases out the pollution effect due to agricultural activities from the non-water-pollution effects of these activities (e.g., changes in agricultural income). However, the mechanisms through which water pollution adversely affects human health not only include drinking polluted water, but also intaking agricultural products that are produced or processed using polluted water. β_1^1 in Equation 1 and β_1^2 in Equation (2) capture the total effect of both mechanisms. In the following section, we attempt to disentangle these two effects.

2.4.2 Health Effects through Contaminated Drinking Water

Residents who drink untreated contaminated water experience greater drinking water exposure to polluted water than those who have access to treated water. Other factors relating to food safety and agricultural air pollution are also associated with agricultural pollution and can have a negative impact on health (Lai, 2017). These sources should similarly affect individuals with or without access to treated drinking water. Therefore, to disentangle these two channels, we allow for heterogeneity in the water pollution effect modeled in Equations (1) and (2) across individuals with and without access to treated water. We include a triple interaction between water treatment status, water quality, and the post-2006 indicator as follows:

$$\begin{aligned} Health_{it} = \beta_0^3 &+ \beta_1^3 Post2006_{it} \times Water_{it} \times Untreatedwater_{it} \\ &+ \beta_2^3 Water_{it} \times Untreatedwater_{it} \\ &+ \beta_3^3 Post2006_{it} \times Untreatedwater_{it} \\ &+ \beta_4^3 Water_{it} \times Post2006_{it} \\ &+ \beta_5^4 Untreatedwater_{it} + \beta_6^3 Post2006_{it} \\ &+ \beta_7^3 Water_{it} + \beta_8^3 X_{it} + \lambda_t + \mu_i + \varepsilon_{it} \end{aligned} \tag{3}$$

$Untreatedwater_{it}$ equals 1 if the household individual i lives in at year t does not have access to water treated at water plants. While access to treated versus untreated water is endogenous to health outcomes, we are not specifically interested in the health effects of access to treated water. Rather, we are interested in the heterogeneous effects of agricultural water pollution across these two groups in order to disentangle the health impacts of water pollution due to contaminated drinking water from that of other factors such as food safety (Lai, 2017; Kellogg and Wolff, 2008).

As in Equation (2), we also replace the $Post2006_{it}$ in Equation (3) with $Bornafter2006_{it}$ to examine the difference in the effect of water pollution on the treated and untreated water groups for children born before and after the policy in Equation (4).

$$\begin{aligned}
Health_{it} = \beta_0^4 & \\
& + \beta_1^4 Water_{it} \times Untreatedwater_{it} \\
& \times Bornafter2006_{it} \\
& + \beta_2^4 Water_{it} \times Untreatedwater_{it} \\
& + \beta_3^4 Untreatedwater_{it} \times Bornafter2006_{it} \\
& + \beta_4^4 Water_{it} \times \ Bornafter2006_{it} \\
& + \beta_5^4 Untreatedwater_{it} + \beta_6^4 \ Bornafter2006_{it} \\
& + \beta_7^4 Water_{it} + \beta_8^4 X_{it} + \lambda_t + \mu_i + \varepsilon_{it}
\end{aligned} \tag{4}$$

β_1^3 in Equation (3) and β_1^4 in Equation (4) estimates the difference in the effect of post-2006 water pollution on individuals with untreated water and thus at higher risk of contaminated drinking water. Therefore, these coefficient should reflect the additional effect of agricultural pollution in drinking water, while β_4^3 and β_4^4 in Equations (3) and (4), respectively, should capture the effect of agricultural water pollution through non-drinking water channels.

2.5 Results

Interpreting β_1^1 as the effect of agricultural water pollution would be invalid if other policies and/or conditions in China simultaneously caused increased water pollution from non-agricultural sources. While we cannot test for this circumstance directly, we feel safe in assuming the marginal increases in post-2006 water pollution is due to agricultural activities for three reasons. First, to our knowledge, China enacted no other policies that would similarly increase water pollution from non-agricultural sources at the same time as these policies. Second, as seen in Figure 2.2, general water quality has been steadily improving in China over time, including during the time of these agricultural policies. So, the water degradation we identify off of post-2006 is counter to these trends and is unlikely to be due to non-agricultural economic activities. However, to further dispel this concern, we conduct a placebo test by replicating all of our results below with a falsely imputed policy year of 2000 (well before the agricultural support policies were implemented). Unfortunately, we cannot use the water pollution index for this test, as this measure is not available in 2000 (the first pre-2004 CHNS survey wave available). We, therefore, can only use province-level drinkable water percentage as the water quality measure. These results are reported in appendix Table A.9 and Table A.10. Overall, we do not find significant effects around the placebo policy year. Only one estimated placebo effect, using the triple interaction model in Equation (3) (Table A.10), is statistically significant but has the opposite sign of what we would expect. This, therefore, may due to spurious correlation.

Finally, Figure 2.3 plots average levels of the individual pollutants, NH3-N and COD, over time measured in our data. While each of these pollutants can come from industrial, agricultural, or residential sources, NH3-N is *primarily* sourced from agricultural activities and COD is *primarily* sourced from industrial activities. For example, Zuo et al. (2013) found that industrial pollution contributed to 44% of COD in the Yangtze River in China while agricultural sources only contributed to 16%. On the other hand, agricultural sources contributed to almost 60% of NH3-N pollution in the river while industrial pollution only contributed 5%. In Figure 2.3, we clearly see NH3-N uptick after 2006, while COD steadily declines over the entire sample period. We, therefore, feel that the negative health effects of water pollution we identify are largely due to agricultural activities.

2.5.1 Health Effects of Agricultural Water Pollution

Table 2.3 reports the estimates from Equation (1) on the effect of water quality on a variety of health outcomes. Columns (1) -(2) of Table 2.3 report the effect of agricultural water pollution on the incidence of sickness and diarrhea in people of all ages in our sample. Column (3) of Table 2.3 reports the estimated effect on BMI for adults (aged 18 and older). Columns (4) -(5) of Table 2.3 focus on children and report the estimated effects on BMI-for-age z-score and height-for-age z-score for children under the age of 18 in our sample. Although not reported in Table 2.3, all estimates include all controls and individual and year fixed effects. The individual fixed effects control for time-invariant characteristics that are correlated with water quality and health, such as genetic diseases, birth defects, individual behaviors, and household environment as well as other pollution sources, sanitation conditions, and health infrastructure.

The coefficient on the variable $Post2006_{it}$, β_3^1, captures the conditional, de-trended average difference in health before and after 2006. The coefficient on the water pollution index alone, β_2^1, captures the association between levels of general water pollution and health, conditional on control variables and individual and time fixed effects. The primary coefficient of interest is that on the interaction between $Post2006_{it}$ and the water pollution index. This is the additional effect of water pollution on health outcomes due to pollution changes that occurred after the agricultural support policies were implemented. We, therefore, assume these changes are due to exogenous changes in agricultural activities and interpret this as the health effect of agricultural water pollution. For example, in Column (2), we see that, on average, individuals are healthier over time as the post-2006 period is associated with a 7.16% decrease in diarrhea incidence.

However, agricultural water pollution resulting from the implementation of the 2004-2006 agricultural support policies exerts a significant and positive impact on the diarrhea incidence, a common waterborne disease. Specifically, a one-unit increase in the water pollution index results in a 0.316% increase in diarrhea incidence. The average effect of agricultural water pollution on other measured health outcomes is not statistically significant.

Instead of examining the average current health effects of changes in water pollution due to the agricultural policies, in Table 2.4 we examine the effects of in utero and infant exposure to agricultural water pollution resulting from the policies by replacing the 2006 policy year indicator with an indicator for whether a child's birth year is after 2006. Children born in 2006 and before were not exposed to the water pollution resulting from these policies during the in utero and infant stages while those born after 2006 were. We never observe the subsample of children born after 2006 when they are older than five or six years old. We therefore limit the sample for this analysis to children six years old and younger. In this way we are comparing the effects of in utero exposure to water pollution for similar age cohorts. In this analysis, we are unable to control for individual fixed effects since we only observe each child once during this age range. We therefore, control for community fixed effects in addition to year fixed effects in addition to our other controls. Interestingly, the effect of agricultural water pollution resulting from the policies does not exert a statistically significant effect on either BMI z-score or HAZ for these two cohorts.

2.5.2 The Contaminated Drinking Water Channel

The results reported in Table 2.3 and Table 2.4 capture the total effect of agricultural water pollution due to both contaminated drinking water as well as other channels such as reduced food safety. These results also represent a weighted average of the effect on households with access to treated water and those without. The former group is much less likely to be exposed to contaminated drinking water than the latter. So if water pollution primarily acts through, say, contaminated drinking water, then it is possible that individuals in a pollution exposed county but with access to treated water may wash out the potential effects on those with greater exposure in their drinking water. This may be a reason most of the results reported in Table 2.3 and Table 2.4 are statistically insignificant.

In Table 2.5 and Table 2.6, we estimate Equations (3) and (4), respectively, which compare the effect of agricultural water pollution on households with and without access to treated water. In this case, our primary coefficient of interest is that on the triple interaction of water pollution, an indicator for the post-2006 period, and an indicator for whether a household's water is untreated at a water plant. We interpret this estimate as the effect of agricultural water pollution through the channel of contaminated drinking water. All results are estimated with all controls and individual and year fixed effects.

According to the results reported in Table 2.5, for those without access to treated drinking water, agricultural water pollution significantly increases the likelihood of sickness and decreases adult BMI and child HAZ. Increasing agricultural water pollution by one unit results in a 1.45% increase in the likelihood of being sick in the last 4 weeks, a 0.10 reduction in adult BMI and reduction in child HAZ by 0.10 standard deviations.

The estimated effects on diarrhea incidence and child BMI z-scores are not statistically significant. One explanation for the insignificance of the effect on diarrhea may be that households without access to treated water may undertake some avoidance behaviors such as boiling drinking water to remove the bacteria, which is a major cause of diarrhea. However, while boiling water may protect against diarrhea, it would not remove other toxic components such as nitrates and heavy metals that can worsen health in other ways. Regardless, it is also worth noting that although it is insignificant, the point estimate on the triple interaction for diarrhea reported in Table 2.5 is almost identical to the agricultural water pollution effect reported in Table 2.3. Additionally, while we cannot interpret these estimates as causal effects, the significant coefficients estimated for interaction indicate the drinking water sources cause significant difference in the impact of water pollution on health after 2006.

In Table 2.6, we report estimates from Equation (4) to compare the health impact of infant and in utero exposure to agricultural water pollution for children in households with and without access to treated drinking water. Like with Equation (2), we do this by replacing the indicator for the post-2006 period with one indicating if a child was born after 2006 and thus exposed to agricultural water pollution during the in utero/infancy period resulting from the policy changes.[5] According to Table 2.6, agricultural water pollution in drinking water during the uterine and infant periods imposes an adverse effect on children's HAZ for our subsample of children 6 years old and younger. For

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[5] Even though the children born after 2006 will have also been exposed to this agricultural water pollution throughout their entire first 6 years of life, we do not interpret this effect as the effect of early childhood exposure. This is because while some of the children born before 2006 would have never been exposed to these policies, some of them would have had some exposure. For example, a child born in 2003 would not have been exposed to the full thrust of policies during the uterine/infant period, but she/he would have been exposed during ages 3 to 6.

children in households with untreated water, increased agricultural pollution in drinking water decreases child HAZ by 0.30 standard deviations. We see no significant effect on BMIZ, which makes sense given that weight is more sensitive to current exposure while HAZ would capture the cumulative effects of past exposure (e.g., during infancy). Overall, the results reported in Table 2.5 and Table 2.6 suggest that agricultural water pollution adversely affects health, primarily through contaminated drinking water.

Finally, while we cannot interpret these estimates as causal effects, it is worth noting that the significant coefficients on the interaction between $Post2006_{it}$ / $Bornafter2006_{it}$ and water pollution reported in Table 2.5 and Table 2.6 (for sickness and HAZ, respectively) suggest that increased agricultural pollution outside the drinking water channel improves health. While this may seem counter-intuitive, remember that our identifying variation on post-2006 water pollution is based on changes in agricultural activities. Thus if the adverse effects of water pollution due to these activities are largely captured by the drinking water channel in the triple interaction, then this coefficient may be capturing the positive health effects of increased agricultural activities in the post-policy period such as higher farm income.

2.5.3 Measurement Error

We are concerned about potential measurement error in the water quality data collected from nearest monitoring sites. Therefore, as a robustness check, we conduct the above analysis using water quality averaged at the province level. Specifically, we use the province-level water pollution index calculated as the mean value of all the monitoring sites in a province in a given year. Results from estimating Equations (1) – (4) using province-level water pollution are reported in Tables A.1 - A.4, respectively. While there are some minor differences in magnitudes and significance, these results are largely similar to our main results reported in Tables 2.3 - 2.6.

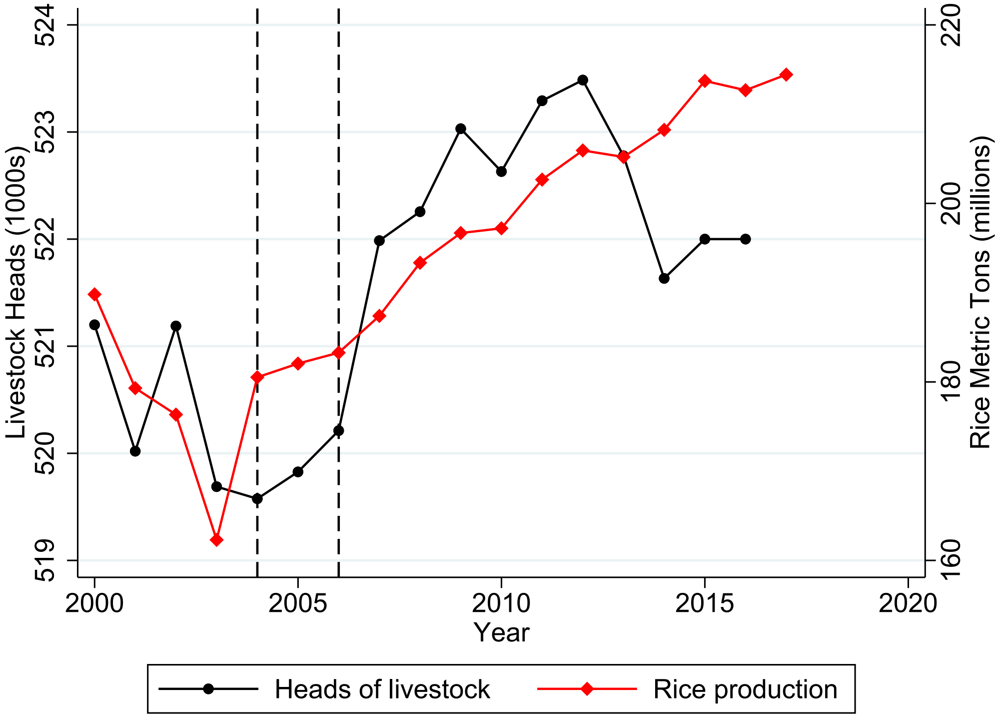
We also check the robustness of our results to using an alternative source and measure of water quality. We conduct the above analysis using province-level percentage of drinkable water rather than the water pollution index. To do so, we recorded the drinkable water percentage from province annual water resource bulletins. Percentage of drinkable water is measured as the percentage of the river length that meets the minimum standard for drinking water. A higher percentage of drinkable water reflects better water quality at the province level. The results estimating Equations (1) – (4) are reported in Tables A.5 - A.8 respectively. Overall these results support the results using the water pollution index. However, none of the results reported in Table A.7 are statistically significant.

2.6 Conclusion and Discussion

Non-point agricultural pollution is hard to monitor and control. Our research aims to explore the health impact of agricultural water pollution and the different channels through which this influence occurs. Our findings indicate that agricultural water pollution increases morbidity (i.e., sickness and diarrhea) and decreases BMI. We also find that exposure to agricultural water pollution in utero and in infancy reduces child height-for-age z-scores. Our findings suggest that contaminated drinking water appears to be the primary channel through which these effects operate.

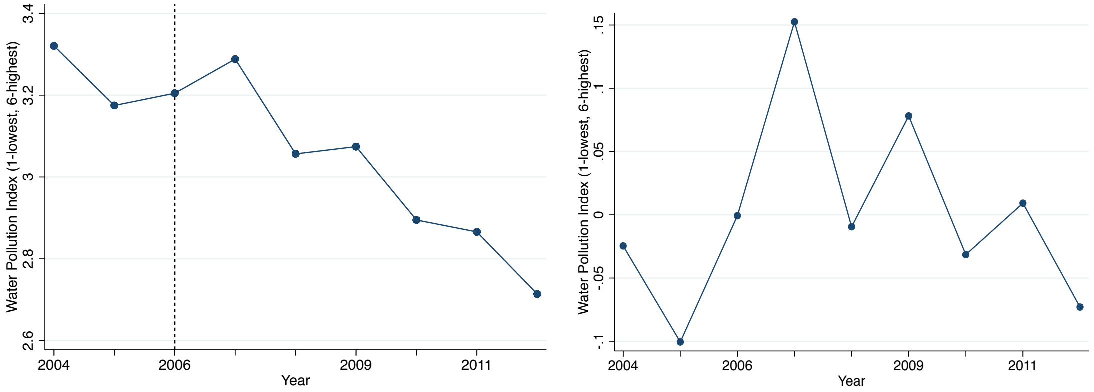
Food security and economic development are always a priority in developing countries. However, the health cost from environmental damage should not be overlooked in the policy design as we seek to improve rural livelihoods. This research will be of interest to policymakers in China concerned with agricultural water pollution. Recently, the Chinese government has demonstrated increasing interest in improving the health and quality of life of people in rural areas. Rural development policies include agricultural taxes abolition to narrow the income inequality, agricultural subsidies to support and protect agriculture, rural infrastructure improvement, the introduction of rural cooperative medical care system and pension insurance, the expansion of free compulsory education. All these policies aimed at improving rural households' income, living standards, health, social security, and education. However, some of these positive effects may be mitigated by the policies' effects on agricultural water pollution. Specifically, agricultural water pollution increases even as other sources of water pollution are decreasing. Given the negative health impact found in this research and other papers, it is important to implement policies that targeting at rural development as well as reducing agricultural pollution. In fact, some regional governments have implemented programs and regulations targeted at agricultural pollution control by subsidizing agricultural inputs based on necessary needs, providing free agricultural education and direction for farmers to use agricultural inputs appropriately, and giving incentives for green agricultural products. These environmental friendly policies can reduce the negative impacts from agriculture without sacrificing the benefits brought by the policies, and we suggest them to be expanded on a national scale.

Figure 2.1: Livestock and Rice Production in China

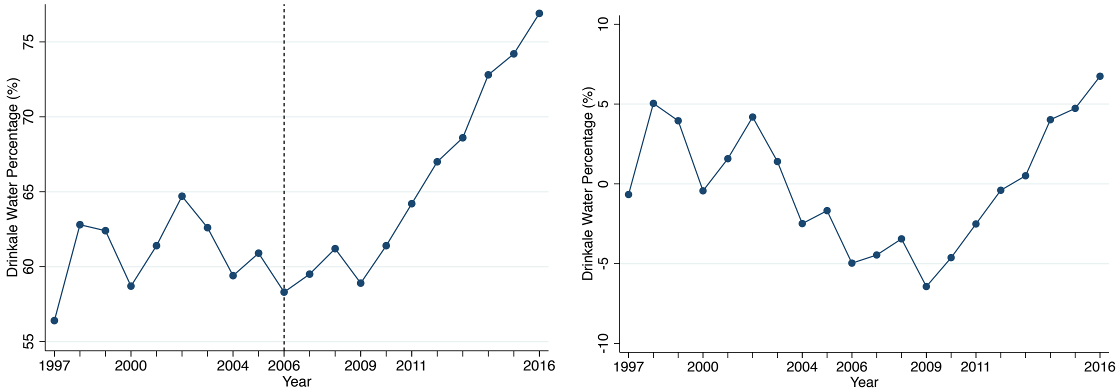


Source: Food and Agricultural Organization (FAO): http://www.fao.org/faostat/en/#data

Figure 2.2: Water Quality Over Time



(a) Water Pollution Index (Higher Means Worse), Right Panel is De-trended over Time



(b) Drinkable Water Percentage, Right Panel is De-trended over Time

Note: Water quality is affected by multiple factors and is clearly improving over time. The de-trended plots allow us to explore the fluctuations of water quality that were possibly caused by agricultural policies. The vertical axis in these two graphs is the annual average water quality data over the 8 study provinces.

