Summer 7-15-2017

REACTIONS TO MARKET FAILURE AND APPROACHES TO REDUCE MARKET FAILURE

Yingzhe Cheng
University of New Mexico

Yingzhe Cheng
Candidate

Economics
Department

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

Approved by the Dissertation Committee:

Janie Chermak, Co-Chairperson

Jennifer Thacher, Co-Chairperson

Alok Bohara

Gabriel Huerta

REACTIONS TO MARKET FAILURE AND APPROACHES TO REDUCE MARKET FAILURE

BY

YINGZHE CHENG

B.S., Financial Mathematics and Financial Engineering, South China Normal University, 2007

M.A., Economics, University Of New Mexico, 2011

M.S., Statistics, University Of New Mexico, 2016

DISSERTATION

Submitted in Partial Fulfillment of the

Requirements for the Degree of

Doctor of Philosophy

Economics

The University of New Mexico

Albuquerque, New Mexico

July 2017

DEDICATION

献给我的爸爸妈妈——你们让我享受生命的快乐

ACKNOWLEDGMENTS

I started the PhD program with limited knowledge of economics. A number of people helped me become an economist. I would like to thank Dr. Alok Bohara, Dr. Kristine Grimsrud and Dr. Melissa Binder for making economics fun, providing me a solid foundation in econometrics and modeling, and teaching me how to write a paper. I would also like to thank Dr. Huerta for expanding my knowledge in statistics. But foremost, I would like to thank my dissertation advisors Dr. Janie Chermak and Dr. Jennifer Thacher. Dr. Chermak mentored me throughout the program. She always led me to a solution for problems I cannot solve. She helped me to see my potential, supported my interests both in and outside economics, and provided me opportunities to fix short planks of my bucket. It was also a great joy to work closely with Dr. Thacher on a project for this dissertation. She spent a tremendous amount of time to guide me, inspired me with interesting and unique perspectives, and generously shared her research experience which otherwise may take me a long time to learn by myself. Most importantly, I learnt to think deeply, creatively, rigorously and think as an economist from both Dr. Chermak and Dr. Thacher. Thank you for your great influence and always keeping my best interest in mind.

The dissertation would not have been possible without funding from Graduate Studies, Graduate and Professional Student Association, Economics Department, and Economic Graduate Student Organization at the University of New Mexico. I would also like to extend a special thanks to Veronica Salinas and Wenmei Guo for being great friends and study partners, Heidi Pitts for always sharing her notes and helping with Stata code for this dissertation, and all the people who helped implement the survey.

REACTIONS TO MARKET FAILURE AND APPROACHES TO REDUCE MARKET FAILURE

by

Yingzhe Cheng

B.S., Financial Math and Financial Engineering, South China Normal University, 2007

M.A., Economics, University of New Mexico, 2011

M.S., Statistics, University Of New Mexico, 2016

ABSTRACT

Market failure can have serious negative consequences on human welfare, including various health risks to people. How to best correct market failure becomes an important question. Different approaches may reduce market failure, such as direct government regulation, or market based approaches. This research explores consumers' or societies' reactions to market failure and approaches to reduce market failure.

The first study uses a random utility model and a choice experiment method to estimate Chinese parents' marginal willingness-to-pay for potential policy changes that target overall food safety. Results suggest that a policy that provides both direct government regulation and information to create incentives for market solutions can obtain more financial support and be supported by a larger share of respondents.

The second study explores money-risk tradeoffs when risks are due to information asymmetry. The data suggest that a majority of respondents prefer a brand that is more

expensive and perceived to be safer compared to a brand that is cheaper and perceived to be less safe. Respondents' choices may be influenced by how they weigh the concern of inconsistency between price and safety and health concerns, as well as the relative magnitude of the price difference and perceived safety difference between the two brands.

The last study develops a dynamic model of resource extraction and pollution emissions between two agents under a cap-and-trade system, using general functional forms. It explores the tradeoff between the use of pollution reduction technology and the purchase of emissions permits, the relationship between resource extraction and pollution emissions, and the interaction between two agents. Possible optimal time path of resource extraction and pollution emissions are also discussed.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1 INTRODUCTION

Market failure is a common issue in real-world markets, which can happen when a market allocates resources inefficiently. Different approaches may reduce market failure, including government approach such as direct regulation or market approach such as the creation of a market with clearly defined property rights. The latter approach involves little or no government intervention. A good approach should be feasible, effective, and cost efficient.

A market can be a complicated system that is formed by different parties with heterogeneous interests. Each party's reactions to an issue and interactions among parties can have a significant impact on the market. This research focuses on reactions to market failure and different approaches to provide insight to the process of finding and evaluating solutions to reduce market failure. Specifically, I focus on reactions to market failure to find potential solutions, reactions to potential solutions to find a preferred solution, and reactions under a preferred solution. I use the Chinese food market and a general carbon market as examples.

Different markets or sectors have their unique characteristics, which can lead to different approaches to reduce market failure. In the food market, there is no consensus on the best approach. Therefore, I focus on reactions to market failure and potential solutions. On the other hand, in the environmental sector, approaches to decrease market failure like climate change, such as command-and-control and cap-and-trade, have been studied for years. Cap-and-trade is considered as a preferred solution. Therefore, I study reactions under a preferred solution in the carbon market.

1.1 Market Failure in Food Markets

Market failure in food markets happens when there is asymmetric information between consumers and producers or imperfect available information (Verbeke 2005). In most cases, consumers lack information about the true level of food safety. This offers producers the opportunity to produce food that is less safe at a lower cost, without being revealed in the short run.

Compared to other products, food is closely related to our daily lives. Information asymmetry may make it difficult for people to choose among food brands. More importantly, safety issues in the food market can have an immediate and massive impact on human health and lives. Unsafe food is the cause of more than 200 diseases. Every year about one out of ten people fall ill and 420,000 die, with 40% of them children under 5 years old, due to the consumption of unsafe food in the world (WHO 2015a).

In other markets, a market approach may solve market failure by compensating the damaged party. But this is not applicable in the food market, because damage to life and health cannot be adequately compensated for by money. Food safety issues should be prevented before they cause any damage (Stiglitz 2008).

1.2 Climate Change

Climate change, a market failure caused by an externality, is considered by some as the greatest and widest-ranging market failure ever seen (Stern 2007). A society can emit greenhouse gas (GHG) that increases in concentration in the atmosphere and can cause damage to other societies.

Climate change also influences human health and lives. For instance, extreme temperature increases death rates from heart and respiratory diseases; higher pollen and other aeroallergen levels in extreme heat can cause asthma; heavy precipitation also influences the quality of drinking-water and causes disease (WHO 2012; Solheim et al. 2010).

However, the consequences of climate change are much more insidious because they happen slowly over time, especially when compared to some issues in the food market. Some consequences of climate change, such as the reduction of biodiversity, may be less observable in our daily lives. But the transboundary and cumulative damage over time can have a profound negative impact on the earth and human welfare all over the world, for generations to come.

1.3 Contributions of This Dissertation

Considering the characteristics and causes of market failure in the food and carbon markets discussed in sections 1.1 and 1.2, Chapter 2 uses the choice experiment method to investigate Chinese parents' preferences for potential changes in food safety policies and estimate parents' marginal willingness-to-pay (MWTP) for those changes. Chapter 3 applies logistic regression and expected utility theory to investigate the implicit tradeoff parents make between money and health risks under an information asymmetry framework in the Chinese milk market. Chapter 4 builds a dynamic game model to investigate the optimal time path of resource extraction and greenhouse gas emissions between two societies under a cap-and-trade policy.