Figure 2.3: Average Levels of NH3-N and COD

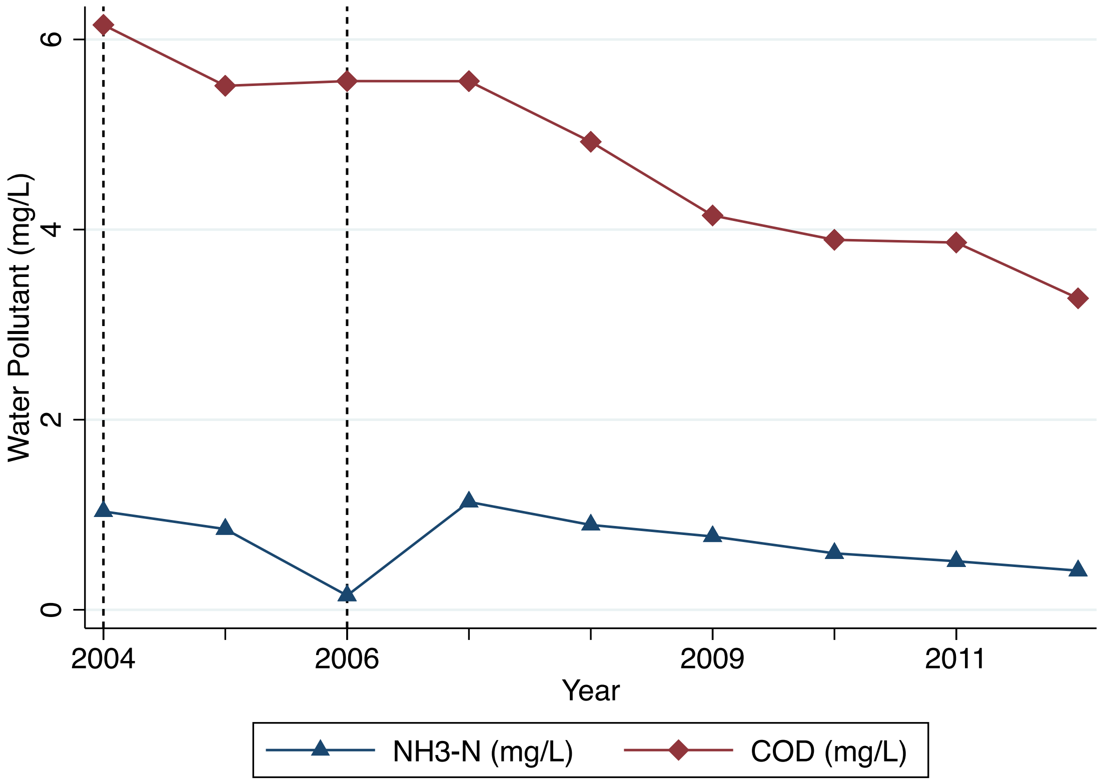
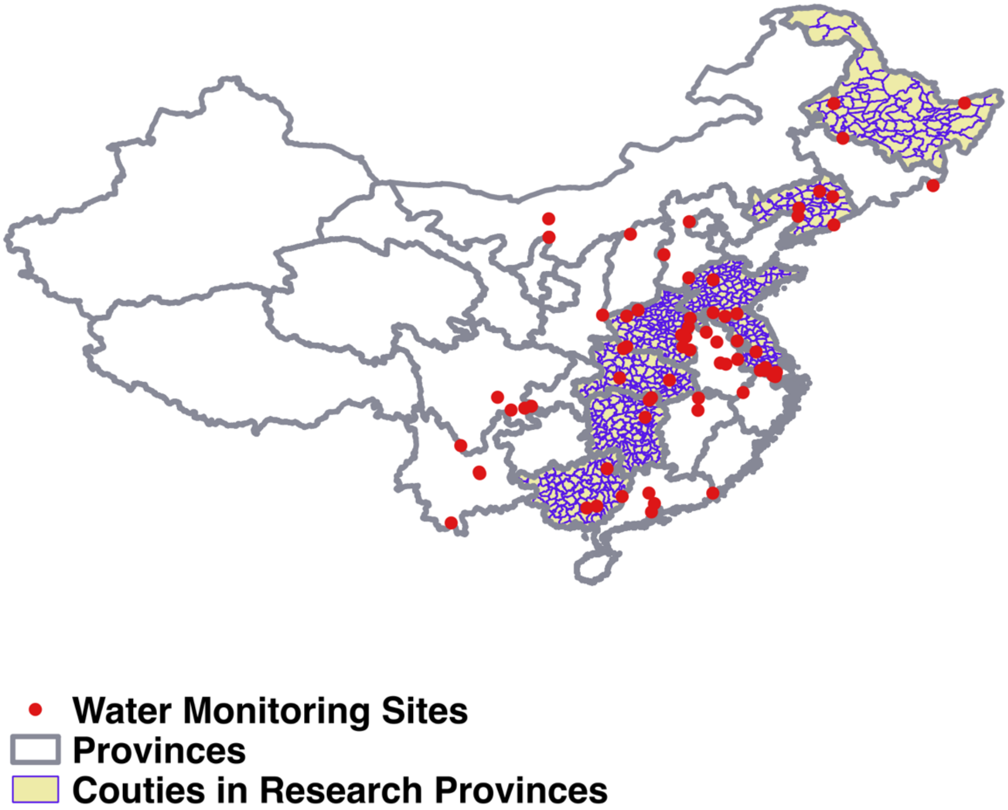


Figure 2.4: Study Provinces and Water Monitoring Sites



Note: The map shows the locations of the 8 provinces that are included in this study and all the monitoring sites with water quality grade data recorded on the Ministry of Environmental Protection website during 2004-2011. Although CHNS contains 9 provinces in the 2004-2009 survey and 12 provinces in the 2011 survey, we exclude Guizhou Province because the lack of monitoring sites in that province and the three newly added provinces in the 2011 wave for analysis consistency.

Table 2.1: Descriptive Statistics

	All Age	Age below 18	Age 18 to 55	Age 55 and above
Health Status				
Sick in recent 4 weeks	0.190	0.119	0.140	0.322
	(0.393)	(0.324)	(0.347)	(0.467)
Have diarrhea in recent 4 weeks	0.0206	0.0159	0.0179	0.0281
	(0.142)	(0.125)	(0.133)	(0.165)
Farming Status				
Maximum individual farming months in the household	2.318	2.838	2.398	1.876
	(3.829)	(4.066)	(3.840)	(3.618)
Household own at least one agricultural machine	0.197	0.226	0.217	0.146
	(0.398)	(0.418)	(0.412)	(0.353)
Household’s farming land area	2.999	3.439	3.406	2.004
	(9.460)	(10.34)	(10.20)	(7.184)
Individual				
Male	0.489	0.534	0.482	0.477
	(0.500)	(0.499)	(0.500)	(0.499)
Age	41.98	9.637	39.32	65.31
	(20.35)	(4.456)	(9.774)	(8.084)
Prenventive health care	0.0429	0.0600	0.0324	0.0525
	(0.203)	(0.237)	(0.177)	(0.223)
Calorie intake	2045.7	1622.5	2204.6	1997.4
	(967.0)	(662.6)	(917.2)	(1113.2)
Unhealthy diet	0.662	0.710	0.649	0.658
	(0.473)	(0.454)	(0.477)	(0.474)
Household				
Raise livestock	0.296	0.365	0.292	0.263
	(0.456)	(0.481)	(0.455)	(0.440)
Treated water by water plant	0.554	0.498	0.542	0.608
	(0.497)	(0.500)	(0.498)	(0.488)
Have tap water	0.780	0.738	0.776	0.812
	(0.414)	(0.440)	(0.417)	(0.391)
Have flush toilets	0.503	0.446	0.503	0.534
	(0.500)	(0.497)	(0.500)	(0.499)
Excreta around the house	0.249	0.302	0.237	0.240
	(0.432)	(0.459)	(0.425)	(0.427)
Log household income	9.739	9.636	9.820	9.647
	(1.165)	(1.131)	(1.121)	(1.250)
Observations	58724	9873	31562	17289

Table 2.2: Descriptive Statistics: Water Quality by Survey Year

	2000	2004	2006	2009	2011	Total
Water Quality						
Water pollution index	.	3.270	3.148	2.981	2.808	3.044
	(.)	(1.211)	(1.214)	(1.010)	(0.812)	(1.084)
Drinkable water percentage	0.560	0.521	0.490	0.503	0.575	0.528
	(0.243)	(0.261)	(0.199)	(0.205)	(0.206)	(0.224)
Health Status						
Sick in recent 4 weeks	0.0645	0.167	0.126	0.137	0.156	0.131
	(0.246)	(0.373)	(0.332)	(0.344)	(0.363)	(0.338)
Have diarrhea in recent 4 weeks	0.00807	0.0259	0.0178	0.0106	0.0112	0.0144
	(0.0895)	(0.159)	(0.132)	(0.102)	(0.105)	(0.119)
Disabled according to IADL score (age 55 and above)	0.292	0.206	0.204	.	.	0.228
	(0.455)	(0.405)	(0.403)	(.)	(.)	(0.420)
Height-for-age z-scores(age 17 and under)	-0.810	-0.660	-0.602	-0.336	-0.117	-0.518
	(1.204)	(1.278)	(1.327)	(1.329)	(1.422)	(1.335)
BMI z-scores(age 17 and under)	-0.286	-0.133	-0.135	-0.143	0.119	-0.119
	(1.220)	(1.255)	(1.359)	(1.371)	(1.445)	(1.333)
BMI(age 18 and above)	22.80	23.06	23.16	23.33	23.87	23.29
	(3.260)	(3.375)	(3.357)	(3.478)	(3.996)	(3.558)
Observations	93957					

Table 2.3: Estimated Effect of Agricultural Water Pollution on Health Post 2006 - Using County-Level Water Pollution Index

	All age		Age 18 and above	Age below 18	
	(1) Sick	(2) Diarrhea	(3) BMI	(4) BMI Z-Score	(5) Height-For-Age Z-Score
Post 2006 X Water Pollution Index	-0.000833 (0.00460)	0.00316* (0.00182)	-0.0266 (0.0223)	-0.0246 (0.0410)	-0.0357 (0.0362)
Water Pollution Level	0.0305*** (0.00969)	0.00641 (0.00396)	-0.173*** (0.0514)	-0.148 (0.0911)	-0.0158 (0.0684)
Post 2006	0.131 (0.0906)	-0.0716** (0.0352)	0.608 (0.527)	-0.374 (0.555)	0.230 (0.408)
Individual Fixed Effects	Yes	Yes	Yes	Yes	Yes
Observations	38525	38489	31011	4919	4995

Note: Significant levels are indicated by *** $p<0.01$, ** $p<0.05$, * $p<0.1$. All results include the following controls: gender, minority group, age, age squared, preventive medical service, calorie intake, unhealthy diet, livestock raising, tap water access, flush toilet, excreta near house, log income

Table 2.4: Estimated Effect of Early Childhood Agricultural Water Pollution Exposure on Health - Using County-Level Water Pollution Index

	Age 6 and below	
	(1) BMI Z-Score	(2) Height-For-Age Z-Score
Born after 2006 X Water Pollution Index	-0.0817	0.0920
	(0.102)	(0.0895)
Born after 2006	0.251	-0.0747
	(0.330)	(0.290)
Water Pollution Index	-0.140	-0.0315
	(0.178)	(0.155)
Year Fixed Effects	Yes	Yes
Community Fixed Effects	Yes	Yes
Observations	1404	1445

Note: Significant levels are indicated by *** p<0.01, ** p<0.05, * p<0.1. All results include the following controls: gender, minority group, age, age squared, preventive medical service, calorie intake, unhealthy diet, livestock raising, tap water access, flush toilet, excreta near house, log income

Table 2.5: Estimated Effect of Agricultural Water Pollution on Health Based on Access to Treated Water - Using County-Level Water Pollution Index

	All age		Age 18 and above	Age below 18	
	(1) Sick	(2) Diarrhea	(3) BMI	(4) BMI Z-Score	(5) Height-For-Age Z-Score
Untreated water X Post 2006 X Water Pollution Index	0.0145*	0.00317	-0.0971**	0.0431	-0.0991*
	(0.00860)	(0.00336)	(0.0428)	(0.0754)	(0.0571)
Post 2006 X Water Pollution Index	-0.0107*	0.000944	0.0278	-0.0283	0.0122
	(0.00592)	(0.00229)	(0.0295)	(0.0506)	(0.0462)
Untreated water X Water Pollution Index	-0.00753	-0.00106	0.0144	-0.0464	-0.00116
	(0.00652)	(0.00293)	(0.0314)	(0.0594)	(0.0437)
Untreated Water X Post 2006	-0.0466*	-0.00621	0.428***	-0.130	0.249
	(0.0279)	(0.0109)	(0.145)	(0.244)	(0.181)
Untreated Water	0.0178	-0.000176	-0.0520	0.110	-0.0227
	(0.0233)	(0.0104)	(0.114)	(0.215)	(0.158)
Individual Fixed Effects	Yes	Yes	Yes	Yes	Yes
Observations	38525	38489	31011	4919	4995

Note: Significant levels are indicated by *** p<0.01, ** p<0.05, * p<0.1. All results include the following controls: gender, minority group, age, age squared, preventive medical service, calorie intake, unhealthy diet, livestock raising, tap water access, flush toilet, excreta near house, log income

Table 2.6: Estimated Effect of Early Childhood Agricultural Water Pollution Exposure on Health Based on Access to Treated Water - Using County-Level Water Pollution Index

	Age 6 and below	
	(1) BMI Z-Score	(2) Height-For-Age Z-Score
Untreated Water X Born after 2006 X Water Pollution Index	0.0923	-0.302*
	(0.191)	(0.182)
Untreated Water X Water Pollution Index	-0.0674	-0.00984
	(0.129)	(0.113)
Born after 2006 X Water Pollution Index	-0.123	0.228*
	(0.145)	(0.122)
Untreated Water X Born after 2006	-0.307	0.707
	(0.566)	(0.542)
Untreated Water	0.153	0.0999
	(0.412)	(0.342)
Born after 2006	0.381	-0.370
	(0.441)	(0.372)
Water Pollution Index	-0.0967	-0.0205
	(0.194)	(0.177)
Year Fixed Effects	Yes	Yes
Community Fixed Effects	Yes	Yes
Observations	1404	1445

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Note: Significant levels are indicated by *** $p<0.01$, ** $p<0.05$, * $p<0.1$. All results include the following controls: gender, minority group, age, age squared, preventive medical service, calorie intake, unhealthy diet, livestock raising, tap water access, flush toilet, excreta near house, log income

Chapter 3: Better off or Worse off? The Economic Analysis of Income and Pollution Effect of China's Agricultural Support Policies

3.1 Introduction

With the increasing demand of agricultural products due to its huge population, in addition to the enlarging income inequality between rural as China's urbanization accelerates, rural development is one of the policy priorities in China from the beginning of the 21st century. The main intended goals of China's agricultural support policies include increasing the agricultural production, improving rural households' living standards, and developing rural economy. Started from 2000, China started the agricultural tax reform that aimed at abolishing all the agricultural taxes and fees step by step by the end of 2005. As the second stage of agricultural development policies, in 2006 the Chinese government implemented a series of agricultural support policies, including subsidies to purchase agricultural inputs such as chemical fertilizers and pesticides (Lai, 2017). These policies resulted in substantial increases in grain production and development of rural economy (Gale, 2013). As part of the series of rural development policies, these policies are intended to improve the well-being of rural residents. However, as we found in Chapter 2, the increasing use of fertilizers and pesticides also resulted in increased water pollution from agricultural activities which cause adverse health impacts. Thus, policymakers need a clearer understanding of both the positive intended effect and negative unintended effect, and implement more efficient polices by incorporating and reducing these negative impacts in the future.

In a traditional farming household in China, farmers are both consumers and producers. As they produce more, their income is higher and they are able to have more consumption, including investment on their health. However, agricultural pollution is created during the production process. On a given land, more production means more use of pesticides and fertilizers, which also leads to more pollution. As the consumer of the goods themselves, farming household bear the externalities from agriculture. Health risk of drinking water is larger in rural areas in China, especially for children (Chen et al., 2016; Su et al.,2013). So it could be the case that better health is caused by more agricultural production or the case that worse health is caused by that.

Water pollution is one of major pollution caused by agricultural production. Drinking untreated water causes water-related diseases and harms human health. Some researchers focus on estimating the effect of drinking water quality on public health in rural area. Mangyo (2008) and Zhang (2012) estimate the causal effect of water access and improved water infrastructure on health in China. However, these studies don't have real water quality data as a proxy for water pollution exposure. In addition, they don't focus on the water pollution caused by agricultural activities. Lai (2017) explores the health impact of agricultural pollution by using pesticide intensity as a proxy. But due to the lack of water quality related data in his research, the results are not purely water pollution impacts.

Despite agricultural pollution might negatively impact health, increased agricultural income could improve the health by investing more on nutrients and medical care. Thus, the overall outcome of agricultural production remains uncertain. However, some researchers argue that income affect food consumption but not necessarily nutrition intake. These findings could be interpreted as that health status is not always positively determined by income. Behrman and Deolalikar (1987) argue that high income does not brings high nutrition intake for poor households. While Slavchevska (2015) finds evidence that higher long-term effect of agricultural production on nutritional status for younger children and higher short-term effect for older children. Pitt and Rosenzweig (1985) also find vitamins and minerals affect short-term health as much as calorie does.

There is no previous literature studying the impact of agricultural pollution on health with the disturbance of income effect. First, increases in agricultural production is accompany with the increased usage of fertilizers and pesticides. These pollutions negatively impact human health through drinking water and food intake. Second, increased income from agricultural production make people invest more on nutrition and medical care which could improve the health.

The main objective of this research is to disentangle the income and water pollution effects of agricultural support policies on health for both adults and children. A challenge to estimating the health effects of agricultural policies is that household income change directly affected by the policies cannot be observed. Moreover, it can be difficult to capture variation in water pollution specifically due to agricultural activities. Therefore, to obtain exogenous variation in agricultural water pollution and household income, I use a quasi-experimental design and exploit a series of agricultural support policies enacted in China. These policies were nationwide and exogenous and led to dramatic increases in grain production (Lai, 2017). I further employ a difference-in-difference-in-differences (DDD) framework to examine the differential effect of agricultural support policies on farming and non-farming households. Specifically, I look at the effect of agricultural water pollution on morbidity, diarrhea incidence, body mass index, and height-for-age z-score. To reduce the mixed effects on different health outcome measures, I also predict the overall health index at individual and household level from all the observed health measures using factor and principal component analysis.

I find that the agricultural water pollution worsens health outcomes through increased incidence of diarrhea and lower body mass index (BMI) and increased household income improves health outcomes through decreased incidence of sickness. I further find negative pollution effect dominates the positive income effect among children, while positive income effect dominates the negative pollution effect among adults. Finally, I don't find consistent evidence on the differences in these income and pollution effect between farming and non-farming households.

3.2 Theoretical Model

3.2.1 Farmer's Profit Maximization Problem

Assume a farming household's income comes from the net profit from agricultural production. The agricultural production requires two inputs: labor and other inputs (including seeds, fertilizers, pesticides and tools). Agricultural machines, tools are fixed cost that I assume do not impact the household's profit maximization decision. Seeds per acreage, total land area, and agricultural products' prices are also assumed constant in this simple model. Thus, the non-labor inputs affect the agricultural revenue are fertilizers and pesticides. A household is assumed to maximize their total profit as follows:

$$\max_{L,N} B = Y(L,N) - P_N N \tag{1}$$

where B is the profit from agricultural production, $Y(.)$ is the revenue from selling their agricultural products, L is the labor input for agricultural production, N is the non-labor inputs for agricultural production. P_N is the price set of non-labor inputs.

Profit maximization requires the marginal benefit of non-labor inputs Y_N is equal to the marginal cost of non-labor inputs P_N. Here we assume Y is concave with a diminishing return, that is $\frac{dY}{dN}$ decreases as N increases. When subsidies apply to the non-labor inputs, the actual cost of non-labor inputs P_N decreases. To achieve the optimal solution by decreasing the marginal benefit, the rational farming household increases N so that Y and B also increase.

3.2.2 Impact of Agricultural Subsidies on Health

A simple health production function is denoted as the following:

$$H = H(D, X_i, X_h) \tag{2}$$

where H is the health status, D is the environmental pollution caused by fertilizer and pesticide application. X_i is the vector of health inputs and health behaviors under the control of individuals, X_h is the vector of non-controllable individual and household conditions that affect health, in other words, is exogenous.

Agricultural pollution is a function of non-labor agricultural inputs N:

$$D = D(N) \tag{3}$$

To maximize the agricultural profit B, under the constant L level, the optimal non-labor inputs levels are determined by the prices of non-labor inputs. Thus, the optimal non-labor input should be a function of the unit cost of the input:

$$N^* = N(P_N) \tag{4}$$

Substitute Equation (4) into Equation (3), a reduced form of pollution function is:

$$D = D(P_N) \tag{5}$$

Health Investment X_i is assumed to be a function of household income B. Substitute Equations (1) and (4) into X_i, such that:

$$X_i = X_i(Y(P_N)) \tag{6}$$

Then, substitute Equation (4) into Equation (3) and Equation (2), a reduced form of my research question is:

$$H = H\big(D(P_N), X_i(Y(P_N)\big), X_h) \tag{7}$$

To explore the impact of agricultural subsidies on health outcomes, I differentiate Equation (7) with respect to P_N, such that:

$$\frac{\partial H}{\partial P_N} = \frac{\partial H}{\partial D} \cdot \frac{\partial D}{\partial P_N} + \frac{\partial H}{\partial X_i} \cdot \frac{\partial X_i}{\partial Y} \cdot \frac{\partial Y}{\partial P_N} \tag{8}$$

The total health effect of agricultural subsidy policy in Equation (8) consists of two parts. The first term on the right-hand side is interpreted as the externality of the input subsidies which is expected to be negative as the fact that environmental pollution worsens human health. The second term indicates the wealth effect of the subsidies that lead to higher household income and more investment on health improvement, which is expected be to positive. The sign of the total effect remains ambiguous, and this paper focuses on the analysis of the first term, that is, the impact from environmental damage caused by agricultural subsidies.

3.3 Data

To explore the relationship between agricultural policies and health through change in income and water pollution, I exploit unique longitudinal household data and merge it with longitudinal data on water quality. I am thus able to connect variation in observed levels of agricultural water pollution to individual-level health outcomes. This allows us to improve upon previous research which proxies for water pollution exposure with water source type (Mangyo, 2008; Zhang, 2012; Zhang and Xu, 2016) or with the interaction of water source type and regional-level pesticide use (Lai, 2017).

3.3.1 China Health and Nutrition Survey (CHNS)

My household data come from the China Health and Nutrition Survey (CHNS). The CHNS is a rich longitudinal data set that follows approximately 4,400 households with around 19,000 individuals over nine survey waves in the years 1989, 1993, 1997, 2000, 2004, 2006, 2009, and 2011.[6] The surveys cover both rural and urban areas in nine Chinese provinces from 1989 to 2009 with three additional provinces included in the 2011 wave. My primary water quality data began in 2004. Therefore, I focus on CHNS data collected in the 2004, 2006, 2009 and 2011 survey waves.

I only include the 8 provinces and exclude the 3 newly added provinces in the 2011 survey in order to exploit the panel. I also exclude Guizhou province because there are no water quality monitoring sites there during the study period. The 8 provinces in my study are located in the Northeast, East, Middle and Southwest parts of China. These provinces are representative of China and are diverse in terms of geographic location, economic development, population, urban to rural ratio, agricultural intensity, and water availability.

The CHNS collects extensive information at the individual- and household-level, particularly with regards to health and nutrition. In every survey round, information on morbidity and anthropometric measurements were collected for all sample individuals

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[6] The number of observed households and individuals vary across survey waves as the project also follows households formed out of sample households.

making these data uniquely suited towards examining health in China. The specific health measures I examine are whether or not the respondent reported being sick or having diarrhea in the last four weeks, adult body mass index (BMI), child BMI-for-age z-scores (BMIZ), and child height-for-age z-scores (HAZ).

Table 3.1 reports the descriptive statistics from my study sample across age groups. 15.6% of individuals in my sample reported being sick in the last 4 weeks, while only 1.91% of them had diarrhea during that time. Children younger than 18 years have the lower sickness and diarrhea rate. Children are usually considered to be more vulnerable with respect to their health. The low sickness rate among children may indicate the high value placed on children in China due to its one-child policy, evidenced by the fact that children received the higher rate of preventive health care than adults.

The average maximum individual farming months are 7.192 months, and children on average work a little bit longer in months than adults. Descriptive statistics by waves are summarized in Table 3.2. Sickness and diarrhea incidence is much higher in the post-2000 waves than in the 2000 wave, but both measures fluctuate across waves. The anthropometric measurements BMI, BMI z-scores and height-for-age z-scores exhibit an increasing trend over time.

3.3.2 Household Income Data

Both Table 3.1 and Table 3.2 record the summary statistics of different income measures. All the income measures in this research are the logarithm of the actual income inflated to year 2015. Per capital income is the income divided by the family size. Farming income only include the net income from farming, while the total income includes all the household income including the government subsidies.

The theory part of this research assumes the agricultural support policies lead to changes in both household income and water pollution level. Table 3.2 shows the increasing trend of all the income measures over time. Figure 3.1 plots the sample average of per capita household income over the survey period. I split the data sample into two groups, farming households are shown in the blue and non-farming households are illustrated in red. In the first survey year 2009 after the 2006 policy year, the de-trend per capita household income in farming households exceeds the de-trend per capita household income in non-farming households which support our income increase assumption.

3.3.3 Water Quality Data

My water quality data come from two sources. The primary data I use in my main analysis is measured from water monitoring sites throughout the country by China's Ministry of Environmental Protection. At each of these sites, water pollutants were recorded weekly including surface water levels of chemical oxygen demand (COD), dissolved oxygen (DO), and nitrogen in hydrazoic acid. These measurements were then used to generate a water quality grade index ranging from 1 to 6. This index increases with pollution level, thus a higher grade represents lower water quality. An index higher than 3 means the water cannot be used for drinking purpose. From this point forward, I will refer to the water quality index as the water pollution index for clarity.

To join with my household data at the county-level, I calculate the annual mean value of the water pollution index. I then assign each county in the sample provinces the annual mean water pollution index measured at the monitoring sites nearest to the county centroid. These measures were then linked with the CHNS data at the county-level.

County is a level 3 administrative division in China, which is smaller than province and prefecture. The water pollution index is my main treatment variable of interest.

Table 3.2 also reports the mean and standard deviation of my water quality measures in the sample provinces. Drinkable water percentage is lowest in 2006, and the water pollution index exhibits a decreasing trend. Nonetheless, the average water pollution index hovers around 3 for the duration of the sample period indicating that much of the water in sample provinces is unsafe to drink. Figure 3.2 plots the water pollution index (Panel a) and drinkable water percentage (Panel b) over the survey period de-trended by year. In Figure 3.2, I clearly see reductions in water quality during the first few years after the implementation of agricultural support policies after 2005-2006. In particular, the water pollution index peaks in 2006 when the input subsidies were introduced. This supports my hypothesis that water quality worsened due to increased agricultural activities.

3.4 Empirical Model

In order to explore the health benefits brought from China's agricultural support policies, the first step I'm interested in taking is to explore the farmer's behavior change as well as income change because they are potential channels for these policies to improve the rural health. After understanding the income change impacted by the policies, I use both the variation in income and water pollution change caused by polices to disentangle the income and pollution effects on health outcomes. Finally, I am interested in looking at the difference in both of these impacts between farming and non-farming households.

3.4.1 Impact on Farmer's Producing Behavior

First, I am interested in the farmers' producing behavior change after the implementation of agricultural support policies starting from 2006. As labor is an important input for agricultural production, the change in labor input also indicates the change in other inputs, such as fertilizer and pesticide. In addition, the labor is also associated with household income or wealth. To examine the impact of agricultural support policies on farmers' labor inputs on farming, I adopt a before-after comparison econometric model as follows:

$$Farming_{it} = \beta_0^1 + \beta_1^1 Post2006_{it} + \beta_2^1 X_{it} + \lambda_t + \mu_i + \varepsilon_{it} \tag{9}$$

Equation (9) models the household and individual i 's farming labor input at survey wave t. The farming labor input we examine, $Farming_{it}$, include: maximum individual farming months at household level, annual individual farming hours, and annual individual farming months. Since not each individual in the farming household does the farming work, I use the highest individual farming months in a household to represent the household farming months. Both farming months and farming hours are measures of labor inputs. Farming hours are the actual work time on farming and are directly associated with other non-labor inputs. While farming months' change indicate the farming structure change as the fixed agricultural seasonality. For example, the increase in farming months might be caused by choosing a different portfolio of farming products. $Post2006_{it}$ is a policy indicator that equal to 1 if the survey was conducted after 2006. β_1^1 from Equation (9) is therefore interpreted as the difference in the farming labor inputs after the policy. X_{it} include household and individual controls, such as log household income, individual daily calorie intake, unhealthy diet (=1 if diet is not healthy[7]), whether the individual uses preventive health care, household sanitation conditions, age, gender, and ethnic group (=1 if belong to ethnic minorities). λ_t is the year trend and μ_i is a vector of individual or household fixed effects.

3.4.2 Impact on Household Income

Next, I am interested in exploring the impact of agricultural policies on household income. According to the theory base of this research, income effect is the positive impact that improve human health through more investment in nutrition and health. To demonstrate the validity of this income effect, I use a before-after comparison econometric model as follows:

$$Income_{it} = \beta_0^2 + \beta_1^2 Post2006_{it} + \beta_2^2 X_{it} + \lambda_t + \mu_i + \varepsilon_{it} \tag{10}$$

Equation (10) models the household and individual i 's income at survey wave t. This analysis not only looks at the farming individuals and households, but also considers the possible spillover impact on the rural and urban areas. $Income_{it}$ include household income, per capita household income and individual income. β_2^2 from Equation (10) is therefore interpreted as the difference in the income after the policy implementation.

As farming households are more likely to be affected by agricultural support policies, I further examine the heterogeneous effects across farming and non-farming households.

$$\begin{aligned} Income_{it} = \beta_0^3 &+ \beta_1^3 Post2006_{it} \times FarmingDummy_{it} \\ &+ \beta_2^3 Post2006_{it} + \beta_3^3 FarmingDummy_{it} \\ &+ \beta_4^3 X_{it} + \lambda_t + \mu_i + \varepsilon_{it} \end{aligned} \tag{11}$$

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[7] According to the US recommendations on dietary reference intake for total energy (Institute of Medicine, 2005), I define unhealthy diet as having at least one of three macronutrients out of the US dietary reference intake range.

$FarmingDummy_{it}$ equals 1 if the household or individual i at year t works on farming. β_1^3 from Equation (11) is therefore the income difference between the farming and non-farming households after the policy implementation.

3.4.3 Impact on Health

The main objective of this research is to identify the impact of policies on human health. The net impact can be disentangled to income effect and pollution effect. To explore the two effects simultaneously, I use a quasi-experimental design by interacting water quality and per capita household income with the 2006 agricultural supporting policies.

$$\begin{aligned} Health_{it} = \beta_0^4 &+ \beta_1^4 Post2006_{it} \times Water_{it} + \beta_2^4 Water_{it} \\ &+ \beta_3^4 Post2006_{it} + \beta_4^4 Post2006_{it} \times Income_{it} \\ &+ \beta_5^4 Income_{it} + \beta_6^4 X_{it} + \lambda_t + \mu_i + \varepsilon_{it} \end{aligned} \tag{12}$$

Equation (12) models the health outcome of individual i at survey wave t. The health outcomes we examine, $Health_{it}$, include: a dummy variable indicating whether the individual was sick in the last 4 weeks, had diarrhea in the last 4 weeks, adult BMI (for individuals aged 18 and above), child BMI-for-age z-score (for individuals aged below 18), and child Height-for-age z-score (for individuals aged below 18). County-level water pollution exposure for individual i at survey wave t is captured by $Water_{it}$. I use the annual average water pollution index, calculated as the mean value at the nearest monitoring site to individual i at year t to measure water quality - the higher the value the worse the water quality.

Equation (12) allows us to estimate the impact difference of income and water quality on health before and after the agricultural subsidy policy starting from 2006 at the same time. β_1^4 from Equation (12) captures the difference in the impact of water quality on health after the policy, while β_4^4 captures the difference in the impact of income on health after the policy.

3.4.4 Factor and Principal Component Analysis

The above analysis considers multiple health measures as health outcome variable. However, the income and pollution effect might have different magnitude on different health indicators. Thus, it might cause difficulties on drawing a conclusion on the health impacts.

I use factor and Principal Component Analysis methods to predict a health index that corporates all the health measures I use in the above analysis. And then I replace the health outcome variables with the predicted health index as follows:

$$\begin{aligned} HealthIndex_{it} &= \beta_0^5 + \beta_1^5 Post2006_{it} \times Water_{it} + \beta_2^5 Water_{it} \\ &+ \beta_3^5 Post2006_{it} + \beta_4^5 Post2006_{it} \times Income_{it} \\ &+ \beta_5^5 Income_{it} + \beta_6^5 X_{it} + \lambda_t + \mu_i + \varepsilon_{it} \end{aligned} \tag{13}$$

$HealthIndex_{it}$ is the predicted health index of individual or household i at survey wave t. β_1^5 and β_4^5 are variables of interest that capture the impact of policies on overall health.

3.4.5 Further Analysis

Farming households are closer to the pollution source as well as directly motivated by the agricultural support policies. Therefore, I apply a Difference-in-Difference-in-Differences (DDD) design to look at the heterogeneous effects across farming and non-farming households. This allows us to explore the difference in the health impact of water pollution and household income due to the household's farming status.

$$\begin{aligned} Health_{it} = \beta_0^6 &+ \beta_1^6 Post2006_{it} \times Water_{it} \times Farming_{it} \\ &+ \beta_2^6 Post2006_{it} \times Income_{it} \times Farming_{it} \\ &+ \beta_3^6 Post2006_{it} \times Water_{it} \\ &+ \beta_4^6 Post2006_{it} \times Farming_{it} \\ &+ \beta_5^6 Water_{it} \times Farming_{it} \\ &+ \beta_6^6 Post2006_{it} \times Income_{it} \\ &+ \beta_7^6 Income_{it} \times Farming_{it} + \beta_8^6 Post2006_{it} \\ &+ \beta_9^6 Water_{it} + \beta_{10}^6 Farming_{it} \\ &+ \beta_{11}^6 Income_{it} + \beta_{12}^6 X_{it} + \lambda_t + \mu_i \end{aligned} \tag{14}$$

$Farming_{it}$ equals 1 if the household individual i lives in a farming household at year t. $Income_{it}$ is the per capita household income of individual i at year t. β_1^6 from Equation (14) then estimates the difference in the effect of post-2006 water pollution on individuals in or not in the farming households. β_2^6 examines the difference in the effect of post-2006 household income change on individuals in or not in the farming households.

3.5 Results

3.5.1 The Effect of Agricultural Support Policies on Household Income

Table 3.3 reports the estimates from Equation (9) on the effect of 2006 agricultural support policies on farming activities. Column (1) reports the effect of policies on the household-level farming activities, which is represented by the maximum individual farming months in the household. Columns (2) and (3) report the effect of policies on individual farming activities, which are represented by the annual farming hours and annual farming months. Although not reported in Table 3.3, all estimates are estimated with robust standard errors and include all controls, individual or household fixed effects, and year trend. The individual fixed effects control for time-invariant characteristics that are correlated with water quality and health, such as genetic diseases, birth defects, individual behaviors, and household environment as well as other pollution sources, sanitation conditions and health infrastructure. The year trend captures the time-variant characteristics that affect farming activities.

The coefficient on the variable Post2006 captures the conditional average difference in household and individual farming activities before and after 2006. It can therefore be interpreted as the effect of agricultural support policies on the farming labor input since I am identifying this effect of variation in farming behaviors resulting from these policies. For example, in Column (1), I see that on average households spend more months on farming over time in that the post-2006 period is associated with a 1.062 months' increase in the largest individual farming months in the same household. In Column (2), I also find evidence that on average individuals spend more hours annually on farming over time in that the post-2006 period is associated with a 41.09 hours' increase in the annual individual annual farming hours. However, I don't find significant change in individual annual farming months, which can be explained by the fact the individuals tend to spending more hours in the fixed farming months rather than expanding the farming months of a year.

Instead of examining the average farming time change due to the agricultural policies, in Table 3.4 I examine the effect of 2006 agricultural support policies on income based on Equation (10). In the first panel of Table 3.4, I examine the effect of the polices on the income of farming households, including household farming income, per capita household farming income, household total income, per capita household total income. I consider both farming income and total income because other non-farming income might also be affected by these policies indirectly. While household income is the measure of household wealth, per capita household income is used more widely in the economics literature as it captures the family size and living standard. In the next three panels I also analyze the household and individual level income change in rural, urban, and all households. In the last panel, I explore the income difference of farming individuals on both farming and total income.

I find on average household total income, per capita household income, and individual total income is increasing significantly over time after 2006, which happens not only in the farming households, but also other rural and urban households. It is also interesting to notice the average increase in rural households is higher than the average increase in farming and urban households, which indicates the non-farming income in rural area benefits most from the policies. Since subsidies are part of the non-farming income and these polices have huge spill-over effect on overall rural economy, this phenomenon is also reasonable. On the contrast, the pure farming income is decreasing over time after 2006, meaning the farming itself doesn't bring wealth to the households. However, as the assumption of this research lies on the fact of total income increase, this unfortunate finding doesn't really impact the foundation of this research.

In order to further detect the income change difference between farming and non-farming households, Table 3.5 reports the estimation results of Equation (11). Columns

(1) – (2) report the estimated income change difference at household level, including the household total income and per capita household total income. Column (3) reports the estimated income change difference at individual level. The primary coefficient of interest is that interaction between Post2006 and the farming status indicator. This is the effect on income difference between farming and non-farming households or individuals that occurred after the agricultural support policies were implemented. In Columns (1) and (2), I see that on average farming households' income is increasing faster than non-farming households over time in that the post-2006 period is associated with a 0.0757% increase in total income and 0.0687% increase in per capita total income. However, Column (3) shows farming individuals' total income is increasing slower than non-farming individuals. These findings again indicate that although farming households have higher income increase than non-farming households due to the agricultural support policies, this income increase is mostly from non-farming source.

3.5.2 The Effect of Agricultural Support Policies on Health Outcomes: Income Effect and Pollution Effect

As evidence shows the income is increasing in the post-2006 years, it is valid to discuss both the income and pollution effect on health caused by the agricultural support polices simultaneously using a quasi-experimental design. The results reported in Table 3.6 based on Equation (12), capture the income effect of policies and the pollution effect of polices due to both contaminated drinking water as well as reduced food safety on a variety of health outcomes. Columns (1) - (2) of Table 3.6 report health effect on the incidence of sickness and diarrhea in people of all ages in my sample. Column (3) of Table 3.6 reports the estimated effect on BMI for adults (aged 18 and older). Columns

(4) - (5) of Table 3.6 focus on children and report the estimated effects on BMI-for-age z-score and Height-for-age z-score (HAZ) for children under the age of 18 in my sample. The coefficient on the water pollution index alone captures the association between levels of pollution and health conditional on control variables and individual and time fixed effects, while the coefficient on the per capita household total income captures the association between income and health. The coefficient on the variable Post2006 captures the conditional average difference in health before and after 2006. The interaction between Post2006 and water pollution index is known as the pollution effect, is the effect on health outcomes from changes in the water pollution index that occurred after the agricultural support policies were implemented. The interaction between Post2006 and per capita household total income, known as the income effect, is the effect on health outcomes from changes in the household income that occurred after the agricultural support policies were implemented. In Columns (2) and (3), I see that on average individuals are unhealthier over time due to the water pollution in that the post-2006 period is associated with a 0.310% increase in diarrhea incidence and a 3.77% decrease in adult BMI. In Column (1), I find on average individuals are healthier over time due to the increasing household income in that the post-2006 period is associated with a 1.12% decrease in sickness. In other words, water pollution has significant negative effect on health outcomes such as diarrhea and adult BMI, while income has significant positive effect on reducing the sickness. However, the other estimates of both effects are insignificant and in mixed signs, there might be some other factors affect different health outcomes that cannot be observed in this data.