The contribution Chapter 2 makes is that it considers Chinese parents' preferences towards three types of food safety policies, rather than safety related characteristics of one food item or one group of food. Given that food safety incidents involve a variety of food products in China, the analysis in this chapter can provide a more thorough analysis to evaluate potential food safety policies for the improvement of overall food safety. Data collected through a unique discrete choice survey in China's Hunan province is used to estimate the marginal willingness-to-pay (MWTP) for food safety policy changes. Both the population mean MWTP and individual-specific MWTP are estimated using multinomial logit models and random parameter logit models, which allow for heterogeneous preferences. Individual-specific MWTP is not commonly discussed in the choice experiment literature on food. But the two types of MWTP allow policy makers to evaluate policies from different perspectives in terms of maximizing funding and/or obtaining greater consumer support.

Chapter 3 investigates parents' choice of milk with information asymmetry in a market that is similar to the "lemons principle" (Akerlof 1970). But instead of assuming the choice is between a product with a low price/low quality and a product with a high price/possible high quality, this chapter replaces quality by safety to reflect an important issue in food market. It also includes multiple levels of safety and price to capture how the magnitude of safety and price can influence parental choice. The empirical analysis explores influential factors for the choice of milk. It also compares parents' choice of milk with the lemons principle. In some markets, consumers' main concern may be the inconsistency between price and quality. But in the food market, consumers are also concerned about health. Also, the risk neutral assumption in the lemons principle may not be sufficient to describe all consumers. Therefore, a theoretical model is built to address these issues and explain empirical results.

Chapter 4 incorporates resource extraction, clean technology and carbon trade into a dynamic game of pollution emissions between two agents under a cap-and-trade system, using general functional forms. To find the optimal resource extraction and GHG emissions over time, it graphically explores the tradeoff between the use of clean technology and the purchase of emission permits, allowing for damage from pollution stock. It also graphically explores the interdependency of resource extraction with clean technology, carbon trade, and pollution stock over time for two identical agents. Finally, using the scenario of identical agents as the starting point, this chapter discusses how the optimal path of resource extraction and pollution emissions differ, when there is a difference in net benefits from resource extraction, difference in cost of clean technology, or difference in damage from pollution stock, separately.

1.4 Overview of Results

In the food market, I find that parents prefer a strong tool that allows both government and market approaches to reduce market failure in Chapter 2. Meanwhile, parents' choices of food in Chapter 3 create the potential for a market solution. Given that some government approaches can be costly, policies that only involves a market approach may be a good supplement for policies involves both government and market approaches.

In the carbon market, I find that cap-and-trade reduces pollution emissions over time. It also allows agents to maximize the welfare by choosing the resource extraction and different methods to deal with each unit of pollution generated from the resource, such as the use of technology to eliminate the pollution, and the purchase of permits to emit the pollution. Therefore, it is effective and efficient.

CHAPTER 2: You Are What You Eat: The Choice of Food Safety Policies in China

2.1 Background

Ensuring food safety is a challenge for many countries. 600 million people fell ill and 420,000 people died worldwide from foodborne diseases in 2010 (WHO 2015b). As incomes grow, consumers have increasing demand for safe food (IAASTD 2009). But consumers face a variety of both old and new food safety risks, including foodborne diseases caused by diarrheal disease agents and the use of new materials by the food industry that impact the safety of food products (Lin et al. 2010; WHO 2015b).

China provides a good example of the challenges of trying to ensure food safety. Historically, as a developing country with a large population and limited farm land, China experienced food shortages. After market reforms in 1978, China's GDP growth rate averaged nearly 10% a year (The World Bank 2016). This rapid economic growth relieved the pressure of food shortages and allowed people to turn their attention to food quality and safety. The Chinese Household Survey shows that urban households purchase higher-quality food as income increases; food safety concerns are one of the reasons cited for additional food spending by high-income households (Gale and Huang 2007; FORHEAD 2014)

In recent years, several high-profile food safety incidents have resulted in death, risks to health, and economic loss in China (Jiang et al. 2011). Three of the most publicized cases included the addition of industrial dyes and chemicals to food products and baby formula and the recycling of waste cooking oil.[1]

---

[1] An industrial dye (Sudan IV) was fed to hens and ducks to enhance the appearance of egg yolks, even when there was experimental evidence that industrial dyes caused cancer in animals and damaged their

A number of factors have contributed to China's food safety situation. First, China has many small-scale food producers that are hard to regulate. The lack of effective regulation and enforcement practices, coupled with a highly competitive and non-credible food sector, has incentivized food producers to lower costs and to improve food appearance by using unsafe raw materials or illegal additives. In addition, increased consumption of processed food and longer and more complicated food supply chains has also increased food safety risks (FORHEAD 2014; Qiu 2011).

A survey of Chinese people found that 39% of the urban respondents thought food available in China was unsafe (P. Zhang, Zhang, and Tian 2008). In response, both consumers and the Chinese government have been seeking effective ways to improve food safety.

On the consumer side, there have been changes in the food consumption behavior. For example, organic food consumption as a share of total food consumption increased from 0.4% in 2007 to 1% in 2012, with a large proportion of these consumers residing in large cities such as Beijing and Shanghai (Shanghai World Expo Exhibition & Convertion Center, n.d.; Li, n.d.). Given the higher cost of organic food compared to its conventional counterparts (for instance, organic vegetables may be 3 to 15 times more expensive), this consumption increase likely reflects that people are willing to pay more for food that is perceived to be safer (Lagos et al. 2010). There is also evidence that Chinese customers, especially parents, are paying more attention to food labeling and

genes (Kwok and Yau 2006). Another case revealed that melamine, an industrial chemical, was added to baby formula to replace the nitrogen from protein in diluted raw milk, since the test of protein level of milk usually focuses on its nitrogen content (WHO 2016). This caused six deaths and affected the health of 300,000 infants (NBC News 2008). A third incident exposed the practice of using recycled waste cooking oil from the drains by street food vendors and restaurants. This oil is unhygienic and contains carcinogens and heavy metals that cause various diseases (Food Safety Information 2016).

ingredients. In a recent survey, 62% of parents stated that food ingredients and additives always or often affected their purchasing behavior (Weber Shandwick 2014).

The Chinese government has also taken actions to improve food safety. There are several types of policies that can improve food safety, including regulatory policies, information policies, and third party policies. *Regulatory policies* use laws and government regulations to ensure food safety in food production chains. This type of policies allows consumers to put less effort into improving food safety themselves. Requiring a food safety management system is an example of a regulatory policy. *Information policies* provide safety related information about food to the government and consumers. Development of a traceability system is an information policy. This type of policies allows consumers to obtain better knowledge about the safety of their food and helps them make purchasing decisions, which can influence the market from the demand side. *Third-party policies* encourage the participation of third parties in improving food safety, such encouraging food safety inspections by a non-governmental organization (NGO). This type of policies can potentially increase the number of unbiased sources that supervise food safety.

In the early 2000s, the Chinese government started developing and promoting Hazard Analysis Critical Control Point (HACCP), a food safety management system, initially for food exports (China Quality Certification Centre 2016).[2] However, HACCP has a low implementation rate in the domestic market, both because the system is voluntary for food producers and because there is a lack of financial support and incentives (Bai, Zhang, and Jiang 2013; WHO 2015b; Jin, Zhou, and Ye 2008). At the

---

[2] HACCP is a food management system in which food safety is addressed through the analysis and control of biological, chemical, and physical hazards from raw material production, procurement and handling, to

same time, the government also began gradually developing food traceability systems, a mix of regulatory and information policies, in cities such as Shanghai and Beijing. But these traceability systems currently exist only for limited food categories and regions. One barrier to developing food traceability systems in China is the high implementation costs due to the number of small-scale food producers (Xu and Wu 2010; He and Chen 2014; S. Wang et al. 2014). Both traceability systems and food safety management systems are effective approaches in the prevention and management of food safety hazards (FAO and WHO 2003; Revision Committee on the Handbook for Introduction of Food Traceability Systems 2007). However, better incentives and greater financial support may be required to get the government and food producers to further develop and implement those systems in the Chinese domestic food market.