To reduce the impact of unobserved health factors on different health outcomes, one of the ways is to create a comprehensive health index based on all the health outcome variables. I am using both factor analysis and principal analysis to predict a health index for each individual according to his or her observed health outcome variables used for Table 3.6. Table 3.7 shows the results using predicted health index from factor analysis, and Table 3.8 shows the results using predicted health index from principal component analysis. I predict adult health index using sickness, diarrhea incidence and adult BMI and children health index using sickness, diarrhea incidence, BMI-for-age z-score and Height-for-age z-score (HAZ). Since the predicted health index has the same sign as the sickness and diarrhea sickness and opposite sign as the anthropometric measures, I name it predicted sickness index for easier interpretation. The higher the predicted sickness index, the unhealthier the individuals are. The odd numbered columns are controlled for year fixed effects, while the even numbered columns are not. The upper panel of both Table 3.7 and Table 3.8 are individual level results, and the lower panel are average individual effects at household level.

In Table 3.7, individual adults have significant larger negative health effects of water pollution after 2006 and significant positive health effect of household income after 2006. I also find household-level children have significant larger negative health effects of water pollution after 2006 and significant positive health effect of household income after 2006. These findings are consistent as my assumption that the policies have positive income effect and negative pollution effect on human health.

Table 3.8 using principal component analysis gives us similar but more significant results, especially on the individual children's pollution effects. From these two tables, it is interesting to note that the magnitude of average income effect is slightly higher than the average pollution effect among adults, while the magnitude of average income effect is slightly lower than the average pollution effect among children. This finding indicates different age groups are affected differently by the policies. For children, the negative pollution impact exceeds the positive income effect, and might have a net negative health effect of agricultural support policies.

3.5.3 Health Effect Difference in Farming and Non-Farming Households

In Table 3.9, I estimate Equation (14), respectively, which employs a DDD design to compare the effect of agricultural water pollution and per capita household income increase on a variety of health measures between farming and non-farming households. In this case, my primary coefficients of interest are that on the triple interaction of water pollution, an indicator for the post-2006 period, and an indicator for household farming status and the triple interaction of per capita household income, an indicator for the post-2006 period, and an indicator for household farming status. These estimate then measures the difference in the income effect and pollution effect of policies on health outcomes between farming and non-farming households. All results are estimated with robust standard errors and include all controls and individual and year fixed effects.

According to the results reported in Table 3.9, for those live in farming households, agricultural water pollution significantly decreases adult BMI. A one-unit increase in the water pollution index results in a 0.137 reduction in adult BMI on average than non-farming households. In addition, farming households have higher likelihood of being sick in the last 4 weeks from income effect than non-farming households. The mixed results don't draw any conclusion on the difference in the impacts between farming and non-farming households. One explanation may be that non-farming households invest more than farming households with the same amount of income increase.

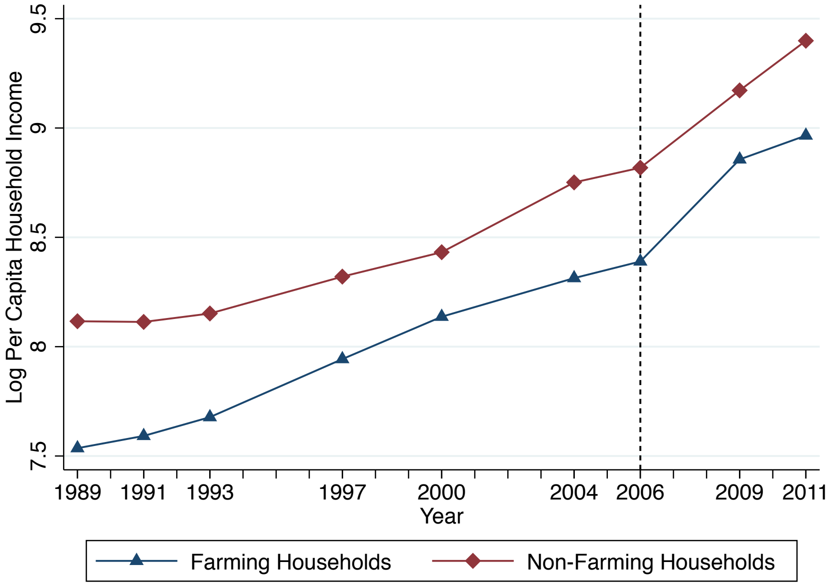
3.6 Conclusion

Agricultural pollution is a severe problem and threatens public health in rural China. The major objective of this paper is to explore both the positive and negative impacts of agricultural support policies on human health using longitudinal data. The first part of this research focus on the policy impact analysis of agricultural support policies on famers' farming activities and income by utilizing before-after comparison and natural experiment method. Regression results show that the policies has positive impact on farming labor input and income. The second part of this paper is to estimate the health impact of water pollution and income affected by the policies. I find that income effect dominates among adults, while the pollution effect dominates among children.

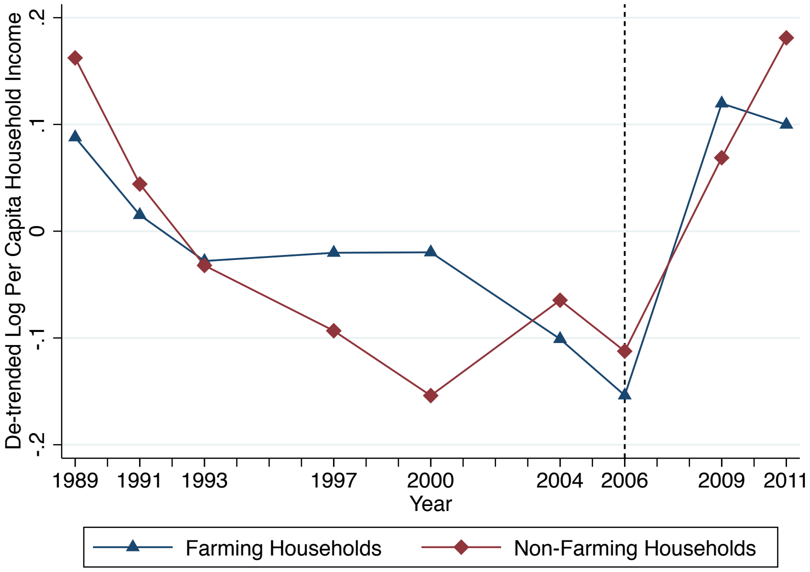
Our results indicate that although the agricultural support policies improve the household income and further improve health through the income channel, the negative impact brought from agricultural water pollution mitigate the positive impact on human health, especially children’s health. Given the findings, I think it is critical for policymakers to incorporate the pollution effects into the policy evaluations and make environmental friendly policies in the future.

This research has a lot of limitations. The water quality data might not perfectly capture the households' drinking water pollution level. The income change might not capture the change in the real health investment and avoidance behavior. Some unknown factors associated with the polices might also affect the health outcomes.

Figure 3.1: Per Capita Household Income



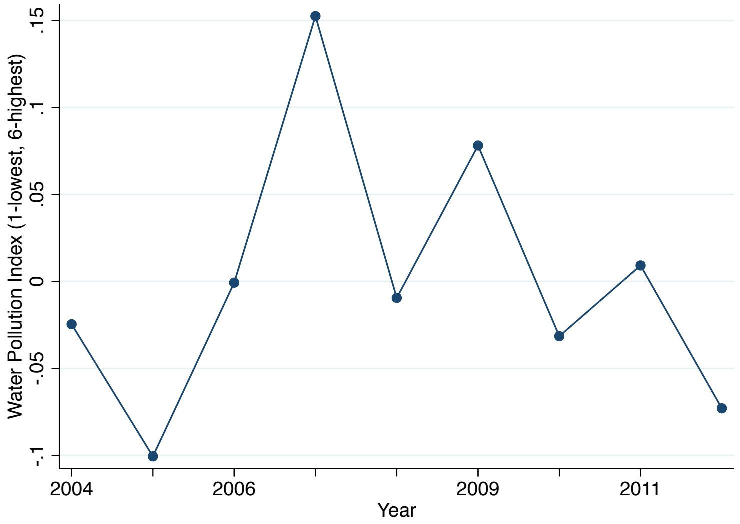
(a) Per Capita Household Income



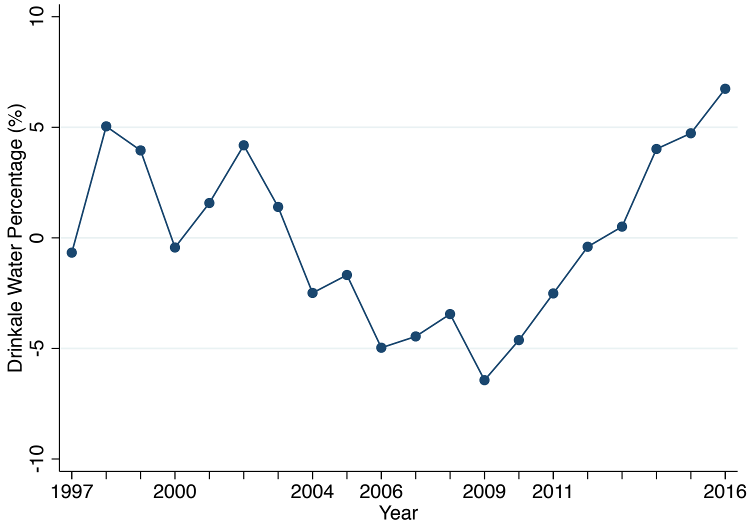
(b) De-trend Per Capita Household Income

Note: Per capita household income is affected by multiple factors and has a clear increasing time trend over time. De-trending per capita household income allows us to explore the fluctuations of household income that were possibly caused by agricultural policies. The y axis in these two graphs is the deflated per capita household income across the data sample.

Figure 3.2: De-trend Water Quality



(a) De-trend Water Pollution Index (Higher Means Worse)



(b) De-trend Drinkable Water Percentage (Higher Means Better)

Note: Water quality is affected by multiple factors and has a clear decreasing time trend since the beginning of the 21st century. De-trending water quality allows us to explore the fluctuations of water quality that were possibly caused by agricultural policies. The y axis in these two graphs is the annual average water quality data of the 8 study provinces.

Table 3.1: Descriptive Statistics by Age Groups

	All Age	Age below 18	Age 18 and above
Farming Status			
Maximum individual farming months in the household	7.192 (3.264)	7.546 (3.296)	7.144 (3.262)
Household own at least one agricultural machine	0.409 (0.492)	0.404 (0.492)	0.408 (0.491)
Household's farming land area	7.795 (13.25)	6.317 (10.16)	7.986 (13.62)
Individual			
Male	0.502 (0.500)	0.546 (0.499)	0.491 (0.500)
Age	45.69 (13.10)	14.25 (2.441)	46.59 (12.40)
Prenventive health care	0.0164 (0.127)	0.0219 (0.147)	0.0164 (0.127)
Calorie intake	2301.0 (714.7)	2034.3 (563.7)	2304.0 (718.0)
Unhealthy diet	0.705 (0.456)	0.760 (0.429)	0.701 (0.458)
Individual Farming Income	7.704 (1.118)	6.218 (1.580)	7.749 (1.088)
Individual Total Income	8.641 (1.154)	6.778 (1.554)	8.698 (1.110)
Household			
Raise livestock	0.624 (0.484)	0.749 (0.435)	0.620 (0.485)
Treated water by water plant	0.256 (0.437)	0.224 (0.418)	0.255 (0.436)
Have tap water	0.582 (0.493)	0.481 (0.501)	0.589 (0.492)
Have flush toilets	0.146 (0.353)	0.169 (0.376)	0.146 (0.353)
Excreta around the house	0.464 (0.499)	0.596 (0.492)	0.457 (0.498)
Household Total Income	9.790 (0.910)	9.647 (0.839)	9.805 (0.910)
Per Capita Household Total Income	8.481 (0.933)	8.112 (0.855)	8.508 (0.931)
Household Farming Income	8.467 (0.909)	8.400 (0.869)	8.472 (0.915)
Per Capita Household Farming Income	7.157 (0.964)	6.864 (0.888)	7.175 (0.972)
Health Status			
Sick in recent 4 weeks	0.156 (0.363)	0.115 (0.320)	0.159 (0.366)
Have diarrhea in recent 4 weeks	0.0191 (0.137)	0.0164 (0.127)	0.0191 (0.137)
BMI z-score		-0.632 (0.966)	
Height-for-age z-score		-1.202 (1.063)	
BMI			22.84 (3.303)
Observations	11385	183	10442

Table 3.2: Descriptive Statistics by Survey Year

	2000	2004	2006	2009	2011	Total
Water Quality						
Water pollution index	.	3.270	3.148	2.981	2.808	3.044
	(.)	(1.211)	(1.214)	(1.010)	(0.812)	(1.084)
Drinkable water percentage	0.560	0.521	0.490	0.503	0.575	0.528
	(0.243)	(0.261)	(0.199)	(0.205)	(0.206)	(0.224)
Income Status						
Individual Farming Income	7.214	7.765	7.834	7.823	8.035	7.673
	(1.048)	(1.057)	(1.011)	(1.176)	(1.166)	(1.131)
Individual Total Income	8.533	8.660	8.924	9.400	9.681	9.061
	(1.151)	(1.289)	(1.294)	(1.156)	(1.082)	(1.272)
Household Total Income	9.608	9.732	9.772	10.17	10.34	9.955
	(1.018)	(1.031)	(1.093)	(1.098)	(1.119)	(1.115)
Per Capita Household Total Income	8.276	8.484	8.530	8.943	9.125	8.704
	(0.986)	(1.042)	(1.112)	(1.098)	(1.126)	(1.125)
Household Farming Income	8.163	8.512	8.541	8.410	8.469	8.425
	(0.812)	(0.854)	(0.853)	(0.968)	(1.085)	(0.933)
Per Capita Household Farming Income	6.731	7.147	7.180	7.055	7.127	7.056
	(0.820)	(0.902)	(0.895)	(1.025)	(1.189)	(0.993)
Health Status						
Sick in recent 4 weeks	0.0645	0.167	0.126	0.137	0.156	0.131
	(0.246)	(0.373)	(0.332)	(0.344)	(0.363)	(0.338)
Have diarrhea in recent 4 weeks	0.00807	0.0259	0.0178	0.0106	0.0112	0.0144
	(0.0895)	(0.159)	(0.132)	(0.102)	(0.105)	(0.119)
Height-for-age z-scores(age 17 and under)	-0.810	-0.660	-0.602	-0.336	-0.117	-0.518
	(1.204)	(1.278)	(1.327)	(1.329)	(1.422)	(1.335)
BMI z-scores(age 17 and under)	-0.286	-0.133	-0.135	-0.143	0.119	-0.119
	(1.220)	(1.255)	(1.359)	(1.371)	(1.445)	(1.333)
BMI(age 18 and above)	22.80	23.06	23.16	23.33	23.87	23.29
	(3.260)	(3.375)	(3.357)	(3.478)	(3.996)	(3.558)
Observations	93957					

Table 3.3: Estimated Effect of 2006 Policy on Farming Activities

	Households	Individuals	
	(1) Maximum Individual Farming Months in the Household	(2) Annual Farming Hours	(3) Farming Months Per Year
Post 2006	1.062***	41.09***	-0.0230
	(0.0442)	(4.779)	(0.0928)
Individual Fixed Effects	Yes	Yes	Yes
Year Trend	Yes	Yes	Yes
Observations	76122	18780	19695

*** $p<0.01$, ** $p<0.05$, * $p<0.1$, $^{+}$ $p<0.15$

Notes: All results include the following controls: gender, minority group, age, age squared, preventive medical service, calorie intake, unhealthy diet, livestock raising, tap water access, flush toilet, excreta near house

Table 3.4: Estimated Effect of 2006 Agricultural Support Policies on Income

	Farming Households			
	(1) Household Farming Income	(2) Per Capita Household Farming Income	(3) Household Total Income	(4) Per Capita Household Total Income
Post 2006	-0.165***	-0.188***	0.295***	0.273***
	(0.0164)	(0.0170)	(0.0162)	(0.0161)
Individual Fixed Effects	Yes	Yes	Yes	Yes
Year Trend	Yes	Yes	Yes	Yes
Observations	37586	37583	38215	38212

	Rural Households		
	(1) Household Total Income	(2) Per Capita Household Total Income	(3) Individual Total Income
Post 2006	0.344***	0.316***	0.604***
	(0.0157)	(0.0156)	(0.0257)
Individual Fixed Effects	Yes	Yes	Yes
Year Trend	Yes	Yes	Yes
Observations	42010	42007	26955

	Urban Households		
	(1) Household Total Income	(2) Per Capita Household Total Income	(3) Individual Total Income
Post 2006	0.287***	0.248***	0.278***
	(0.0182)	(0.0177)	(0.0209)
Individual Fixed Effects	Yes	Yes	Yes
Year Trend	Yes	Yes	Yes
Observations	38897	38892	24335

	All Households		
	(1) Household Total Income	(2) Per Capita Household Total Income	(3) Individual Total Income
Post 2006	0.318***	0.285***	0.465***
	(0.0119)	(0.0117)	(0.0171)
Individual Fixed Effects	Yes	Yes	Yes
Year Trend	Yes	Yes	Yes
Observations	80907	80899	51290

	Farming Individuals	
	(1) Individual Farming Income	(2) Individual Total Income
Post 2006	-0.102***	0.465***
	(0.0299)	(0.0171)
Individual Fixed Effects	Yes	Yes
Year Trend	Yes	Yes
Observations	19076	51290

*** p<0.01, ** p<0.05, * p<0.1, $^{+}$ p<0.15

Notes: All results include the following controls: gender, minority group, age, age squared, preventive medical service, calorie intake, unhealthy diet, livestock raising, tap water access, flush toilet, excreta near house

Table 3.5: Estimated Effect of 2006 Policy on Income Based on Farming or Not

	Households		Individuals
	(1) Household Total Income	(2) Per Capita Household Total Income	(3) Individual Total Income
Farming Household * Post2006	0.0757***	0.0687***	
	(0.0191)	(0.0188)	
Post 2006	0.288***	0.258***	0.476***
	(0.0135)	(0.0132)	(0.0183)
Farming Household	0.0684***	0.0589***	
	(0.0134)	(0.0131)	
Farming Individual * Post2006			-0.0855***
			(0.0270)
Farming Individual			0.204***
			(0.0207)
Individual Fixed Effects	Yes	Yes	Yes
Year Trend	Yes	Yes	Yes
Observations	80907	80899	51290

*** $p<0.01$, ** $p<0.05$, * $p<0.1$, $^{+}$ $p<0.15$

Notes: All results include the following controls: gender, minority group, age, age squared, preventive medical service, calorie intake, unhealthy diet, livestock raising, tap water access, flush toilet, excreta near house

Table 3.6: Estimated Effect of 2006 Policy on Health Based on Water Quality and Income

	All age		Age 18 and above	Age below 18	
	(1) Sick	(2) Diarrhea	(3) BMI	(4) BMI Z-Score	(5) Height-For-Age Z-Score
Post 2006 X Water Pollution Level	0.000427	0.00310*	-0.0377*	-0.0418	-0.0290
	(0.00462)	(0.00184)	(0.0226)	(0.0411)	(0.0362)
Water Pollution Level	0.0292***	0.00668*	-0.166***	-0.141^{+}	-0.0183
	(0.00968)	(0.00396)	(0.0512)	(0.0912)	(0.0684)
Post 2006	0.161***	-0.0137	0.153	-0.458	0.432
	(0.0443)	(0.0178)	(0.220)	(0.402)	(0.310)
Post 2006 X Per Capita Household Income	-0.0104**	-0.000212	-0.0271	0.0531	-0.0249
	(0.00479)	(0.00198)	(0.0237)	(0.0451)	(0.0349)
Per Capita Household Total Income	0.0112***	0.000840	0.0417**	-0.0316	0.0146
	(0.00400)	(0.00165)	(0.0192)	(0.0346)	(0.0263)
Individual Fixed Effects	Yes	Yes	Yes	Yes	Yes
Observations	38525	38489	31011	4919	4995

*** $p<0.01$, ** $p<0.05$, * $p<0.1$, $^{+}$ $p<0.15$

Notes: All results include the following controls: gender, minority group, age, age squared, preventive medical service, calorie intake, unhealthy diet, livestock raising, tap water access, flush toilet, excreta near house

Table 3.7: Estimated Effect of 2006 Policy on Health Based on Water Quality and Income (Factor Analysis)