After the series of food safety incidents, the Chinese government implemented additional regulatory policies actions to improve the efficiency of food safety regulation. In 2013, several food regulatory departments were combined to form the China Food and Drug Administration. Previously, several departments were in charge of food regulations with different, but sometimes unclearly divided, responsibilities. The stated goal of creating the China Food and Drug Administration was to eliminate segmented management and to create a single agency that could guarantee the supervision of each stage in the food supply. In 2015, the government implemented a new Food Safety Law considered to be the toughest food safety law in Chinese history. It includes a stricter regulatory system, more and harsher punishments for non-complying food producers, and it emphasizes greater accountability from government agents (Legal Daily 2015).

Implementing policy changes to increase food safety costs money and will likely increase food prices. This is notable because of the large share that Chinese consumers already spend on food. For example, in 2013, 26% of the total expenditures by Chinese consumers was on food, which was almost four times that of US consumers (USDA 2015). Effective policies require knowing whether consumers can and are willing to pay for increased food safety. It is also important to understand whether consumers are more supportive of regulatory, information, or third-party policies to increase food safety. Understanding these two issues can provide policy makers insight on consumers' demand for food safety policies and allow policy makers to evaluate the feasibility of policies.

The choice experiment (CE) method can be used to find consumers' marginal willingness-to-pay (MWTP) for different food safety policies simultaneously through their trade-offs among policies and the increase of food expenditure caused by the implementation of policies. This method is increasingly applied in the food literature to find consumers' MWTPs for attributes of certain products in a number of countries (Loureiro and Umberger 2007; Combris et al. 2009; Tonsor et al. 2009; Ortega, Wang, Wu, et al. 2011; Probst et al. 2012; Doherty and Campbell 2014; Yahaya, Yamoah, and Adams 2015).

Previous studies have found that in most cases, attributes related to safety, such as certification and traceability, tend to have relatively higher MWTPs than other attributes such as appearance and taste. Chinese consumers tend to have lower MWTPs for safety-related attributes that involve private organizations compared to safety-related attributes that involve government; government is considered more trustworthy than private organizations (Loureiro and Umberger 2007; Ortega et al. 2011; Ortega et al. 2012; Wolf, Tonsor, and Olynk 2011; Van Loo et al. 2011; Lim et al. 2013; Wu et al. 2015).

Previous choice experiment studies have focused on the mean MWTPs for safety-related attributes of one food or one category of food, such as beef or vegetables (Probst et al. 2012; Loureiro and Umberger 2007). However, most food policy will target overall food safety. Using the mean MWTPs from studies of specific foods or general categories of food to target overall food safety can only provide limited information due to three issues.

First, one food or one category of food is not particularly representative of all food in the market. Consumers may value the same attribute for a variety of products differently. For instance, compared to some fruit they barely eat, consumers may be willing to pay more to make beef traceable. Therefore, their willingness-to-pay for traceable beef is not the same as their willingness-to-pay for having a traceability system on all food items in the market.

Second, people may have competing preferences towards safety-related attributes, which cannot be reflected by the mean MWTPs. In other words, it is possible that the average people are willing to pay for an attribute but a few people are not willing to pay for it. If policy makers implement the change based on the average people, those who are not willing to pay for the change will not be satisfied. When this change is for one food or one category of food, people who are not willing to pay for the change may switch to a substitute and may not be affected. But when this change is for all food, people who are not willing to pay for the change may not find substitutes and be forced to pay for something they do not like. Therefore, a food safety policy that intends to benefit more people would require a good understanding of the distributions of MWTP for all respondents instead of only the average respondents.

Finally, affordability is not an important concern to consumers when they only face a small change in the unit price of one product. But affordability may play a very important role in consumers' attitudes and preferences when policy changes affect all food products and cause a large change in total food expenditures. For instance, if the price of beef has to increase by one dollar when it becomes traceable, consumers may not pay much attention to whether they can afford this relatively small increase. Consumers who prefer untraceable beef are more likely to be those who do not like traceability or those who do not think a traceability system for beef worth one more dollar. However, if the total food expenditure increases by 200 dollars when all food items in the market become traceable, this relatively large increase of food expenditure can easily exceed their budget. It is more likely that some consumers who like traceability are forced to prefer untraceable food since they cannot afford such increase. Therefore, it is important to address affordability issue when I consider MWTP for overall food safety; otherwise, I may overestimate the MWTPs.

In this study, I address these limitations of previous studies by considering four potential food safety changes that target overall food safety: a government requirement that food producers must implement a food safety management system (*Management*), an increase in the percentage of traceable food in the market to 10% from its current level of less than 1% (*Traceability*), publication of all food safety inspection results on a centralized governmental website (*CentralizedWeb*), and provision of routine supplemental food safety inspection by non-governmental organizations (*NGO*). These four changes represent regulatory policy, a mix of regulatory and information policies, information policy and third-party policy respectively. Each of these food safety changes were attributes in a CE question survey, along with the increase in monthly household food expenditures. I also asked respondents to state their largest affordable increase in food expenditure, so as to account for affordability in my model. In this study, I explore the distributions of individual-specific MWTP for all four changes, in addition to the average MWTPs.

I find and compare consumers' MWTPs for the four food safety changes using primary data collected from a choice experiment (CE) survey of parents' attitudes towards food safety in Hunan province, China. This survey had a response rate of 87%. The data shows that in general respondents were strongly opposed to the status quo. They were willing to pay for all four changes that potentially improve food safety. The mean MWTPs tended to be higher for regulatory policies, including *Management* and *Traceability*. However, respondents differed significantly in terms of their attitudes and values for the four changes. *Traceability* and *NGO* had more supporters than *Management* and *CentralizedWeb*.

2.2 Survey and Data

2.2.1 Survey Population

In 2013, I conducted an anonymous valuation and attitudinal survey about food safety issues among urban parents of young children (approximately six and seven years old) in two cities (Changsha and Huaihua) of Hunan province, China. I targeted urban parents because urban families tend to consume more processed food and, thus, are more likely to be exposed to food safety risks. In addition, young children are also more vulnerable to food safety risks.

Hunan province was chosen as the study site because it is an important agricultural province in south central China that faces a number of food safety concerns such as heavy-metal polluted agricultural products and the use of illegal additives (C. Zhang, Liu, and He 2014; L. Wang et al. 2008). It also has a high population density with an area of 211,800 square kilometers (2.2% of China) and a population of 66 million (5% of Chinese population), including 4.7 million elementary students (Population Census Office under the State Council and Department of Population and Employment Statistics National Bureau of Statistics 2012; Xiao 2014). Food safety incidents could have a wide impact in this province.

2.2.2 Survey Instrument

The survey development process included focus group discussions, individual interviews, and a pretest. The final questionnaire consisted of four sections and a total of 33 questions, which took approximately 20 minutes to complete.

The first section of the survey describes the five attributes from the CE questions (see Table 2.1). After the description of each attribute, there are two to three questions designed to gauge respondents' attitudes, knowledge, and/or behaviors related to each attribute.

The first attribute is whether or not the government should require food producers to implement a food safety management system (*Management*), such as HACCP. Food safety management systems are designed to identify, evaluate, and control hazards to food safety in each segment of the food production, processing and distribution chain (Codex 1997). These can be applicable to large businesses as well as small and/or less developed businesses, which are common in the Chinese food industry (WHO 1999). Food safety management systems are not mandatory in China. Therefore, only about 5,000 food enterprises had HACCP certifications by 2011 and 4,000 food enterprises with the certification were involved in international trade in 2015 (China Quality Certification Centre 2016; China National Accreditation Service for Conformity Assessment 2015). Those enterprises are a small proportion of the over 100,000 licensed food producers (The State Council Information Office 2007). The government could make food safety management systems mandatory to improve food safety in the domestic market. This attribute is an example of regulatory policy.

The second attribute is the percentage of traceable food in the market (*Traceability*). Traceable food allows consumers to obtain detailed information about each stage of the food production, processing and distribution.[3] A traceability system also helps the government to identify and control sources of hazard when food safety incidents occur. At the time of the survey, less than one percent of the food sold in Hunan was traceable and the city of Changsha was planning development of a traceability system for certain foods such as meat and vegetables (implemented in 2016) (Sanxiang Metro News 2012; Liu 2016). *Traceability* is an example of the mix of regulatory and information policies.

The third attribute is how the government publishes food safety inspection results online (*CentralizedWeb*). 62% of Chinese urban residents can access the internet and

[3] For example, the Chinese branch of an international chain supermarket called Metro has a unique code for its products so that consumers can access information regarding the farmer who produced the raw materials, the factory that processed the food, and the food safety inspection reports.

more than half of internet users were between 20 and 39 years old in 2013 (China Internet Network Information Center 2013). Thus, the population of my study had internet access. But at the time of the survey, different food safety inspection results were published on different websites. It is inconvenient for consumers to check on multiple websites whether the food they purchased passed the safety inspections. The government could build a centralized website that publishes all food safety inspection results from agencies across the country. This will make it easier for consumers to access the information and guide their choices of food brands. This attribute is an example of information policy.

The fourth attribute is whether or not NGOs should provide routine supplemental food safety inspections (*NGO*). In general, NGOs have a relatively small presence in China. Currently, there are very few domestic NGOs that focus on food safety, with the first food NGO formed in 2013 (Woodpecker Food Safety Center, n.d.). NGOs currently provide a limited number of sporadic small-scaled supplemental food safety inspections to help consumers identify unsafe food. If NGOs conduct routine supplemental food safety inspections, the number of inspections and the chances of detecting unsafe food would increase. This attribute is an example of third-party policy.

The last attribute is the size of the increase in monthly household food expenditures (*Cost*). The *Cost* attribute has 12 levels ranging from 25 yuan to 1,500 yuan per month.[4] The status quo of the cost attribute is 0 yuan.

The second section of the survey has four CE questions. Each CE question provided two food safety plans with potential changes related to food safety and the status quo (see Figure 2.1). It asked respondents to choose the most preferred alternative.

[4] At the time of the survey, 1 yuan=0.16 US dollar.

Focus groups and individual interviews did not suggest any potential interactions between attributes; thus, I created a main-effects generic design (i.e., no interactions between attributes and generic alternatives). Given the number of attributes and corresponding levels, I elected to create a design of 16 choice sets. Focus groups and individual interviews suggested that individuals could comfortably complete four choice sets of three alternatives (two alternatives plus status quo) without a sense of burden; thus, elected to have four choice sets per version, resulting in four versions of the survey.

The design was generated using a modified Fedorov candidate-set-search algorithm using the "%choiceff" macro in SAS (Kuhfeld 2001). Under this macro, a random design of the specified size is selected from the full factorial design. Alternatives are swapped in, in an attempt to minimize the D-error. 200 initial random designs were used. The design with the minimum D-error, which minimizes the variance matrix for a multinomial logit discrete choice model, is chosen. For my design, I made no assumptions about the value of the βs (i.e., β=0). While this resulted in a less efficient design than would have been achieved with using assumed values for the βs, I determined it provided a safer design. While I was confident about the expected sign of cost, I suspected significant heterogeneity with respect to some of the other variables and thus did not want to impose an expected sign on these attributes. After the final design was chosen, I added a constant status-quo alternative to each choice set.

The third section of the survey includes questions on choices of food, averting behaviors, and reactions towards food safety and quality problems. The last section asks for demographic information such as gender, education, and age. These two sections allow me to find whether there are heterogeneous preferences among people with different characteristics.

2.2.3 Survey Implementation

I randomly selected eight elementary schools from Changsha and Huaihua, two cities in Hunan province. The survey was implemented among parents of first- and second-year students (i.e., approximately six and seven years old). I did not focus on younger children from daycare or preschools because elementary school is free and mandatory, resulting in almost a 100% enrollment rate. In contrast, daycare/preschool is optional and parents must cover the cost. Thus, elementary school provides a more representative sample of households.

I sent out 1,385 hard copies of the Chinese-version of the survey to parents via their children. Children were asked to return the completed surveys at their schools within two days. As this was an IRB-approved anonymous survey, parents were only contacted once.

2.2.4 Survey Respondents

I received 1,205 responses, resulting in a response rate of 87%. This provides choices from 4,820 CE questions. Summary statistics of the attributes from the survey responses are very close to the survey design, which indicates fairly even responses across four versions of the survey. After dropping choices of unaffordable plans, I have choices from 1,185 respondents and 4,540 CE questions.[5]

---

[5] I asked respondents to provide the maximum amount of increase in food expenditure that they can afford in the survey. In some choice sets, some respondents chose a plan with a cost higher than their affordable

Summary statistics of selected variables used in the models are presented in Table 2.2.[6] On average, respondent households can afford a maximum increase of 170 yuan per capita for monthly food expenditure, which was approximately 2% of the average disposable income of urban residents of Hunan.[7] It is common for them to have various averting behaviors to food safety, with a median of three behaviors.[8] Respondents had a median of 12 years of education; the majority of respondents had finished high school or junior college.

I cannot test the representativeness of this sample because there is no available demographic information for urban parents of elementary students in first and second year in these two cities. I can only present a comparison between all residents of Changsha and Huaihua and my sample (see Table 2.3). The possible range of per capita food expenditure in my sample was lower than the population per capita food expenditure in Changsha. But the possible range of food expenditure per capita in my sample included the population per capita food expenditure in Huaihua. Therefore, my sample had a lower per capita food expenditure in Changsha and a comparable per capita food expenditure in Huaihua. Respondents in my sample also tended to be more educated than the population. This is likely because, as parents of young children, my respondents were from a cohort that had more access to schooling. Given the high response rate of 87%, the mandatory nature of early elementary education, and the distribution of schools included

---

increase in food expenditure. I drop responses from those plans since they are not realistic. However, the results before and after dropping those responses are not significantly different.

[6] Several of the variables in Table 2 are centered around median values for the purpose of analysis. Here, for ease of presentation, I discuss the uncentered data.

[7] The annual per capita disposable income of urban residents of Hunan is 23,414 yuan at the time of the survey (National Bureau of Statistics Survey Office in Hunan, n.d.).

[8] Averting behaviors in this study include avoiding food with high safety risks, only choosing brands they trust, using rules of thumb to choose relatively safer food, making processed food at home, growing vegetables or raising poultry by themselves, getting agricultural products from their farmer relatives, and purchasing imported foods.

in the study, it seems reasonable to conclude that this sample was representative of the population of interest.

2.3 Model

I utilize the typical Random Utility Model (McFadden 1974). Model 2.1 is multinomial logit (MNL) model assuming homogeneous preferences across respondents. All ε are assumed independent and identically distributed. The indirect utility function of respondent n choosing alternative i in a choice set k is

$$V_{nki} = ASC\_sq_{nki} + \beta_1 \times Management_{nki} + \beta_2 \times Traceability_{nki} + \beta_3 \times CentralizedWeb_{nki} + \beta_4 \times NGO_{nki} + \beta_5 \times Cost_{nki}$$

where ASC_sq is an alternative specific constant associated with the status quo. It captures potential status quo bias.

The assumption of homogeneous preferences is a simplifying assumption: in fact, one would expect respondents to differ in their attitudes towards attributes and the status quo. Respondents' behaviors and demographics may influence or reflect their preferences. To account for group-wise differences among respondents with different characteristics, interactions between some of those characteristics and attributes or *ASC_sq* are included in the indirect utility function for Model 2.2.