	Adults		Children	
	(1) Predcited Sickness Index	(2) Predcited Sickness Index	(3) Predcited Sickness Index	(4) Predcited Sickness Index
Post 2006 X Water Pollution Level	0.0199^{+}	0.0238*	0.0635	0.0679^{+}
	(0.0125)	(0.0125)	(0.0452)	(0.0450)
Water Pollution Level	0.0809***	0.0789***	0.0904	0.0884
	(0.0274)	(0.0274)	(0.0773)	(0.0768)
Post 2006	0.172	0.282**	-0.0305	0.186
	(0.264)	(0.125)	(0.861)	(0.340)
Post 2006 X Per Capita Household Income	-0.0271*	-0.0314**	-0.0231	-0.0253
	(0.0139)	(0.0138)	(0.0374)	(0.0373)
Per Capita Household Total Income	0.0297***	0.0311***	-0.0128	-0.0118
	(0.0111)	(0.0111)	(0.0288)	(0.0289)
Individual Fixed Effects	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes		Yes	
Year Trend		Yes		Yes
Observations	30984	30984	4909	4909

	Adults		Children	
	(1) Household Predcited Sickness Index	(2) Household Predcited Sickness Index	(3) Household Predcited Sickness Index	(4) Household Predcited Sickness Index
Post 2006 X Water Pollution Level	0.0168	0.0204^{+}	0.0631^{+}	0.0707*
	(0.0138)	(0.0138)	(0.0413)	(0.0414)
Water Pollution Level	0.0721**	0.0687**	0.0901	0.0857
	(0.0310)	(0.0311)	(0.0719)	(0.0718)
Post 2006	0.0726	0.224^{+}	0.282	0.496
	(0.140)	(0.139)	(0.343)	(0.347)
Post 2006 X Per Capita Household Income	-0.0204	-0.0234^{+}	-0.0579^{+}	-0.0619^{+}
	(0.0158)	(0.0157)	(0.0379)	(0.0376)
Per Capita Household Total Income	0.0237*	0.0247**	0.00482	0.00627
	(0.0125)	(0.0126)	(0.0277)	(0.0277)
Individual Fixed Effects	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes		Yes	
Year Trend		Yes		Yes
Observations	14781	14781	4461	4461

*** $p<0.01$, ** $p<0.05$, * $p<0.1$, $^{+}$ $p<0.15$

Notes: All results include the following controls: gender, minority group, age, age squared, preventive medical service, calorie intake, unhealthy diet, livestock raising, tap water access, flush toilet, excreta near house

Table 3.8: Estimated Effect of 2006 Policy on Health Based on Water Quality and Income (Principal Component Analysis)

	Adults		Children	
	(1) Predcited Sickness Index	(2) Predcited Sickness Index	(3) Predcited Sickness Index	(4) Predcited Sickness Index
Post 2006 X Water Pollution Level	0.0207*	0.0247**	0.0725^{+}	0.0763*
	(0.0125)	(0.0125)	(0.0449)	(0.0448)
Water Pollution Level	0.0812***	0.0792***	0.0854	0.0836
	(0.0274)	(0.0274)	(0.0773)	(0.0769)
Post 2006	0.162	0.276**	-0.131	0.147
	(0.264)	(0.125)	(0.862)	(0.340)
Post 2006 X Per Capita Household Income	-0.0265*	-0.0309**	-0.0192	-0.0211
	(0.0139)	(0.0138)	(0.0374)	(0.0373)
Per Capita Household Total Income	0.0296***	0.0310***	-0.0149	-0.0140
	(0.0111)	(0.0111)	(0.0289)	(0.0289)
Individual Fixed Effects	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes		Yes	
Year Trend		Yes		Yes
Observations	30984	30984	4909	4909

	Adults		Children	
	(1) Household Predcited Sickness Index	(2) Household Predcited Sickness Index	(3) Household Predcited Sickness Index	(4) Household Predcited Sickness Index
Post 2006 X Water Pollution Level	0.0177	0.0213^{+}	0.0711*	0.0779*
	(0.0138)	(0.0138)	(0.0412)	(0.0412)
Water Pollution Level	0.0723**	0.0689**	0.0849	0.0810
	(0.0310)	(0.0311)	(0.0723)	(0.0722)
Post 2006	0.0653	0.217^{+}	0.229	0.488
	(0.140)	(0.139)	(0.342)	(0.346)
Post 2006 X Per Capita Household Income	-0.0200	-0.0229^{+}	-0.0563^{+}	-0.0599^{+}
	(0.0157)	(0.0157)	(0.0378)	(0.0376)
Per Capita Household Total Income	0.0235*	0.0245*	0.00379	0.00509
	(0.0125)	(0.0126)	(0.0277)	(0.0277)
Individual Fixed Effects	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes		Yes	
Year Trend		Yes		Yes
Observations	14781	14781	4461	4461

*** $p<0.01$, ** $p<0.05$, * $p<0.1$, $^{+}$ $p<0.15$

Notes: All results include the following controls: gender, minority group, age, age squared, preventive medical service, calorie intake, unhealthy diet, livestock raising, tap water access, flush toilet, excreta near house

Table 3.9: Estimated Effect of 2006 Policy on Health Based on Water Quality and Income

	All age		Age 18 and above	Age below 18	
	(1) Sick	(2) Diarrhea	(3) BMI	(4) BMI Z-Score	(5) Height-For-Age Z-Score
Post 2006 X Water Pollution LevelX Farming Household	0.00134 (0.00896)	0.00404 (0.00377)	-0.137*** (0.0469)	-0.0298 (0.0846)	-0.0422 (0.0666)
Post 2006 X Per Capita Household Income X Farming Household	0.0280** (0.0112)	-0.00147 (0.00452)	0.0786^{+} (0.0526)	-0.0802 (0.0918)	0.0724 (0.0710)
Post 2006 X Water Pollution Level	-0.0000517 (0.00564)	0.00198 (0.00223)	0.0202 (0.0259)	-0.0219 (0.0503)	-0.0143 (0.0438)
Post 2006 X Farming Household	-0.238** (0.0995)	0.000874 (0.0400)	-0.219 (0.477)	0.797 (0.822)	-0.498 (0.608)
Farming Household X Water Pollution Level	-0.0116^{+} (0.00762)	-0.00207 (0.00324)	0.0417 (0.0311)	-0.0194 (0.0646)	-0.0355 (0.0520)
Post 2006 X Per Capita Household Income	-0.0153*** (0.00571)	0.000240 (0.00237)	-0.0651** (0.0282)	0.0662 (0.0553)	-0.0441 (0.0445)
Farming Household X Per Capita Household Income	-0.00771 (0.00917)	-0.00248 (0.00385)	-0.00771 (0.0408)	0.103^{+} (0.0690)	-0.0387 (0.0561)
Post 2006	0.257** (0.102)	-0.0689* (0.0395)	1.025* (0.582)	0 (.)	0 (.)
Water Pollution Level	0.0327*** (0.00998)	0.00722* (0.00402)	-0.193*** (0.0523)	-0.135^{+} (0.0926)	-0.00247 (0.0708)
Farming Household	0.0982 (0.0796)	0.0340 (0.0337)	-0.0241 (0.361)	-0.821 (0.607)	0.468 (0.470)
Per Capita Household Total Income	0.0115** (0.00451)	0.00140 (0.00191)	0.0470** (0.0214)	-0.0546 (0.0407)	0.0226 (0.0301)
Individual Fixed Effects	Yes	Yes	Yes	Yes	Yes
Observations	38525	38489	31011	4919	4995

*** $p<0.01$, ** $p<0.05$, * $p<0.1$, $^{+}$ $p<0.15$

Notes: All results include the following controls: gender, minority group, age, age squared, preventive medical service, calorie intake, unhealthy diet, livestock raising, tap water access, flush toilet, excreta near house

Chapter 4: Optimal Fertilizer Management in Agriculture Internalizing Health Cost of Nitrate Pollution

4.1 Introduction

Nitrate contamination in drinking water threatens public health in at least three medical conditions: methemoglobinemia (blue-baby syndrome), adverse birth outcome, and cancer (Hester et al. 1996; Powlson et al. 2008; Haden et al. 2016). A major source of nitrate in groundwater comes from excessive use of chemical fertilizers and livestock manure for crop production (Haden et al. 2016). Nitrogen is a key element of nutrients to crops and nitrogen fertilizers are widely used to help improve the crop production. However, not all the nitrogen can be absorbed by crops. Some of the nitrogen flows into the groundwater and converts to nitrate through a series of chemical reactions which is called nitrification. When the nitrate accumulates in the groundwater, it takes decades for nitrate reduce back to nitrogen gas. With the increasing demand for chemical fertilizers in agriculture, nitrate accumulates faster in the agricultural area. Given groundwater is the major drinking water source in some rural area, the negative health impact of nitrate pollution has become a big concern. Up to date, it is still very costly to remove nitrate from groundwater. One of the optimal ways to avoid high nitrate contamination in groundwater is to control fertilizer application rate during the crop production process.

The main objective of our research is to develop a dynamic optimization model of chemical fertilizer management by incorporating the health cost of nitrate pollution in groundwater. Much of the optimization studies include a safe water quality level in the constraint (Roseta-Palma, 2002; Wang and Baerenklau, 2014; Yadav,1997). The hole in this literature is that the assumed water quality threshold which they maintain might not be healthy enough. A study from van Grinsven et al. (2010) indicates a negative health impact from nitrate pollution below the local threshold. A few studies consider the removal cost as the damage cost to water pollution (Eiwerth and van Kooten, 2010). It's not realistic to remove all the pollutants in the water, and the removal cost is not a good indicator of the health damage.

Different from existing dynamic optimization studies on the water pollution, we use the economic cost (including both direct and indirect cost) of the disease incidence to form the health cost function. Extended from previous literature, we establish a dynamic optimization model that maximizes the net benefit of fertilizer usage minus the health cost of nitrate concentration in groundwater. By applying parameter values and functional forms to the theoretical model, we simulate the optimization model in three scenarios with different initial nitrate concentration levels: 3 mg/L, 10mg/L, and 30 mg/L.

The simulation results indicate that optimal fertilizer application rates are increasing over time for all three scenarios, with the lowest initial fertilizer application rate and highest increasing speed in the case of 30 mg/L nitrate concentration level. In addition, the nitrate concentration level is decreasing over time for the cases of 10 mg/L and 30 mg/L initial nitrate concentration level, but increasing at a small rate for the case of 3 mg/L initial nitrate concentration level. With high decay rate, however, nitrate concentration is decreasing even when the initial stock level is low. The trend of health cost is similar to the trend of nitrate concentration level since the health cost is assumed to be a function of the nitrate concentration level. The paper finds that at the end of the 50-year period, the optimal fertilizer usage rate in all the scenarios are approaching to the same value; and the nitrate concentration level and health cost in all the scenarios tend to be constant and steady.

Based on the sensitivity analyses, the nitrate decay rate, population, and disease incidence rate all affect the optimal fertilizer application paths, while only decay rate affects the nitrate concentration levels. This study also indicates that policymakers should manage fertilizer application rate based on the initial nitrate concentration levels. Fertilizer application should be strictly controlled at the initial period in the heavily polluted areas. Furthermore, technologies to increase the nitrate decay rate is also helpful to control the nitrate pollution.

4.2 Background

Nitrogen (N) is a key element for nutrient. Crop productivity is largely affected by the nitrogen availability in the soil. Farmers used to apply organic fertilizers, such as livestock manure to help improve the productivity of crops. However, with technology advancement, farmers start to apply the chemical fertilizers to help increase their income. The process that nitrogen gas (N2) convert to ammonium (NH4+) is called fixation. Because the chemical fertilizer is not expensive and easier to use, it largely increases the fixation speed. Furthermore, farmers tend to use excessive nitrogen, creating nitrate (NO3-) in the soil through a process called nitrification. Although nitrogen itself is not a pollutant, nitrate, is a water pollutant affecting public health. The impact has been known to include methemoglobinemia (blue-baby syndrome), adverse birth outcome and cancer (Hester et al. 1996; Powlson et al. 2008; Haden et al. 2016). The nitrate flows to groundwater mainly by leaching in the agriculture.

The bigger problem of nitrate is that it is relatively steady and can only convert to N2 though a slow chemical reaction called denitrification (Haden et al. 2016). It usually takes decades for nitrate to decay due to the high oxygen and low carbon in groundwater (Green et al.,2008). As more fertilizer usage break the balance of the natural nitrogen cycle, some nitrogen escapes from the surface cycle and store in the "dead zone"-groundwater. Since the decay speed of nitrate is too slow in groundwater, nitrate tends to accumulate in groundwater and threaten public health. It is also costly to clean up nitrate from groundwater and not practical in large scale treatment. Thus, the most cost-effective way to control nitrate pollution in groundwater is through nitrogen management. My research is focused on this kind of management in the agricultural context – the fertilizer management.

The United States Environmental Protection Agency (US EPA) sets the maximum contaminant levels (MCL) for Nitrate-N pollution as 10 mg/L for public drinking water supplies under the Safe Drinking Water Act (US EPA). Nitrate contamination of groundwater is becoming a public health threaten in US in recent years, especially in the areas with high agricultural activities. A study by Boyle et al. (2012) shows that 30%-45% of domestic wells in Fresno and Tulare Counties in California has exceeded the EPA MCL, and they estimate that the groundwater nitrate levels are increasing at rate of 0.061mg/L to 0.120mg/L per year.

Nitrate threatens public health when groundwater is the main source of drinking water. Nitrate is thought to be related to three types of medical conditions: methemoglobinemia (blue-baby syndrome), adverse birth outcome and cancer (Hester et al. 1996; Powlson et al. 2008; Haden et al. 2016). Methemoglobinemia happens when a lack of oxygen to the tissues in the body of infants which can be triggered if nitrate is taken by infants. There are mixed results from studies on the relationship between nitrate amount and methemoglobinemia. Thus, the health cost of this disease incidence is still inconclusive (Haden et al. 2016). Nitrate exposure is also thought to affect birth outcomes in several studies (Bukowski et al. 2001; Holtby et al., 2014). However, the magnitude and threshold of this impact is still uncertain (Haden et al. 2016). Nitrate might also relate to the several cancers: breast and genital cancers, brain cancers, stomach cancers, colon cancer, etc. Although uncertainty still exist in these studies, van Grinsven et al. (2010) is the only study that estimate the health damage of nitrate in groundwater based on the colon cancer incidence.

Some optimal control studies try to balance the relationship between agricultural activities and water pollution. Wang and Baerenklau (2014) conduct a dynamic analysis of groundwater nitrate pollution from Concentrated Animal Feeding Operations. The objective of their model is to maximize the net income, which equals to the profits from herd and crop production, less waste management, and the policy cost. They focus on the management of leaching and animal waste as well as the implication of the policy. Roseta-Palma (2002) considers both water quantity and water quality in his dynamic modelling of optimal groundwater extraction. However, the hole in these literature is lack of incorporating the health cost of nitrate pollution into the social planner’s objective function.

A few studies take into account the externality cost of water pollution. Yadav (1997) is the first to explore the dynamic relationship between agricultural production and groundwater pollution. Yadav (1997) also estimates the crop functions through case studies. Instead of using health cost, Yadav (1997) considers the cost to maintain the standard nitrate level. Eiwerth and van Kooten (2010) apply a dynamic optimization model to examine the optimal path of energy crop land use by considering the damage cost of water pollution. The water pollution in their model is connecting to the land use instead of agricultural management. And the benefit of the crop comes from the energy use. The major drawback in this research is that they consider the removal cost of phosphorous rather than health cost.

4.3 Theoretical Model

4.3.1 General Model Set-up

Consider a pure agricultural community with homogeneous farms that plant the same type of crop. To simplify, I assume the whole community is built on a single aquifer, with an area of A hectares. There is no surface water in the community, so the only water source is groundwater with a total volume of G_t in the aquifer. The only income source in this agricultural community is the revenue from harvesting crops, and I assume the only inputs affecting the harvest of the crop are nitrogen chemical fertilizers application rate F_t and irrigation rate I_t. So, other factors, like temperature, soil quality, irrigation are not considered in my model.

The stock pollutant I focus in this paper is the nitrate concentration in groundwater, which needs to satisfy

$$C_t = \frac{N_t}{G_t}$$

where C_t represents the nitrate concentration and N_t is the total nitrate amount in the community's groundwater stock at time t.

The equation of motion of changes in groundwater stock is simplified as

$$\dot{G}_t = -I_t - W_t + R_t \tag{1}$$

W_t is the residential usage of groundwater and R_t refers to the net natural groundwater recharge rate.

Extended from Yadav (1997) and Hellegers *et al.* (2001), the nitrate stock equation in our model is

$$\dot{N}_t = \eta A L(F_t, I_t) - \delta N_t + R_t C_t^R - (I_t + W_t) C_t \tag{2}$$

where $L(\cdot)$ is a function of nitrate leached per hectare determined by fertilizer application rate F_t and irrigation rate W_t. The function of L varies across different types of crops and soil conditions. A is the area of farmland (ha). η is a parameter describing the amount of nitrate leaching in the surface level that flows into the groundwater system at each time period; δ is the parameter representing the degradation rate of nitrate in groundwater. $\eta\ and\ \delta$ are all positive and less than 1. C_t^R is the nitrate concentration in the recharge flows.

I consider four determinants in this function. The first term represents the inflow of nitrate to groundwater caused by nitrate leaching that is not absorbed by crops. It should be noticed here that not all the nitrate in the soil flows to the groundwater directly, ηL of nitrate degrades at the surface area through chemical reactions. η is affected by factors that include the soil properties, weather conditions and surface characteristics. The second term indicates nitrate stock in the groundwater degrades at a speed δ through nitrification- a chemical process that transfers nitrate to nitrogen gas. δ is similar to the decomposition rate in the pollutant literature. In groundwater, δ is usually small and relatively steady. The third term is equal to the nitrate increase brought by the recharge inflows. Similarly, the fourth term means the nitrate reduction due to the groundwater extraction. Inspired by Hellegers *et al.* (2001), we include the third and fourth term to capture the dynamic nitrate concentration changes caused by groundwater changes. Thus, our motion equation of changes in nitrate concentration is

$$\dot{C_t} = \left(\frac{\dot{N_t}}{G_t}\right) = \frac{\dot{N_t} \cdot G_t - \dot{G_t} \cdot N_t}{{G_t}^2} = \frac{\dot{N_t} - \dot{G_t} \cdot C_t}{G_t}$$

Substitute (1), (2) and simplify, we get

$$\dot{C_t} = \frac{\eta AL(F_t, I_t) + R_t(C_t^R - C_t)}{G_t} - \delta C_t \tag{3}$$

Suppose the net benefit to the community from planting crops is extended from Eiwerth and van Kooten (2010), given by the following relation:

$$E_t = B(F_t, I_t) - D(C_t) \tag{4}$$

where E_t stands for the net benefit at time t ; $B\ (\cdot)$ is the net revenue function from cultivating crops. F_t is the amount of fertilizers applied per hectare at time t; I_t refers to the irrigation rate at time t. Since this paper is only interested in the nitrogen in fertilizer, we define F to be the amount of nitrogen in the fertilizer used for crop planting. Irrigation is also a key input that determines the crop yields and we also assume the water used for irrigation is purely from the community's groundwater stock. $D\ (\cdot)$ is health damage function caused by Nitrate concentration in the groundwater with $D_C > 0$. Although Eiswerth and Kooten (2010) assume $D_{CC} > 0$, it might not be true when the pollutant stock is extremely large so that people cannot get sicker if they are nearly mortal. It might be true when the pollutant is small and close to the threshold. Few studies have been conducted on the health impact of nitrate, so I leave D_{CC} as unspecified in the general model part. The crop net revenue function is defined as

$$B(F_t, I_t) = A[Y(F_t, I_t\,) \cdot P_c - F_t \cdot P_F\, - I_t \cdot P_I] \qquad (5)$$

where $Y(\cdot)$ is the crop yield function determined by the applied amount of fertilizer F_t and irrigation rate I_t per hectare ; P_c , P_F are the exogenous prices of crop and fertilizer; P_I is the per cubic meter cost of pumping groundwater for irrigation; A is the area cultivated for the crop. The first term of right hand side of the equation is the revenue from crops. The second term and third term represent the cost of inputs. The yield function is assumed to be concave in F_t and I_t , which indicates $Y_F > 0, \quad Y_{FF} < 0, Y_I > 0, Y_{II} < 0\,, Y_{FI} > 0$. This assumption of diminishing return to production is very common in the economics literature, and it also realistic because the marginal product from fertilizer is smaller and eventfully approaches to zero when the application amount increases to a certain limit.