There may also exist some unobservable individual differences among respondents, which can be captured by the Random Parameter Logit (RPL) model (McFadden and Train 2000). Model 2.3 is an RPL model that allows respondents to have different individual parameters; all parameters are allowed to be random. One must make an assumption about the distribution of those parameters. The normal distribution allows the greatest flexibility in terms of the sign, while the log-normal distribution assumes a certain sign for a parameter. Given that the marginal utility of *Cost* can potentially be strictly negative, I compare models under two possible distributional assumptions: (1) normal distribution for all parameters, and (2) log-normal distribution for parameter of *Cost* and normal distribution for the remaining parameters. The model with a better fit (lower AIC and BIC) is presented for Model 2.3.

Model 2.4.1 allows for both observable and unobservable heterogeneity, by including interactions between socio-demographic variables and attributes or *ASC_sq* within the RPL model. The same process discussed above was followed to determine the appropriate distributional assumption for the random parameters.

Model 2.4.2 also allows for both observable and unobservable heterogeneity, but restricts any random parameters that were found to have an insignificant standard deviation in Model 2.4.1 to be fixed.

Unlike linear model, there is no R^2 to measure goodness of fit for a discrete choice model. The likelihood ratio index $LRI = 1 - \frac{\ln L^{full\ model}}{\ln L^{null\ model}}$ is considered as an analog of R^2 for the discrete choice model. The full model includes all attributes (and interactions) and the null model does not include any attributes or interactions. The LRI ranges between 0 and 1. It does not have an interpretable meaning like R^2. But when LRI approaches 1, it means the model can perfectly predict each respondent's choice. The values of LRI for Models 2.1-2.4.2 are 0.26, 0.35, 0.32, 0.38 and 0.39 respectively. But LRI cannot be used to compare those models (Train 2003). Also, LRI does not measure model fit (Greene 2012).

Estimated coefficients from Models 2.1-2.4.2 can reflect how attributes and status quo influence respondents' utility. But they are not meaningful for evaluating the feasibility of policy changes. A more important measure for policy evaluation is the MWTP, which is the increase of food expenditure associated with a policy change that keeps respondents' utility the same as the utility from the status quo.

The population mean MWTP can be calculated from $-\frac{\beta_m}{\beta_c}$, where β_m is the coefficient of non-cost attribute in the population. β_c is the coefficient of cost attribute in the population. In the RPL model, there is also individual-specific MWTP that vary across respondents. It has the same form as the population mean MWTP but β_m and β_c are individual coefficients for each respondent in the sample.[9]

2.4 Empirical Results

2.4.1 Model Estimation

Estimated results from Models 2.1 – 2.4.2 are presented in Table 2.4. All five models consistently show significant positive coefficients for all four non-cost attributes in the estimated utility function. This provides strong evidence that on average, respondents were supportive of all four potential changes, including a government requirement that food producers must implement a food safety management system (*Management*), an increase in the percentage of traceable food in the market to 10% from its current level of less than 1% (*Traceability*), publication of all food safety inspection

[9] For models 2.2 and 2.4.2, this formula is for the representative respondents with a median level of affordability per person (150 yuan), median number of averting behaviors (3), and median education level (12 years).

results on a centralized governmental website (*CentralizedWeb*), and provision of routine supplemental food safety inspection by non-governmental organizations (*NGO*).

Models 2.2 – 2.4.2 also capture heterogeneous preferences across respondents.[10] The significant estimated coefficients of interactions in Models 2.2 and 2.4.2 indicate group-wise heterogeneous preferences among respondents with different affordability, number of averting behaviors and education level. Meanwhile, the significant estimated standard deviations in the RPL models (Models 2.3 and 2.4.2) indicate heterogeneous preferences across individual respondents.

Among the four models considered, Model 2.4.2 (RPL normal with interactions), that considers both group-wise and individual heterogeneous preference, provides the best fit with the lowest AIC and BIC. This model suggests that respondents had different preferences towards the four policy changes. Moreover, even though households that can afford higher increase in food expenditure per person tended to care less about *Cost* and be more opposed to the status quo, those with the same affordability and *Cost* still had different attitudes toward *Cost* and the status quo.

2.4.2 Marginal Willingness-to-Pay

The monthly mean MWTPs in Chinese yuan from all models are calculated from estimated coefficients and presented with 95% Krinsky-Robb confidence interval (CI) in

[10] Model 4.1 and 4.2 are both RPL with interactions. Given that Model 4.2 is a better fit, I will only focus on Model 4.2 for RPL with interactions. In both Models 3 and 4.1, all parameters were assumed random. The standard deviation of all coefficients are significant in Model 3, but the standard deviation of coefficients of *Cost*, *ASC_sq*, *ASC_sq*averting* and *ASC_sq*edu* were not significant in Model 4.1. Assuming these four variables were fixed provides a better fit than assuming random parameters. Thus, in Model 4.2, I assume the parameters for *Cost*, *ASC_sq*, *ASC_sq*averting* and *ASC_sq*edu* are fixed. Note that even though the parameters of *Cost* and *ASC_sq* are fixed in Model 4.2, respondents' attitude towards *Cost* and status quo still vary since the parameters of *Cost*affordability* and *ASC_sq*affordability* are random.

Table 2.5. The Krinsky-Robb CIs indicate that those mean MWTPs are significantly different from zero. In Models 2.2 and 2.4.2, socio-demographic variables in the interactions are centered to their median level. The mean MWTPs in those two models are from representative respondents who had a median level of affordability per person (150 yuan), median number of averting behaviors (3), and median education level (12 years),

The status quo had negative mean MWTPs ranging from -186 to -136 yuan per month across different models. In the best fitting model (Model 2.4.2), the mean MWTP was -186 yuan per month; all else held constant, parents needed to be compensated 186 yuan per month on average to accept the status quo. 186 yuan represents 11% of the average monthly household food expenditure. While a large number, it seems reasonable: food safety was a serious issue at the time of the survey that affected human health and lives. Similar to the findings of Ortega et al (2011), a large share of respondents (80% in my survey) were concerned about food safety (Table 2.2). Given this, it is not surprising that the mean MWTP to avoid the status quo was so high. In fact, 24% of respondents never chose the status quo alternative in the survey.

The four proposed policy changes were generally viewed as positive by respondents. Therefore, the average parents were willing to pay for all changes. Moreover, the more they were willing to pay for a change, the more important the change was considered by the parents.

The mean MWTPs for *Management*, a regulatory policy, ranged from 165 to 232 yuan per month across models. It consistently has the highest mean MWTP among the policy attributes in all models. In the best fitting model (Model 2.4.2), the mean MWTP was 165 yuan per month, which was 10% of the average monthly household food expenditure. This regulatory policy prevents food safety issues during the production and distribution instead of relying on inspection of the final product. It decreases the food safety risks for consumers without requiring effort from consumers. Therefore, it seems reasonable that parents were willing to pay a significant amount of money for this policy change and consider this change the most important of the four policy changes.

The mean MWTPs for *Traceability,* a mix of regulatory and information policies, ranged from 108 to 136 yuan per month across models. In the best fitting model (Model 2.4.2), the mean MWTP was 115 yuan per month, which was 7% of the average monthly household food expenditure. This mean MWTP was also relatively high among the four policy attributes. From the government perspective, more food safety hazards can be traced and efficiently regulated by the government due to this policy. From the consumer perspective, this policy makes the source of food transparent for more food items. This policy change requires more consumer involvement than *Management*, since the consumer needs to know how to use the information and must spend extra time to use it for food purchasing decisions. Both group discussions and previous studies showed that some participants and consumers were not very familiar with traceable food and therefore less likely to demand the traceability system (He and Chen 2014). Nevertheless, even if consumers do not use the information, this change can still help the government to improve food safety by allowing quicker identification of hazards.