Next, consider a social planner of this community tries to maximize the net benefit in equation (4).

$$max_{F,I} \int_0^T e^{-rt}[B(F_t, I_t) - D(C_t)]dt$$

Combine equations (1) - (5), the optimization problem is

$$max_{F,I} \int_0^T e^{-rt}\{A[Y(F_t, I_t\,) \cdot P_c - F_t \cdot P_F\, - I_t \cdot P_I] - D(C_t)\}\, dt$$

$$s.t \qquad \dot{C}_t = \frac{\eta AL(F_t, I_t) + R_t(C_t^R - C_t)}{G_t} - \delta C_t$$

$$\dot{G}_t = -AI_t - W_t + R_t$$

$$C(0) = C_0$$

$$C(T)\, free$$

where r is the social discount rate. I consider this problem as a finite time problem, for example, the policy maker only target at a certain period that he will be in charge.

4.3.2 A simple model with constant groundwater stock

First, Let's consider a case that the community values their only water source and would like to keep the groundwater level constant overtime, which means $\dot{G}_t$=0 and $G_t = \bar{G}$. To further simplify, we also assume the I_t, W_t and R_t are well controlled by the community and set to be fixed at $\bar{I}$, $\bar{W}$and $\bar{R}$.

The maximizing problem becomes

$$max_F \int_0^T e^{-rt}\{A[Y(F_t,\bar{I}) \cdot P_c - F_t \cdot P_F - \bar{I} \cdot P_I] - D(C_t)\}\, dt$$

$$s.t \qquad \dot{C}_t = \frac{\eta AL(F_t,\bar{I}) + \bar{R}(C_t^R - C_t)}{\bar{G}} - \delta C_t$$

$$C(0) = C_0$$

$$C(T)\, free$$

Assuming an interior solution to the optimization problem, the current value Hamiltonian to this optimization problem is

$$H_c = A[Y(F_t,\bar{I}) \cdot P_c - F_t \cdot P_F - \bar{I} \cdot P_I] - D(C_t) + \mu[\frac{\eta AL(F_t,\bar{I}) + \bar{R}(C_t^R - C_t)}{\bar{G}} - \delta C_t]$$

where μ is the current value costate variable associated with the current-value Hamiltonian which also represents the shadow value of the nitrate concentration stock. The necessary conditions for a solution are

$$\frac{\partial H_c}{\partial F} = A(Y_F P_c - P_F) + \mu \frac{\eta AL_F}{\bar{G}} = 0 \qquad (6)$$

$$\frac{\partial H_c}{\partial C} = -D_C - \mu(\frac{\bar{R}}{\bar{G}} + \delta) = r\,\mu - \dot{\mu} \qquad (7)$$

$$\frac{\partial H_c}{\partial \mu} = \frac{\eta AL(F_t,\bar{I}) + \bar{R}(C_t^R - C_t)}{\bar{G}} - \delta C_t = \dot{C} \qquad (8)$$

$$C(0) = C_0 \tag{9}$$

$$\mu(T) = 0 \tag{10}$$

Equation (6) indicates that the control variable F should be chosen so that the marginal benefit of fertilizer equals the marginal damage of fertilizer through its impact on the future nitrate stock. Equation (7) provides the optimal solution that equals the marginal contribution of nitrate stock with the marginal contribution of the current stock through its impact on the future stock and function of the change rate in shadow values of nitrate stock. The derivate of shadow value of the pollution with respect to time increases with the discount rate, marginal damage of stock pollutant and the degradation rate. Equation (8) indicates the derivate of current value Hamiltonian with respect to time is equal to the state function. The change rate of nitrate concentration stock is affected by fertilizer usage, current stock, degradation rate and conversion rate. Equation (9) is the initial condition of nitrate stock. Equation (10) is the transversally condition that indicates the shadow value of the stock at the end of period is equal to 0. Rearrange Equation (6)

$$\mu = (P_F - Y_F P_c) \cdot \frac{\bar{G}}{\eta A L_F} \tag{11}$$

Take first order derivative with respect to t

$$\dot{\mu} = -P_c Y_{FF} \dot{F} \frac{\bar{G}}{\eta A L_F} + (P_F - Y_F P_c) \frac{\bar{G}}{\eta A} \frac{L_F - L_{FF}}{{L_F}^2} \dot{F} \tag{12}$$

Substitute (11) and (12) into (7) and rearrange

$$\dot{F} \frac{\bar{G}}{\eta A L_F} \left[-P_c Y_{FF} + (P_F - Y_F P_c) \frac{L_F - L_{FF}}{L_F} \right] = \left(r + \delta + \frac{\bar{R}}{\bar{G}} \right) (P_F - Y_F P_c) \frac{\bar{G}}{\eta A L_F} + D_C$$

$$\dot{F} = [\left(r + \delta + \frac{\bar{R}}{\bar{G}}\right)(P_F - Y_F P_c) \cdot \frac{\bar{G}}{\eta A L_F} + D_C] \cdot \frac{\eta A L_F}{\bar{G}} \cdot \frac{L_F}{-P_c Y_{FF} L_F + (P_F - Y_F P_c)(L_F - L_{FF})}$$

Simplify

$$\dot{F} = \left[\left(r + \delta + \frac{\bar{R}}{\bar{G}}\right)(P_F - Y_F P_c) + D_C \frac{\eta A L_F}{\bar{G}}\right] \frac{L_F}{-P_c Y_{FF} L_F + (P_F - Y_F P_c)(L_F - L_{FF})} \tag{13}$$

Setting $\dot{F} = 0$ gives the steady-state condition for F:

$$\frac{\left(r + \delta + \frac{\bar{R}}{\bar{G}}\right)(Y_F P_c - P_F)\bar{G}}{L_F} = D_C \eta A \tag{14}$$

Total differentiate

$$\left(r + \delta + \frac{\bar{R}}{\bar{G}}\right)\bar{G}\frac{Y_{FF} P_c L_F - (Y_F P_c - P_F)L_{FF}}{{L_F}^2} dF = \eta A D_{CC} dC$$

Thus

$$\frac{dC}{dF} = \frac{\left(r + \delta + \frac{\bar{R}}{\bar{G}}\right)\bar{G}M}{\eta A D_{CC} {L_F}^2} \tag{15}$$

where $M = Y_{FF} P_c L_F - (Y_F P_c - P_F)L_{FF}$.

Since $\frac{\left(r+\delta+\frac{\bar{R}}{\bar{G}}\right)\bar{G}}{\eta A {L_F}^2} > 0$, the sign of $\frac{\mathrm{d}C}{\mathrm{dF}}$ depends on the sign of D_{CC} and M which are unspecified in the general model. According to the nitrate leaching function and crop response function from Peña-Haro *et al.*(2009), M should be negative. If $D_{CC} > 0$, $\frac{dC}{dF}$ is negative, which means $\dot{F} = 0$ isocline is downward sloping; If $D_{CC} < 0$, $\frac{dC}{dF}$ is positive, which means $\dot{F} = 0$ isocline is upward sloping.

Similarly, setting $\dot{N} = 0$ in Equation (8) yields

$$\eta L(F_t) = (\delta\bar{G} + \bar{R})C_t - \bar{R}C_t^R \tag{16}$$

$$\frac{dC}{dF} = \frac{\eta A L_F}{\delta\bar{G} + \bar{R}} \tag{17}$$

Since L_F, η, δ are all positive, the slope of $\dot{N} = 0$ isocline is positive.

4.3.3 Joint management of fertilizer and irrigation

Irrigation rate affect crop yields, nitrate leaching and groundwater stock. When the irrigation rate increases, crop yields is higher which brings more benefits; nitrate leached increases which leads to higher nitrate stock and concentration in groundwater; and groundwater stock decreases which might leads to even higher nitrate concentration.

If we consider the joint management of fertilizer and irrigation, by adding I_t as the second control variable and relax the consumption of constant groundwater stock. The Hamiltonian function becomes

$$H_c = A[Y(F_t, I_t) \cdot P_c - F_t \cdot P_F - I_t \cdot P_I] - D(C_t) + \mu\left[\frac{\eta A L(F_t, I_t) + \bar{R}(C_t^R - C_t)}{G_t} - \delta C_t\right]$$

$$+ \lambda[-AI_t - \bar{W} + \bar{R}]$$

First order conditions are

$$\frac{\partial H_c}{\partial F} = A(Y_F P_c - P_F) + \mu\frac{\eta A L_F}{G_t} = 0$$

$$\frac{\partial H_c}{\partial I} = A(Y_I P_c - P_I) + \mu\frac{\eta A L_F}{G_t} - A\lambda = 0$$

$$\frac{\partial H_c}{\partial C} = -D_C - \mu\left(\frac{\bar{R}}{G_t} + \delta\right) = r\,\mu - \dot{\mu}$$

$$\frac{\partial H_c}{\partial G} = -\mu\frac{\eta A L(F_t, I_t) + \bar{R}(C_t^R - C_t)}{{G_t}^2} = r\lambda - \dot{\lambda}$$

$$\frac{\partial H_c}{\partial \mu} = \frac{\eta A L(F_t, I_t) + \bar{R}(C_t^R - C_t)}{G_t} - \delta C_t = \dot{C}$$

$$\frac{\partial H_c}{\partial \lambda} = -AI_t - \bar{W} + \bar{R} = \dot{G}$$

4.4 Numerical Example

My numerical example examines the optimal fertilizer application rate over time under different scenarios. The crop type I focus in this paper is corn used for grain purpose. Some types of corn are planted for energy purpose. Their economic values are different from corn for grain, so I only consider the case of corn for grain in this paper. Several studies have been conduct to examine the corn response function to nitrogen fertilizer. Yadav (1997) discusses different types of functional forms of corn-response function (quadratic, Von Liebig and Mit-Banle) and estimates the crop response based on quadratic form. Quadratic form is the most popular functional form used in crop yields function, based on Peña-Haro *et al.*(2009), the corn yield function in our model is

$$Y(F, I) = -13 + 0.038I - 0.000024I^2 + 0.0067F - 0.000072F^2 + 0.0000517IF$$

where F is the fertilizer application rate (kg) per hectare (ha) of crop land; I is the water applied for irrigation (m^3/ha) ; $Y(F, I)$ is the corn yields per hectare (kg/ha). According to this function, $Y_F = 0.0067 - 0.000144F + 0.0000517I$, $Y_{FF} = -0.000144$, satisfies our assumption that $Y_F > 0\ and\ Y_{FF} < 0$ when the fertilizer application rate is below $(465.28 - 0.36I)$kg/ha. Thus, it seems reasonable to be used as the yield function in my application.

Nitrate leaching function calculates the amount of nitrates leached associated with fertilizer application rate and irrigation rate. Nitrate leaching also depends on crop and soil characteristics. In this paper, we apply the nitrate leaching function of corn from Peña-Haro *et al.*(2009).

$$L(F, I) = 0.0044I - 0.0000669I^2 + 0.396F$$

where $L(F, I)$ is the nitrogen amount in nitrates leached (kg/ha).

Three major health damage from drinking water with high level of nitrate has been found in previous studies: methemoglobinemia (blue-baby syndrome), adverse birth outcome and cancer (Haden *et al.* 2016). However, the magnitude of the first two health impact is uncertain. Our health damage function is based on the research by van Grinsven *et al.* (2010) that estimate colon cancer incidence caused by nitrate pollution in groundwater. van Grinsven *et al.* (2010) estimate that 3% increase of colon cancer incidence is associated with 5.63mg/L nitrate contamination of groundwater. I use a quadratic function form to represent health damage from water pollution as

$$D(N) = E(B \cdot N + C \cdot N^2)$$

where $(B \cdot N + C \cdot N^2)$ is the increase in the disease incidence and E is

$$E = Cost \cdot Incidence\ Rate \cdot (\frac{POP}{100000})$$

where $Cost$ is the economic cost per colon cancer incidence per year; $Incidence\ Rate$ is the current colon cancer incidence per 100000 per year; POP is the total population in the community. Since the actual health damage remains unproven, I will also conduct sensitivity analysis on higher health risk which represent as a higher c in the damage function. The health cost is also sensitive to population density, i.e community with higher population density occurs higher health cost. Thus, a sensitivity analysis that applies higher population is also conducted.

Table 4.1 presents the parameter values. η is determined from a study conducted by Roseta-Palma (2002); γ is derived from the book by Haden *et al.* (2016); P_c is estimated based on corn commodity price[8]; P_F is from NMSU ACES website[9]. δ is the decay speed of nitrate in groundwater and it depends on geographic and groundwater conditions. Nitrate decays very slow in groundwater and can takes decades to complete denitrification process. I assume the δ to be 0.1 in the baseline case and conduct sensitivity analysis for different values of δ.

According to Brown *et al.* (2001), the incidence of colon cancer is 43.9 per 100,000 population and the cost of illness of cancer is \$99,960 per incidence per year in 1996 US dollar value, which is equivalent to \$155,198 per incidence per year in 2017 US dollar value. The population is assumed to be 30,000 in this community in the baseline case. Therefore, E is equal to \$2,043,957 in the baseline case. Based on van Grinsven *et al.* (2010), I use the trendline tool in the Excel and come up with the following functional form

$$D(N) = 2{,}043{,}957\ (0.0007 \cdot N + 0.0008 \cdot N^2)$$

Furthermore, I assume the height of aquifer GH is 50 meters; total area of farming land is 10,000 hectares; the social discount rate r is 0.05.

4.5 Baseline Results

Three scenarios of initial nitrate concentrations are considered in my simulation: 3mg/L, 10mg/L and 30mg/L. The initial nitrate concentration is essential to the optimal decision of fertilizer management. When the initial nitrate concentrate is low, for example, 3mg/L, the health cost is also relatively low. Then it might be the case that the nitrate concentration level becomes higher over time. 10 mg/L is the safe drinking water standard by US EPA, which is my second scenario. 10 mg/L is a moderate risk and not ideal for sensitive groups. I expect the nitrate level decreases to a more accepted level in

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[8] http://www.indexmundi.com/commodities/?commodity=corn

[9] http://aces.nmsu.edu/pubs/_a/A133/welcome.html

this case. In the third scenario, the initial nitrate concentration level is assumed to be 30 mg/L, which is considered to be very high. In this scenario, the nitrate concentration is expected to decrease over time. With the optimal fertilizer application path over time, the nitrate concentration level is expected to drop dramatically.

In all the simulations, I use a time period of 50 years. The social planner tries to find the optimal fertilizer application rate that maximize the sum of present value of net benefits from each year. Figures 4.1-4.7 show the simulation results of all the three scenarios. Figure 4.1 is the optimal path of the fertilizer application rate to all the farming land for the baseline case. It's interesting to see that optimal fertilizer application rate under all the three scenarios are increasing over time. The higher the initial nitrate concentration level, the quicker the optimal fertilizer rate is increasing over time. Note that at the end of the 50-year period, the optimal fertilizer application rates are almost the same for all the three cases. The intuition behind this figure is straightforward. Since the initial net benefits in the regions with high level of nitrate concentration are much lower than those with low level of nitrate concentration, they need lower fertilizer concentration rates to keep the nitrate concentration decreasing to the optimal level. And after they reach the optimal nitrate concentration levels, their fertilizer usage rate will be almost the same as other regions.

Figures 4.4-4.6 present the trend of the stock of nitrate concentration in groundwater. The nitrate concentration level is decreasing rapidly in regions with initial high nitrate concentration and relatively slower in regions with initial moderate nitrate concentration. Regions with low initial nitrate concentration level face an increasing trend in their nitrate stock, though the total increasing level is only about 0.44 mg/L.

Regions with high pollution tend to decrease because the health cost is too high at the beginning period. The decreasing speed becomes slower over time because the opportunity cost to continue decreasing stock pollutant is higher than before. Eventually, the stock nitrate concentrate will be constant at a certain level, which is called the steady state.

Figure 4.7 shows the health cost over time. Since the health cost is a function of nitrate concentration, the trend of health cost is also similar to the trend of the nitrate stock. It is noticeable that the health cost in the scenario of initial high nitrate level is proportionally higher than the health cost in the scenario of moderate nitrate level. It indicates that the marginal health damage is larger as the nitrate concentration level increase. Again, health cost under all the three scenarios are approaching to a constant level. As we can see from the figure, the health cost is huge, as much as 1.52 million US dollars per year at the beginning period and 0.68 million US dollars at the end of the period in the scenario of initial 30mg/L nitrate concentration. However, this cost only consider the incidence of colon cancer caused by nitrate, which ignores cost from other diseases due to the lack of relevant studies in estimating the magnitude of the other health impact. It is very likely that the real health cost is much higher than this and would result in a lower steady state nitrate concentration level.

4.6 Sensitivity Analysis

Because of the uncertainty of the parameter values and functional forms, I also conduct several sensitivity analyses by changing some parameters values.

First I change the value of δ to 0.2 and 0.05 to represent the case with higher and lower nitrate decay rate. The fertilizer application rate paths are shown in Figure 4.2. In the case of high decay rate, the fertilizer application rate is a little higher in the beginning period, and increase at a little lower speed than the baseline case. It makes sense because high decay rate means the outflow of stock pollutant is larger, more nitrate inflow could be allowed through applying more fertilizers. In the case of low decay rate, fertilizer application rate is lower to compromise he lower outflow of nitrate stock. Figures 4.4-4.6 present the nitrate concentration rate in high and low decay rate cases, as well as the baseline case. In the scenario of low initial nitrate stock, nitrate concentration is decreasing when the decay rate is high, while increasing when the decay rate is low and baseline. In the other two scenarios, although nitrate concentration is decreasing with different decay rates, the decreasing speed is slower with lower decay rate. Eventually, the higher the decay rate, the lower the nitrate stock at the end of the period.

The second sensitivity analysis is conducted by replacing with a higher population. This analysis is necessary because the different population density could also affect the total disease incidence and health cost. Figure 4.3 shows the fertilizer application rate by doubling the population of the baseline case. The fertilizer application rates are again lower than the baseline case at the beginning period to compensate the higher health cost cause by higher population. Eventually, at the end of the period, the fertilizer application rate is similar to the baseline case. However, the nitrate concentration trend is almost the same as the baseline case, which lead to a similar slope but higher level of health cost over time (shown in Figures 4.4-4.7).

To test how the result would be different for a different functional form of health damage function, I undertake the third sensitivity analysis by simply replacing C with a larger value which represent a higher disease incidence. The results again shows a lower fertilizer application rate at the beginning period (Figure 4.3) , but almost same trend in the nitrate concentration stock (Figures 4.4-4.6). The health cost is also highest compared to baseline and high population cases.

From the results of last two sensitivity analyses, it seems that the change in the health cost function wouldn't affect the nitrate stock over time. However, the optimal fertilizer application rates are quite different over time to incorporate the change in the total health cost.

4.7 Conclusion

The main objective of this paper is to find the optimal fertilizer application rate in agriculture by incorporating the health cost from nitrate pollution in groundwater. I establish a dynamic optimization model that maximize the net benefit of fertilizer usage minus the health cost of nitrate concentration in groundwater.

By applying parameter values and functional forms to the theoretical model, I simulate the optimization model in three scenarios with different initial nitrate concentration levels: 3 mg/L, 10 mg/L and 30 mg/L. The optimal fertilizer application rates are increasing over time for both three cases, with the lowest initial fertilizer application rate and highest increasing speed in the case of highest nitrate concentration level. In addition, the nitrate concentration level is decreasing over time for cases of 10mg/L and 30 mg/L initial nitrate concentration level, but increasing at a small rate for the cases of 3 mg/L initial nitrate concentration level. However, with high decay rate, nitrate concentration is decreasing even when the initial stock level is low. The trend of health cost is similar to the trend of nitrate concentration level since the health cost is assumed to be a function of the nitrate concentration level. I also find that at the end of the 50-year period, the optimal fertilizer usage rate in all the three scenarios are approaching to the same value; and the nitrate concentration level and health cost in all the three scenarios tend to be constant and steady.

In the sensitivity analyses, I find the nitrate decay rate, population and incidence rate all affect the optimal fertilizer application paths, while only decay rate actually affect the nitrate concentration levels.