The mean MWTPs for *NGO*, a third-party policy, ranged from 99 to 138 yuan per month across models. In the best fitting model (Model 2.4.2), the mean MWTP was 103 yuan per month, which was 6% of the average monthly household food expenditure.

NGOs in China are not as common as in other countries such as the US. Chinese people tend to consider the government as more reliable than NGOs and the respondents tended to be neutral to NGOs as shown in Table 2.2. In the focus group discussions, some participants mentioned that if the government food inspections failed, inspectors might lose their jobs but if NGOs' food inspections failed, there might not be any punishment for the NGO inspectors. This may explain the relatively lower mean MWTP for *NGO*.

The mean MWTPs for *CentralizedWeb*, an information policy, ranged from 63 to 76 yuan per month across models. It has the lowest mean MWTP in almost all models. In the best fitting model (Model 2.4.2), the mean MWTP was 66 yuan per month, which was 4% of the average monthly household food expenditure and significantly lower than the other three changes. This information policy also requires actions by consumers to improve food safety. Therefore, it is reasonable that *CentralizedWeb* had a low mean MWTP.

Overall, respondents showed significant mean MWTPs for all four policy changes. Even though Chinese people already spent a large proportion of their expenditure on food, the mean MWTPs for each attribute ranged from 66 to 165 yuan per month in the best fitting model, which was up to 10% of the average monthly household food expenditure. This is consistent with findings from previous studies, where Chinese people were willing to pay for food produced under HACCP and traceable food (Z. Wang, Mao, and Gale 2008; Ortega, Wang, Wu, et al. 2011). Among the four policy changes, the two regulatory policies (*Management* and *Traceability*) had relatively higher mean MWTPs than the information and third-party policies. Ortega et al. (2011) and Bai et al. (2013) also found that Chinese people were willing to pay more for attributes of safety related service provided by the government over the third parties. The result of mean MWTPs indicates that respondents trusted the government more than a third party, likely due to the current social environment of China. It also suggests that respondents preferred the government to use regulations to ensure food safety directly rather than providing them with information that requires extra effort on their part to identify safe food.

However, not every parent can or was willing to pay the same amount for those changes due to their affordability and heterogeneous preferences. The mean MWTPs discussed before can not reflect preferences of all respondents. Therefore, I explore the variations in MWTPs across groups of respondents and individual respondents to fully understand how parents value the four policy changes and the status quo.

To examine whether group-wise differences in MWTPs existed, I calculate MWTPs using Model 2.2 (MNL with interactions) results for varying levels of affordability, averting behaviors, and education (see Table 2.6). Only differences in affordability led to large differences in MWTP.[11] Those with affordability higher than 90% of respondents were willing to pay more than twice as much as those with affordability higher than only 10% of respondents.

The individual differences or the combination of group-wise and individual differences of MWTP are reflected by the distributions of individual-specific MWTP in the RPL models (Models 2.3 and 2.4.2) (see Table 2.7). A potential issue of estimating individual-specific MWTP through $-\frac{\beta_m}{\beta_c}$ is that any small value of β_c can lead to an unrealisticly large MWTP at the end of the distribution and exaggrate the average

[11] Table 6 does not report results for varying levels of averting behaviors or education. Results available upon request.

individual-specific MWTP (Scarpa, Thiene, and Train 2008). However, 3% of respondents' households can afford an increase of more than 1,500 yuan in food expenditure, while only 1% of respondents' MWTP for *Management* is more than 2,000 yuan (which is much higher than other policy changes). The magnitude of estimated individual-specific MWTP in this study is fairly reasonable, which can support the use of $-\frac{\beta_m}{\beta_c}$ for individual-specific MWTP estimation.

In this sample, all else equal, the majority of respondents did not like the status quo (as shown by the negative individual-specific MWTPs), and supported changes in food safety attributes (as shown by the positive individual-specific MWTPs). Those attitudes were consistent with the finding from the population mean MWTP values. Notably, more than 5% of respondents had negative individual-specific MWTPs for *Management* and *CentralizedWeb*.

Preferences were most diverse towards *Management*, with a higher proportion of more negative values at the lower ends of individual-specific MWTP distributions (see Figure 2.2a and Table 2.7). Since the marginal utility of *Cost* tended to have small variation across respondents with only 1% positive values in Model 2.4.2, the higher proportion of more negative individual-specific MWTPs indicates that a larger share of respondents were more opposed to *Management* than other policy changes. Even though a smaller share of respondents supported *Management*, the high individual-specific MWTPs from its supporters offset the negative values and brought up the overall individual-specific MWTPs for *Management*.

On the other hand, respondents' attitudes towards *Traceability* and *NGO* tended to be less diverse. The majority of individual-specific MWTPs for *Traceability* and *NGO* were smaller than *Management*. But *Traceability* and *NGO* had a larger share of supporters (see Figures 2.2b and 2.2c and Table 2.7), especially in Model 2.4.2 where the percentage of supporters was more than 95% for both attributes - more than 5% higher than *Management*.

Ideally, the proportion of positive individual-specific MWTPs for non-cost attributes should be at least roughly consistent with the claimed attitude towards them (see Table 2.2). This is true for *Traceability* in the best fitting model (Model 2.4.2), which provides some evidence of robustness for the distribution of individual-specific MWTP for *Traceability*. However, the individual-specific MWTPs and claimed attitude were not very consistent for *Management* and *NGO*. Some respondents claimed that they were supportive of *Management* but had negative individual-specific MWTPs for it while some respondents claimed that they were not supportive of *NGO* but had positive individual-specific MWTPs for it. One possible reason for the inconsistency is that answers for attitude questions are more subjective and the standard can vary across respondents. Their claimed supportive and trust level may not exactly reflect their choice of plans. Another possible reason is that some respondents were supportive of *Management* but do not want to pay for it, while some other respondents more or less did not trust NGOs but were still willing to give them a try given the cost.

Overall, the MWTPs for each non-cost attribute varied across groups of respondents and individual respondents. The mean MWTPs suggest that the average parents were willing to provide higher financial support for regulatory policies such as *Management* and *Traceability*. But the individual-specific MWTP distributions in the

RPL models indicate high levels of support for implementing *Traceability* and *NGO*, even though the MWTPs for those policies were not as large as *Management*.

To test the quality of my design, I follow the process suggested in Scarpa and Rose (2008) and calculate the ratio of the D-error of the original design and the D-error of the design that would be generated using the estimated βs. This ratio is equal to 0.81.[12]

2.5 Conclusion and Discussion

Food safety is crucial to human health and lives. In previous studies, Chinese consumers have demonstrated that on average they were willing to pay a small amount of money to improve the safety of certain food items such as milk and pork (Ortega, Wang, Wu, et al. 2011; Bai, Zhang, and Jiang 2013). But the overall food safety situation in China is challenging and needs to be improved by effective food safety policies that target all food items. Previous studies that only focus on one food or one category of food can only provide limited information for designing policies to improve food safety. Analysis that only studies the mean MWTPs may miss identifying lower-valued policies that nonetheless have wide support.

In this study, I focused on the marginal willingness-to-pay for policies that target overall food safety, including regulatory policies, information policies, and third-party policies. My estimates of the mean MWTPs provide the amount that consumers with the median levels of affordability per person, number of averting behaviors and education were willing to pay per month, in terms of food expenditures, in support of these policies. Regulatory policies had a higher mean MWTP. However, examining the distributions of

[12] To make this calculation, I used the estimated βs from the MNL results (Model 1) , excluding the ASC.

individual-specific MWTP reveals that while third-party policy had smaller mean MWTPs, there was very little opposition to this policy among my respondents.