Health cost could be as much high as 1.52million US dollars in my simulations. Without taking into account this health cost, the optimal fertilizer managing will not be social optimal. Policy makers should note the health cost could be potentially larger by adding up all the health cost of nitrate-related morbidity and mortality. The policies regarding this externality include: mandatory nitrate concertation standard and incentives to encourage less chemical fertilizer usage. US EPA (Environmental Protection Agency) currently set the nitrate standard as 10 mg/L. Based on my simulation result, I think this standard might not be lower than social optimal in the areas with high initial nitrate levels. When implementing environmental policies, it is also essential to consider the initial pollution condition in different regions.

4.8 Limitations and Future Work

This research has a lot of limitations. First, it does not consider the change in groundwater level in aquifer. Since irrigation from groundwater causes high variations in groundwater level and thus variations in nitrate concentration. It’s important to consider the change in groundwater by controlling irrigation which might also impact the crop production. Second, we only consider the nitrate in groundwater other than surface water. In reality, surface water is a part of water system and should not be overlooked.

Third, people can help reduce nitrate in groundwater by leaching abatement or remove the nitrate from groundwater at a high expense. This research does not take into account the other treatment. Fourth, excessive fertilizer usage also reduces the fertility of soil that impact the crop productivity which should endogenously affect the optimal fertilizer usage. Finally, this research assumes the policymakers only make plans for 50 years which may not be the case in the real life. If the planning time is long enough, it is possible that the fertilizer application rate and nitrate concentration reach the steady state. A potential future work of this study is to look at the steady states mathematically and discuss the case of longer policy years.

Figure 4.1: Optimal Fertilizer Application Rate: Baseline Case

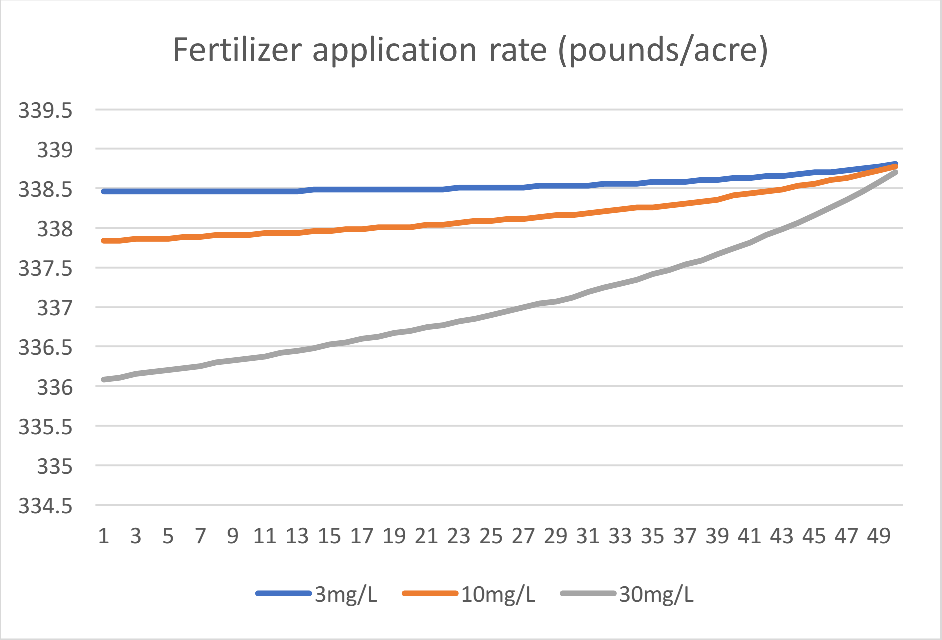
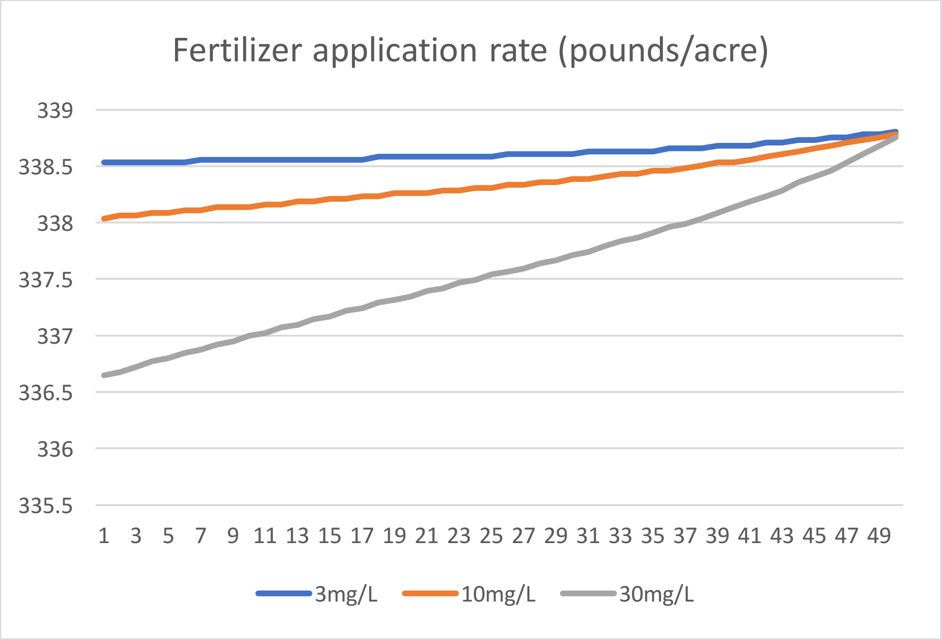


Figure 4.2: Optimal Fertilizer Application Rate: Different Decay Rate

(a) High Decay Rate



(b) Low Decay Rate

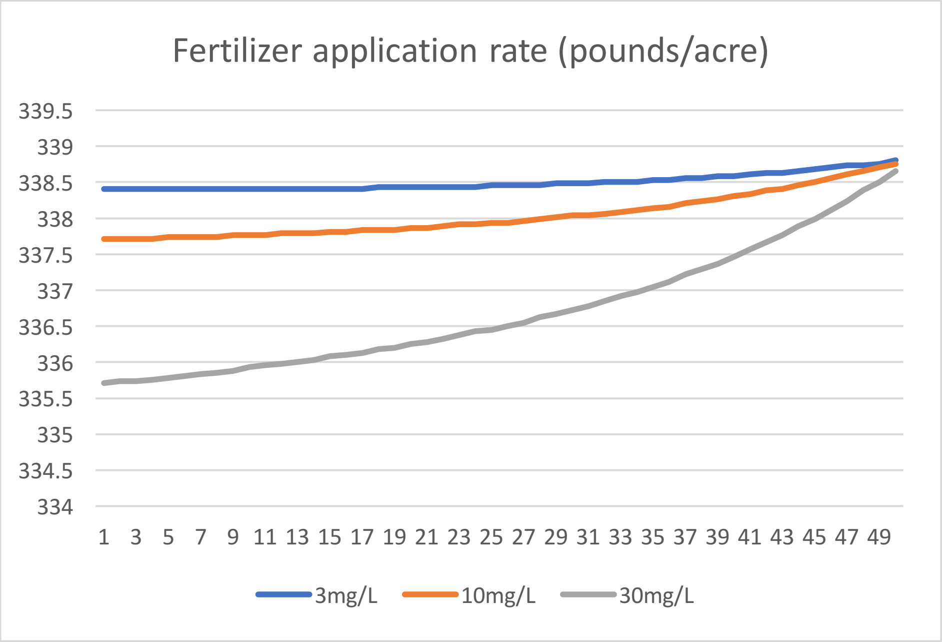
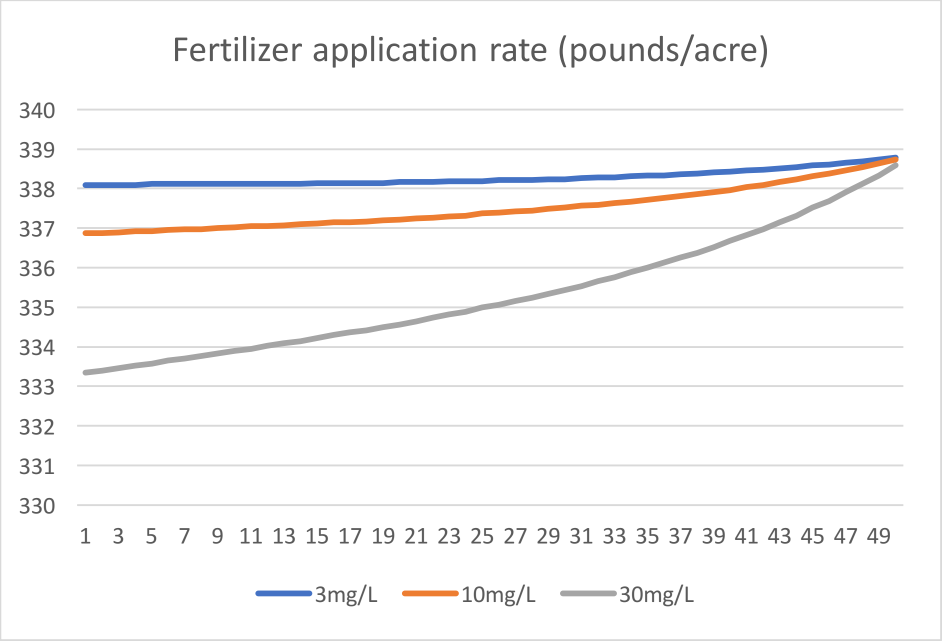


Figure 4.3: Optimal Fertilizer Application Rate: Higher Population and Caner Incidence

(a) Higher Population



(b) Higher Cancer Incidence

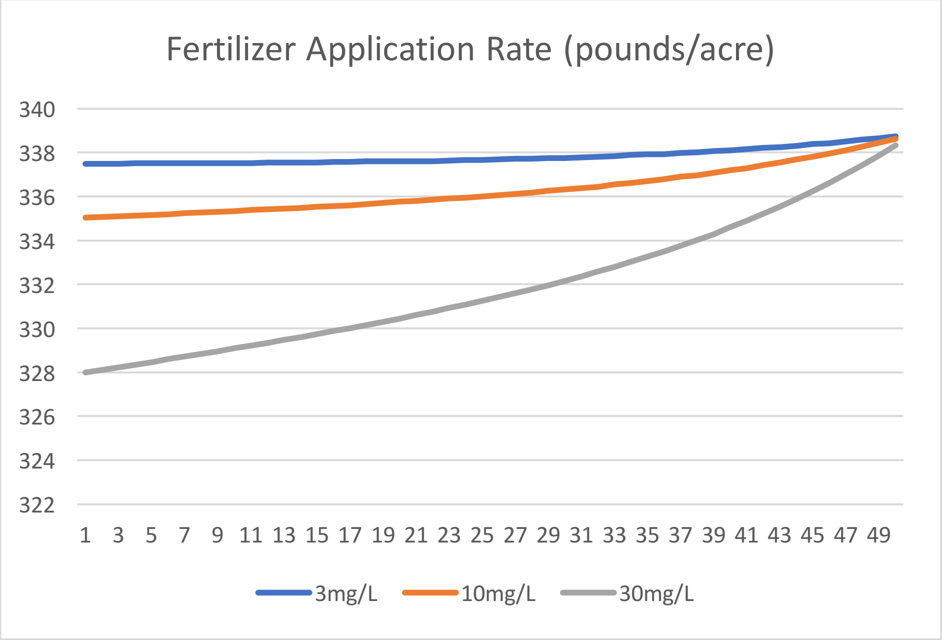
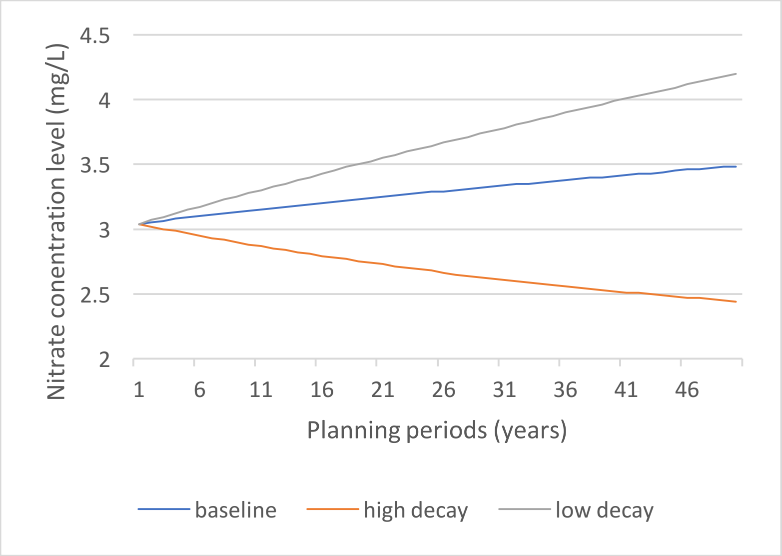


Figure 4.4: Nitrate Concentration Level in Scenario 1 (3mg/L initial value)



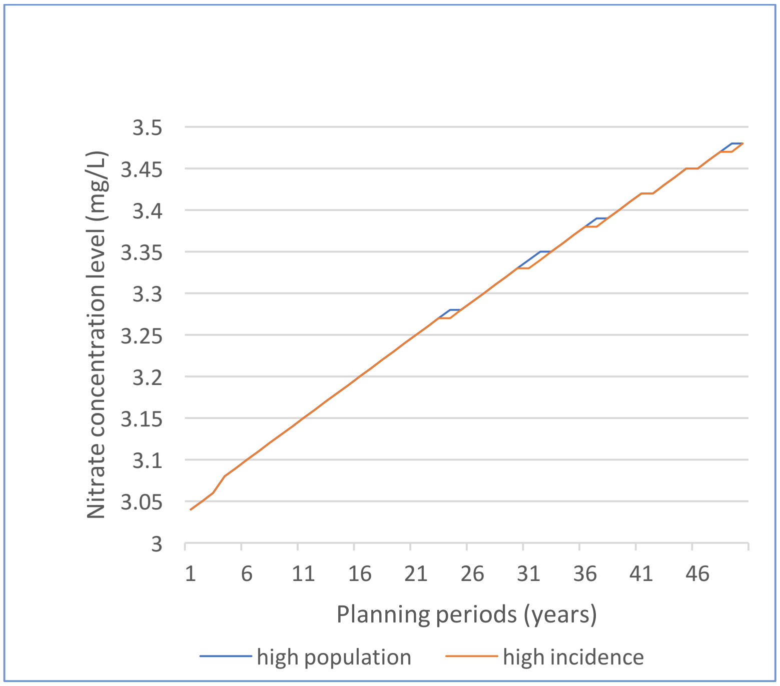
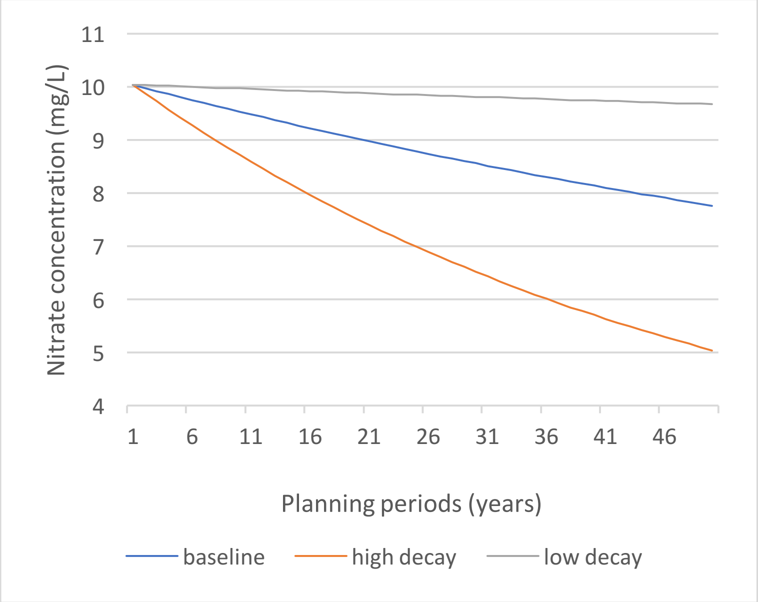


Figure 4.5: Nitrate Concentration Level in Scenario 2 (10mg/L initial value)



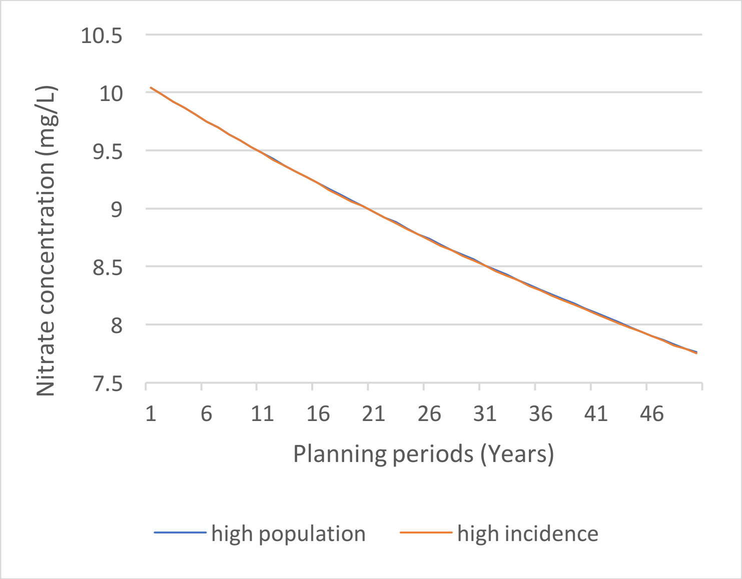
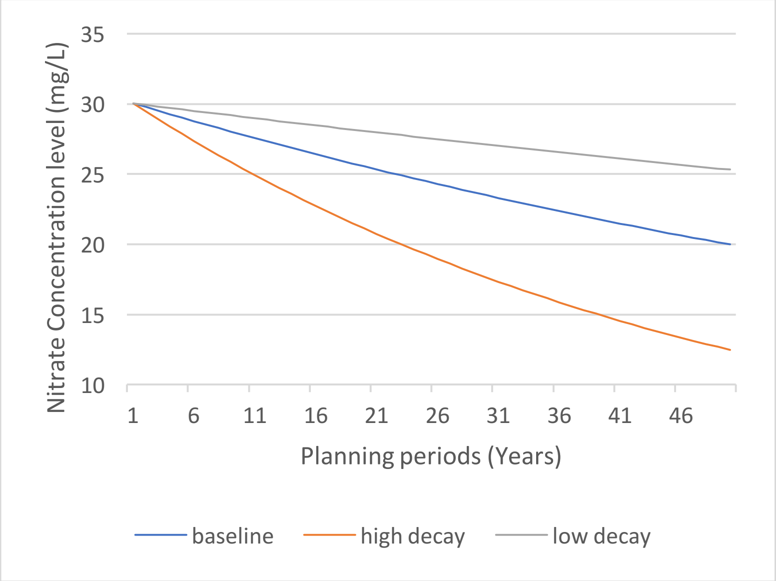


Figure 4.6: Nitrate Concentration Level in Scenario 3 (30mg/L initial value)



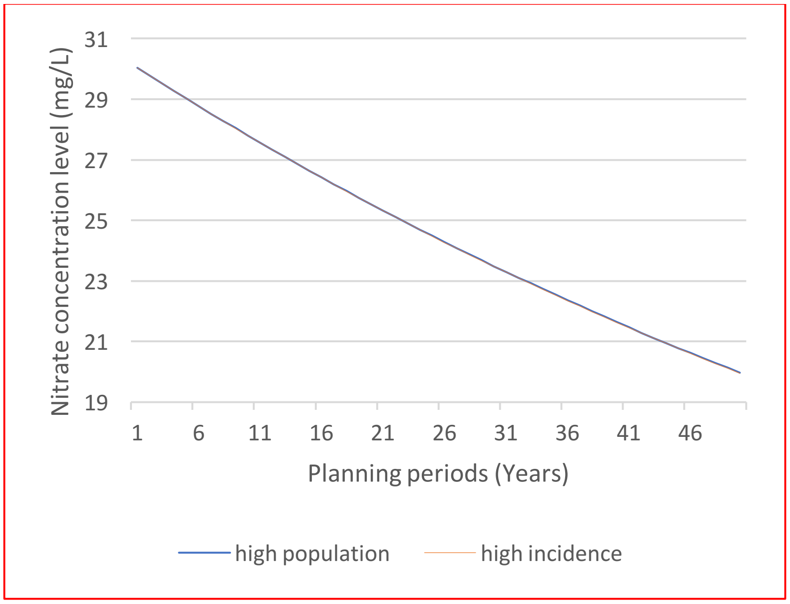
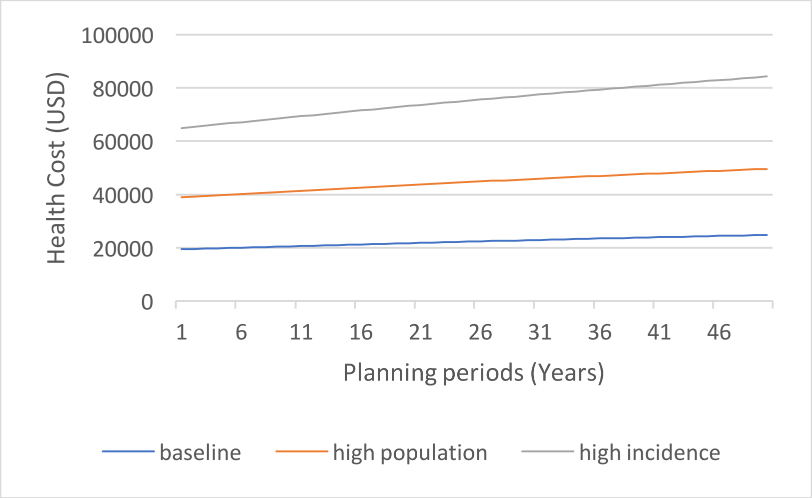
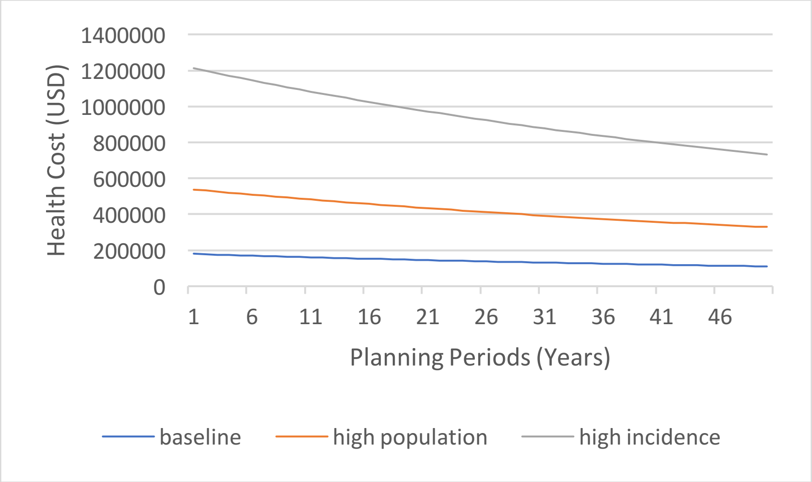


Figure 4.7: Health Cost

(a) Scenario 1 (3mg/L initial value)



(b) Scenario 2 (10mg/L initial value)



(c) Scenario 3 (30mg/L initial value)

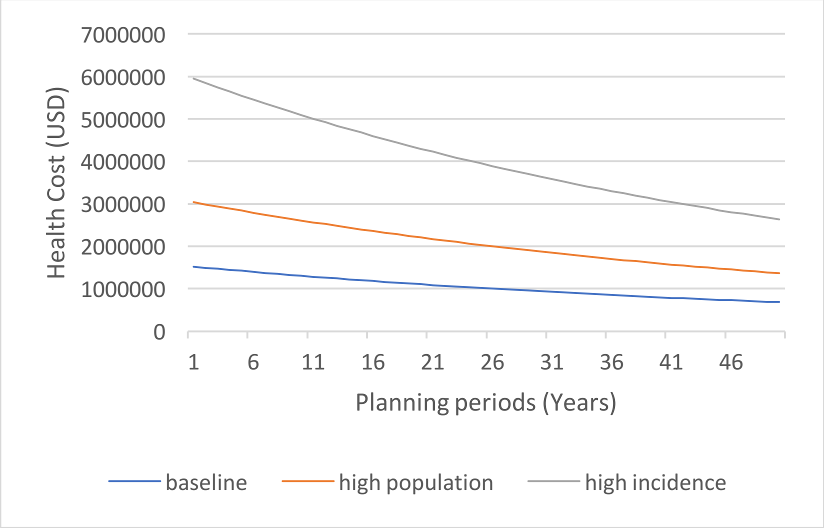


Table 4.1: Description and value of parameters

Parameter	Description	Baseline Value	Units
η[10]	Scaling parameter describing rate of leached nitrate flows into groundwater	0.9	1
δ[11]	Degradation rate of nitrate in groundwater	0.1	1
P_w[12]	Cost of groundwater extraction	0.1	USD/m^3
P_c[13]	Price of corn per kilogram	0.16	USD/kg
P_F[14]	Price of fertilizer per kilogram	0.75	USD/kg
Cost[15]	Economic cost per incidence per year	155,198	USD
$Incidence$[16]	Colon cancer incidence per 100,000 per year	43.9	per 100,000
POP	Population in community	30,000	person
A	Area of farming land	3,600	hectare[17]
G	Volume of groundwater in aquifer	5,000,000	cubic meter
R	Recharge flow to groundwater	3,900,000	cubic meter
CR	Nitrate concentration in recharge flow	20	mg/L
I	Irrigation rate	700	m^3/ ha
r	Social discount rate	0.05	1

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[10] Haden *et al.* (2016)
[11] Roseta-Palma (2002)
[12] USGS website
[13] based on commodity price of corn: http://www.indexmundi.com/commodities/?commodity=corn
[14] NMSU ACES website: http://aces.nmsu.edu/pubs/_a/A133/welcome.html
[15] Brown *et al.* (2001)
[16] van Grinsven *et al.*(2010)
[17] 1 hectare=2.47 acre

Chapter 5: Conclusion

Modern agricultural development solves the basic feeding problems for poor people in the developing areas, but also brings a series of environmental issues. Water pollution, especially nitrate contamination, is the most severe externalities that harm public health, caused by excessive use of chemical fertilizers in agriculture. However, the impact of agricultural water pollution is not well studied in previous literature. The contributions of Chapter 2 are threefold. First, it extends the research on the health impacts of agricultural water pollution. The health impact of water pollution is not a new topic, however much of the existing research does not specifically examine the impact of water pollution due to agricultural activities. Second, most of the current evidence on the relationship between water quality and health from household-level studies use water access or water source as a proxy for exposure to water pollution but lacks actual water quality measurements. I am the first that I am aware of to link administrative water quality data with household data in China. Third, I am also the first that I am aware of to explore the effect of agricultural water pollution on early childhood health using household survey data. The main limitations of this research include: it is possible that the 2006 agricultural support policies also impacted the local non-agricultural economy in ways that also affect water quality; the water quality data might not perfectly capture the households' drinking water pollution level.

Knowing the negative effect doesn't mean we should object to the agricultural policies. In developing countries where some poor people still live without enough food, such policies is very important to help them improve nutrition and health status. But the effectiveness of such polices could easily be overlooked due to unexpected disturbance.

The third chapter's major contribution is examining the effectiveness of China's agricultural supporting policies in the view of both income effect and pollution effect. The limitations of this research include: the income change might not capture the change in the real health investment and avoidance behavior; some unknown factors associated with the polices might also affect the health outcomes.

Agricultural management should incorporate the negative health impact caused by agricultural water pollution. Chapter 4 contributes to existing research by quantifying the health cost of nitrate pollution and adding it into the classic profit optimization problem. It also discusses the current nitrate standard in the simulations which is not common in previous studies. However, this research has limitations, like not considering the complications of the groundwater change in aquifer and only focusing on the fertilizer management.

Appendices A:

Table A.1: Estimated Effect of Agricultural Water Pollution on Health Post 2006 - Using Province-Level Water Pollution Index

	All age		Age 18 and above	Age below 18	
	(1) Sick	(2) Diarrhea	(3) BMI	(4) BMI Z-Score	(5) Height-For-Age Z-Score
Post 2006 X Water Pollution Index	0.0215***	0.00921***	-0.0321	-0.0328	-0.0610
	(0.00625)	(0.00250)	(0.0274)	(0.0588)	(0.0466)
Water Pollution Index	0.0907***	0.0159***	-0.0172	-0.201	-0.162
	(0.0140)	(0.00525)	(0.0836)	(0.158)	(0.113)
Post 2006	0.0871	-0.0792**	0.554	-0.323	0.302
	(0.0906)	(0.0353)	(0.525)	(0.568)	(0.411)
Individual Fixed Effects	Yes	Yes	Yes	Yes	Yes
Observations	38525	38489	31011	4919	4995

Note: Significant levels are indicated by *** $p<0.01$, ** $p<0.05$, * $p<0.1$. All results include the following controls: gender, minority group, age, age squared, preventive medical service, calorie intake, unhealthy diet, livestock raising, tap water access, flush toilet, excreta near house, log income

Table A.2: Estimated Effect of Early Childhood Agricultural Water Pollution Exposure on Health - Using Province-Level Water Pollution Index

	Age 6 and below	
	(1) BMI Z-Score	(2) Height-For-Age Z-Score
Born after 2006 X Water Pollution Index	-0.188	0.130
	(0.136)	(0.109)
Born after 2006	0.537	-0.193
	(0.383)	(0.338)
Water Pollution Index	0.0152	-0.180
	(0.256)	(0.217)
Year Fixed Effects	Yes	Yes
Community Fixed Effects	Yes	Yes
Observations	1393	1434

Note: Significant levels are indicated by *** p<0.01, ** p<0.05, * p<0.1. All results include the following controls: gender, minority group, age, age squared, preventive medical service, calorie intake, unhealthy diet, livestock raising, tap water access, flush toilet, excreta near house, log income

Table A.3: Estimated Effect of Agricultural Water Pollution on Health Based on Access to Treated Water - Using Province-Level Water Pollution Index

	All age		Age 18 and above	Age below 18	
	(1) Sick	(2) Diarrhea	(3) BMI	(4) BMI Z-Score	(5) Height-For-Age Z-Score
Untreated water X Post 2006 X Water Pollution Index	-0.0159	-0.000962	-0.0949**	0.138	-0.0797
	(0.00993)	(0.00403)	(0.0483)	(0.0887)	(0.0699)
Post 2006 X Water Pollution Index	0.00711	0.00577*	0.0158	-0.0836	0.0195
	(0.00789)	(0.00316)	(0.0386)	(0.0745)	(0.0658)
Untreated water X Water Pollution Index	0.00168	0.000912	0.0717*	-0.121*	0.00557
	(0.00808)	(0.00369)	(0.0388)	(0.0713)	(0.0520)
Untreated Water X Post 2006	0.0457	0.00523	0.448***	-0.419	0.197
	(0.0319)	(0.0129)	(0.156)	(0.271)	(0.210)
Untreated Water	-0.0122	-0.00551	-0.240*	0.340	-0.0515
	(0.0264)	(0.0114)	(0.128)	(0.234)	(0.176)
Individual Fixed Effects	Yes	Yes	Yes	Yes	Yes
Observations	38525	38489	31011	4919	4995

Note: Significant levels are indicated by *** $p<0.01$, ** $p<0.05$, * $p<0.1$. All results include the following controls: gender, minority group, age, age squared, preventive medical service, calorie intake, unhealthy diet, livestock raising, tap water access, flush toilet, excreta near house, log income

Table A.4: Estimated Effect of Early Childhood Agricultural Water Pollution Exposure on Health Based on Access to Treated Water - Using Province-Level Water Pollution Index

	Age 6 and below	
	(1) BMI Z-Score	(2) Height-For-Age Z-Score
Untreated Water X Born after 2006 X Water Pollution Index	-0.0648	-0.486**
	(0.256)	(0.207)
Untreated Water X Water Pollution Index	0.0566	0.207*
	(0.132)	(0.121)
Born after 2006 X Water Pollution Index	-0.149	0.435**
	(0.222)	(0.177)
Untreated Water X Born after 2006	0.189	1.201**
	(0.689)	(0.602)
Untreated Water	-0.202	-0.517
	(0.403)	(0.368)
Born after 2006	0.432	-0.912*
	(0.580)	(0.488)
Water Pollution Index	-0.0332	-0.339
	(0.273)	(0.239)
Year Fixed Effects	Yes	Yes
Community Fixed Effects	Yes	Yes
Observations	1393	1434

Note: Significant levels are indicated by *** $p<0.01$, ** $p<0.05$, * $p<0.1$. All results include the following controls: gender, minority group, age, age squared, preventive medical service, calorie intake, unhealthy diet, livestock raising, tap water access, flush toilet, excreta near house, log income

Table A.5: Estimated Effect of Agricultural Water Pollution on Health Post 2006 - Using Province-Level Drinkable Water Percentage

	All age		Age 18 and above	Age below 18	
	(1) Sick	(2) Diarrhea	(3) BMI	(4) BMI Z-Score	(5) Height-For-Age Z-Score
Post 2006 X Drinkable Water Percentage	0.00364	-0.0175**	0.193*	-0.267	0.281
	(0.0203)	(0.00717)	(0.114)	(0.231)	(0.178)
Drinkable Water Percentage	0.0610**	0.0242**	0.729***	0.296	-0.0319
	(0.0284)	(0.0117)	(0.169)	(0.274)	(0.207)
Post 2006	-0.186***	-0.0409***	-0.172**	-0.0745	0.00716
	(0.0146)	(0.00591)	(0.0733)	(0.152)	(0.115)
Individual Fixed Effects	Yes	Yes	Yes	Yes	Yes
Observations	46572	46442	36482	6555	6644

Note: Significant levels are indicated by *** $p<0.01$, ** $p<0.05$, * $p<0.1$. All results include the following controls: gender, minority group, age, age squared, preventive medical service, calorie intake, unhealthy diet, livestock raising, tap water access, flush toilet, excreta near house, log income

Table A.6: Estimated Effect of Early Childhood Agricultural Water Pollution Exposure on Health - Using Province-Level Drinkable Water Percentage

	Age 6 and below	
	(1) BMI Z-Score	(2) Height-For-Age Z-Score
Born after 2006 X Drinkable Water Percentage	0.768* (0.466)	-0.467 (0.410)
Drinkable Water Percentage	-0.158 (0.623)	0.459 (0.509)
Born after 2006	-0.414 (0.317)	0.398 (0.263)
Year Fixed Effects	Yes	Yes
Community Fixed Effects	Yes	Yes
Observations	1694	1741

Note: Significant levels are indicated by *** $p<0.01$, ** $p<0.05$, * $p<0.1$. All results include the following controls: gender, minority group, age, age squared, preventive medical service, calorie intake, unhealthy diet, livestock raising, tap water access, flush toilet, excreta near house, log income

Table A.7: Estimated Effect of Agricultural Water Pollution on Health Based on Access to Treated Water - Using Province-level Drinkable Water Percentage

	All age		Age 18 and above	Age below 18	
	(1) Sick	(2) Diarrhea	(3) BMI	(4) BMI Z-Score	(5) Height-For-Age Z-Score
Untreated water X Post 2006 X Drinkable Water Percentage	-0.0336	-0.00744	0.246	0.0258	0.291
	(0.0391)	(0.0134)	(0.230)	(0.382)	(0.287)
Post 2006 X Drinkable Water Percentage	0.0174	-0.0130	0.199	-0.233	0.178
	(0.0265)	(0.00930)	(0.144)	(0.297)	(0.230)
Untreated water X Drinkable Water Percentage	0.0301	-0.00124	0.125	0.0117	0.0594
	(0.0246)	(0.0100)	(0.144)	(0.228)	(0.175)
Untreated Water X Post 2006	0.0144	0.00589	0.00473	0.0307	-0.183
	(0.0213)	(0.00743)	(0.122)	(0.217)	(0.174)
Untreated Water	-0.0242*	-0.00182	-0.0882	-0.0745	-0.0299
	(0.0144)	(0.00603)	(0.0854)	(0.135)	(0.110)
Individual Fixed Effects	Yes	Yes	Yes	Yes	Yes
Observations	46572	46442	36482	6555	6644

Note: Significant levels are indicated by *** p<0.01, ** p<0.05, * p<0.1. All results include the following controls: gender, minority group, age, age squared, preventive medical service, calorie intake, unhealthy diet, livestock raising, tap water access, flush toilet, excreta near house, log income

Table A.8: Estimated Effect of Early Childhood Agricultural Water Pollution Exposure on Health Based on Access to Treated Water - Using Province-Level Drinkable Water Percentage

	Age 6 and below	
	(1) BMI Z-Score	(2) Height-For-Age Z-Score
Untreated Water X Born after 2006 X Drinkable Water Percentage	0.693	1.841**
	(0.941)	(0.827)
Untreated Water X Drinkable Water Percentage	0.341	-0.723
	(0.514)	(0.473)
Born after 2006 X Drinkable Water Percentage	0.500	-1.390**
	(0.643)	(0.572)
Untreated Water X Born after 2006	-0.409	-1.246**
	(0.615)	(0.510)
Untreated Water	-0.284	0.456
	(0.319)	(0.289)
Born after 2006	-0.247	1.057***
	(0.445)	(0.377)
Drinkable Water Percentage	-0.341	1.037
	(0.730)	(0.644)
Year Fixed Effects	Yes	Yes
Community Fixed Effects	Yes	Yes
Observations	1694	1741

Note: Significant levels are indicated by *** p<0.01, ** p<0.05, * p<0.1. All results include the following controls: gender, minority group, age, age squared, preventive medical service, calorie intake, unhealthy diet, livestock raising, tap water access, flush toilet, excreta near house, log income

Table A.9: Estimated Effect of Agricultural Water Pollution on Health Post 2000 - Using Province-level Drinkable Water Percentage

	Age 6 and below	
	(1) BMI Z-Score	(2) Height-For-Age Z-Score
Untreated Water X Born after 2006 X Drinkable Water Percentage	0.693 (0.941)	1.841** (0.827)
Untreated Water X Drinkable Water Percentage	0.341 (0.514)	-0.723 (0.473)
Born after 2006 X Drinkable Water Percentage	0.500 (0.643)	-1.390** (0.572)
Untreated Water X Born after 2006	-0.409 (0.615)	-1.246** (0.510)
Untreated Water	-0.284 (0.319)	0.456 (0.289)
Born after 2006	-0.247 (0.445)	1.057*** (0.377)
Drinkable Water Percentage	-0.341 (0.730)	1.037 (0.644)
Year Fixed Effects	Yes	Yes
Community Fixed Effects	Yes	Yes
Observations	1694	1741

Note: Significant levels are indicated by *** p<0.01, ** p<0.05, * p<0.1. All results include the following controls: gender, minority group, age, age squared, preventive medical service, calorie intake, unhealthy diet, livestock raising, tap water access, flush toilet, excreta near house, log income

Table A.10: Estimated Effect of Agricultural Water Pollution on Health Post 2000 Based on Access to Treated Water - Using Province-level Drinkable Water Percentage

	All age		Age 18 and above	Age below 18	
	(1) Sick	(2) Diarrhea	(3) BMI	(4) BMI Z-Score	(5) Height-For-Age Z-Score
Untreated water X Post 2000 X Drinkable Water Percentage	-0.0336	0.0141	-0.545**	-0.325	-0.0139
	(0.0390)	(0.0163)	(0.235)	(0.360)	(0.288)
Post 2000 X Drinkable Water Percentage	0.0227	-0.00748	0.591***	0.0691	0.140
	(0.0272)	(0.0113)	(0.166)	(0.268)	(0.203)
Untreated water X Drinkable Water Percentage	0.0410	-0.00879	0.518**	0.289	0.0691
	(0.0332)	(0.0139)	(0.215)	(0.308)	(0.257)
Untreated Water X Post 2000	0.00241	-0.0146	0.339**	0.304	0.147
	(0.0224)	(0.0101)	(0.142)	(0.210)	(0.171)
Untreated Water	-0.0188	0.00962	-0.293**	-0.326*	-0.170
	(0.0206)	(0.00910)	(0.140)	(0.191)	(0.162)
Individual Fixed Effects	Yes	Yes	Yes	Yes	Yes
Observations	46572	46442	36482	6555	6644

Note: Significant levels are indicated by *** $p<0.01$, ** $p<0.05$, * $p<0.1$. All results include the following controls: gender, minority group, age, age squared, preventive medical service, calorie intake, unhealthy diet, livestock raising, tap water access, flush toilet, excreta near house, log income

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