Our results suggest that the appropriate policy choice depends on the goal of policy makers and must be weighed against the marginal costs of implementing the competiting policies. If policy makers want to maximize financial support from parents, it may be better to implement regulatory policies such as *Management* and *Traceability* since those policies had higher MWTPs. But if policy makers want to consider the welfare of advocates and obtain more supporters of the policy, it may be better to implement *Traceability* and *NGO*, which had a larger share of respondents with positive individual-specific MWTPs. *Traceability* may be a good choice among the four proposed policy changes since it had both relatively a larger average amount of MWTP and a relatively larger share of supporters.

It is reasonable that *Traceability* had strong support from respondents since the mix of regulatory and information leaves respondents some choices. If they want to use the information from the traceability systems, the information can help them to choose more reliable food sources. If they do not want to use the information, they can still benefit from the government use of the traceability system.

The traceability system is still under-developed and food safety management systems still have a low adoption rate in China due to a lack of incentives and financial support. But the MWTPs estimated in this study for increasing the share of traceable food in the market and requiring of implementation of a food safety management system suggest that a possible solution to these issues exist.

NGOs still have a relatively small influence in China. But reliable and well organized food NGOs can be more independent, specialized, and efficient compared to the government (Yang 2014). Given that only a relatively small proportion of parents trusted NGOs but the majority of parents were willing to pay for routine supplemental food safety inspections by NGOs, policy makers may wish to consider new policies that work to increase the credibility of NGOs and cooperate with NGOs to improve food safety.

Even though parents were less supportive of having food safety inspection results published on a centralized website, it is important to provide consumers such information in a convenient way. After all, the decrease of demand for unsafe brands of food may be one of the best incentives for food producers to produce safe food.

For the future work, it would be useful to incoporate the estimated MWTPs into a cost-benefit analysis for the four policy changes. Given the heterogenous preferences for each policy change across respondents, there is a potential to design food safety policies that takes affordability and other preferences drivers into consideration so that the chosen policy can satisfy more consumers.

Table 2.1 Survey attributes

Attribute	Description	Level[a]
Management	Whether the government should require food producers to implement a food safety management system.	**No**, Yes
Traceability	The percentage of traceable food in the market	**Less than 1%**, 10%
CentralizedWeb	Whether the government should publish all food inspection results on a centralized governmental website.	**No**, Yes
NGO	Whether NGOs that focus on food safety should provide routine supplemental food safety inspection.	**No**, Yes
Cost	The amount of increase in monthly household food expenditure in yuan [b]	**0**, 25, 100, 200, 300, 400, 500, 600, 700, 800, 1000, 1200, 1500

[a] Status quo levels are in bold.
[b] At the time of the survey, 1 yuan = 0.16 US dollar

Among plan A, plan B and status quo, which one would you choose? ("√"one)

Attributes	Plan A	Plan B	Status quo
① Whether the government should require food producers to implement a food safety management system.	Yes	No	No
② The percentage of traceable food in the market	10%	Less than 1%	Less than 1%
③ Whether the government should publish all food inspection results on a centralized governmental website.	No	Yes	No
④ Whether NGOs that focus on food safety should provide routine supplemental food safety inspection.	Yes	No	No
⑤ The amount of increase in monthly household food expenditure	300 yuan	1000 yuan	No change
I would choose ⟶	A	B	M

Figure 2.1 Sample choice set

Table 2.2 Summary statistics of selected variables

Variable name	Variable description	Obs[a]	Mean	Std. Dev	Min	Max
Affordability	Affordable increase in food expenditure per person centered at median level of 150 yuan (in 100 yuan). [b]	4540	0.20	1.20	-1.50	6
Averting	Number of averting behaviors centered to the median level of 3 behaviors.[c]	4532	0.03	1.40	-3	4
Education	Number of years of education centered to the median level of 12 years education.[d]	4540	1.20	2.60	-12	9
Foodexp	Monthly household food expenditure (in 100 yuan) [e]	4536	17.14	6.12	2.50	30
Concern about current food safety situation in Hunan province						
Concern1	Not at all concerned	4540	0.01	0.11	0	1
Concern2	Somewhat concerned	4540	0.24	0.43	0	1
Concern3	Fairly concerned	4540	0.39	0.49	0	1
Concern4	Very concerned	4540	0.36	0.48	0	1
Support for government requirement that food producers implement a food safety management system						
Supportm1	Not at all supportive	4524	0.02	0.12	0	1
Supportm2	Somewhat supportive	4524	0.07	0.25	0	1
Supportm3	Fairly supportive	4524	0.21	0.41	0	1
Supportm4	Very supportive	4524	0.71	0.46	0	1
Support increasing traceable food from current level of less than 1% to 10%						
Supportt1	Not at all supportive	4540	0.02	0.15	0	1
Supportt2	Somewhat supportive	4540	0.08	0.28	0	1
Supportt3	Fairly supportive	4540	0.23	0.42	0	1
Supportt4	Very supportive	4540	0.66	0.47	0	1
Trust of NGOs						
TrustNGO1	Don’t trust at all	4532	0.07	0.26	0	1
TrustNGO2	Somewhat not trust	4532	0.27	0.44	0	1
TrustNGO3	Neutral	4532	0.39	0.49	0	1

TrustNGO4	Somewhat trust	4532	0.24	0.43	0	1
TrustNGO5	Very trusting	4532	0.03	0.16	0	1

[a] Obs is the number of CE questions.

[b] At the time of the survey, 1 yuan= 0.16 US dollar.

[c] Averting behaviors in this study include avoiding food with high safety risks, only choosing brands they trust, using tricks to choose relatively safer food, making processed food such as soy milk at home, growing vegetables or raising poultry by themselves, getting agricultural products from their farmer relatives, purchasing imported foods, and others.

[d] To simplify the model, I convert the categorical education level into a continuous variable by calculating years of education. In China, it is standard to finish elementary school in six years, junior high school in three years and senior high school in three years. In most cases, people finish junior college in three years, college in four years, and master programs in two years. People need a master degree before entering a PhD program. I assume that it takes them three years to finish a PhD program.

[e] Since the food expenditure data gathered through my survey is categorical, I use the lower bound of the highest category and the middle point of other categories as the food expenditure for each respondent.

Table 2.3 Comparison between sample and city population

	Sample		City Population	
	Changsha	Huaihua	Changsha	Huaihua
Annual food expenditure per capita [a,b,c]	[4896,6467]	[4361, 5881]	7366	4446
Years of education [d]	13.0	13.5	12.5	8.5

[a] Since the food expenditure data gathered through my survey is categorical, I use the lower and higher bounds of each category to calculate the lowest and highest possible average per capita food expenditure, which is the range in sample.
[b] Population data source: Statistical Bureau of Hunan Province
[c] Since Hunan Statistical Yearbook 2014 does not include food expenditure data from 2013, I use food expenditure data from 2012 with adjustment of inflation.
[d] Population years of education in Huaihua is 2010 data.

Table 2.4 Model estimates

	Model 1	Model 2	Model 3	Model 4.1	Model 4.2
	MNL	MNL with interactions	RPL normal	RPL normal with interactions	
Variable	**Coefficient (SE)**	**Coefficient (SE)**	**Coefficient (SE)**	**Coefficient (SE)**	**Coefficient (SE)**
Management	0.865*** (0.054)	0.871*** (0.056)	1.601*** (0.145)	1.367*** (0.111)	1.356*** (0.108)
Traceability	0.510*** (0.046)	0.510*** (0.048)	1.124*** (0.118)	0.940*** (0.095)	0.944*** (0.094)
CentralizedWeb	0.285*** (0.051)	0.295*** (0.053)	0.685*** (0.116)	0.551*** (0.096)	0.541*** (0.093)
NGO	0.516*** (0.049)	0.543*** (0.050)	0.939*** (0.107)	0.851*** (0.088)	0.845*** (0.087)
Costs[a]	-0.374*** (0.012)	-0.470*** (0.013)	-0.944*** (0.059)	-0.830*** (0.047)	-0.821*** (0.044)
ASC_sq	-0.508*** (0.069)	-0.665*** (0.080)	-1.611*** (0.154)	-1.529*** (0.137)	-1.525*** (0.134)
Cost*affordability[a]		0.115*** (0.008)		0.246*** (0.022)	0.243*** (0.020)
ASC_sq*affordability[a]		-0.350*** (0.082)		-0.687*** (0.121)	-0.737*** (0.119)
ASC_sq*averting		-0.108*** (0.037)		-0.160*** (0.056)	-0.160** (0.053)
ASC_sq*edu		-0.081*** (0.020)		-0.075** (0.030)	-0.076** (0.030)
SD	**Coefficient (SE)**	**Coefficient (SE)**	**Coefficient (SE)**	**Coefficient (SE)**	**Coefficient (SE)**
Management			2.470*** (0.229)	1.680*** (0.169)	1.666*** (0.166)
Traceability			1.419*** (0.206)	1.000*** (0.178)	1.000*** (0.161)
CentralizedWeb			1.965*** (0.198)	1.496*** (0.147)	1.465*** (0.142)
NGO			1.177*** (0.216)	-0.749*** (0.209)	0.728*** (0.199)
Costs[a]			0.376*** (0.034)	0.022 (0.056)	
ASC_sq			1.584*** (0.171)	-0.243 (0.329)	
Cost*affordability[a]				0.102*** (0.022)	0.099*** (0.019)
ASC_sq*affordability[a]				1.611*** (0.209)	1.663*** (0.149)
ASC_sq*averting				0.283 (0.318)	
ASC_sq*edu				0.0003 (0.115)	
Number of CE questions	4540	4532	4540	4532	4532
Number of respondents	1185	1183	1185	1183	1183
Log likelihood	-3693	-3256	-3335	-3010	-3011
AIC per respondent	6.243	5.521	5.648	5.123	5.117
BIC per respondent	6.281	5.584	5.725	5.250	5.218

[a] Costs and affordability are original values from choice sets divided by 100.
[b] "***" is significant at less than 1% level. "**" is significant at less than 5% level.
[c] Standard errors are corrected for panel effects

Table 2.5 Monthly mean MWTPs (in yuan) for changes in food safety attributes

	Model 2.1 MNL	Model 2.2 MNL with interactions	Model 2.3 RPL normal	Model 2.4.2 RPL normal with interactions
	MWTP (CI[a])	MWTP for representative respondents[b] (CI[a])	MWTP (CI[a])	MWTP for representative respondents[b] (CI[a])
The government should require food producers to implement a food safety management system.	232 (206, 256)	185 (164, 206)	169 (146, 194)	165 (144, 186)
The percentage of traceable food in the market increases to 10% from less than 1%.	136 (112, 160)	108 (88, 128)	119 (98, 140)	115 (95, 134)
The government should publish food safety inspection results on a centralized website.	76 (52, 102)	63 (43, 84)	73 (50, 96)	66 (45, 87)
NGOs that focus on food safety should provide routine supplemental food safety inspections.	138 (114, 163)	115 (95, 136)	99 (80, 120)	103 (85, 122)
Maintain the status quo, all else held constant	-136 (-168, -105)	-141 (-169, -115)	-170 (-196, -146)	-186 (-211, -161)

[a] 95% Krinsky-Robb CI

[b] The representative respondents are respondents with a median level of affordability per person (150 yuan), median number of averting behaviors (3), and median education level (12 years).

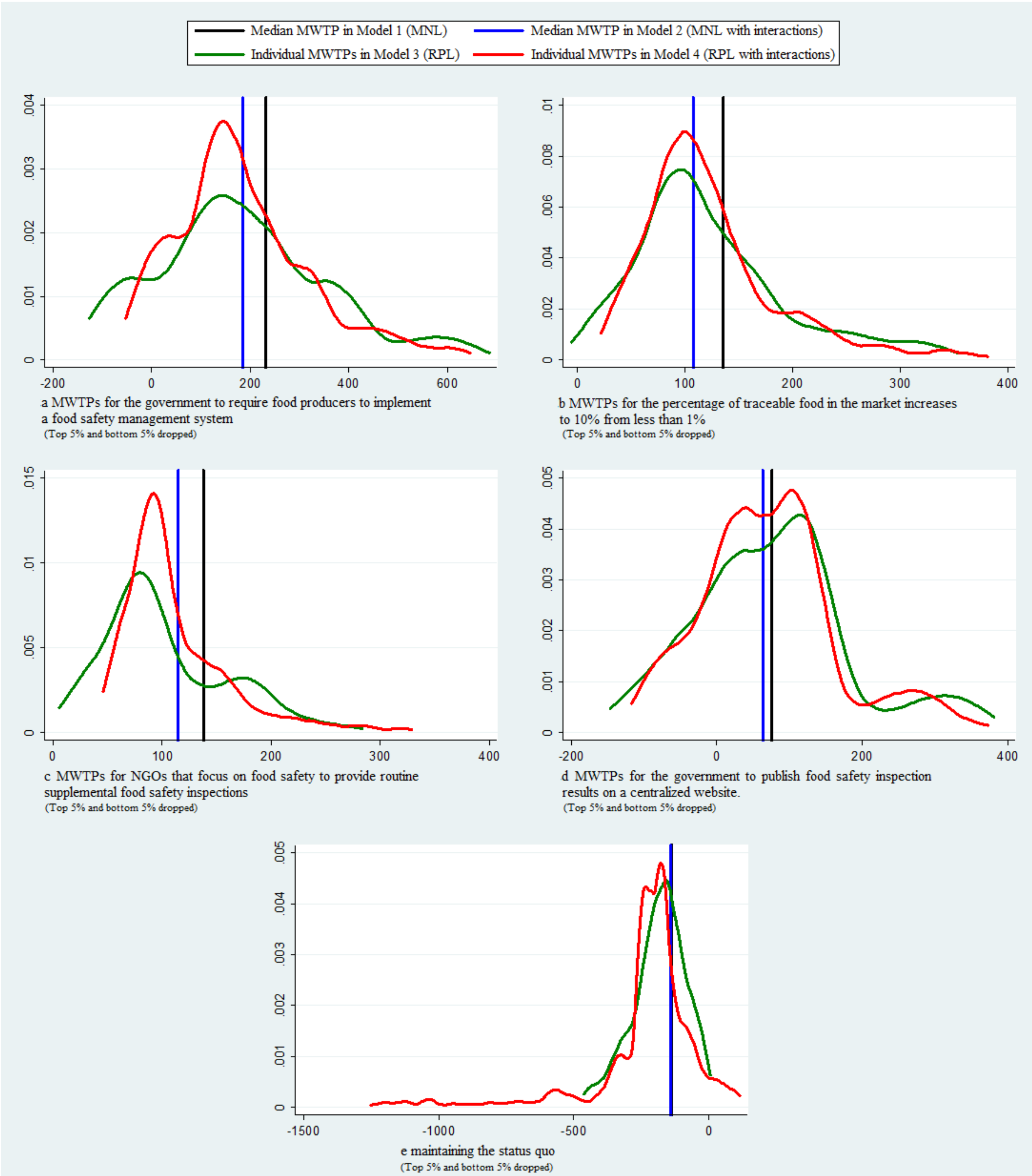


Figure 2.2 Individual-specific MWTP

Table 2.6 Monthly MWTPs for changes in non-cost attributes and status quo in yuan under different scenarios in Model 2.2: MNL with interactions

Changes	MWTP of the representative respondent [a]	MWTP of respondents with affordability higher than 10% of respondents [b,c]	MWTP of respondents with affordability higher than 90% of respondents [c,d]
The government should require food producers to implement a food safety management system.	185	146	334
The percentage of traceable food in the market increases to 10% from less than 1%.	108	86	196
The government should publish food safety inspection results on a centralized website.	63	49	113
NGOs that focus on food safety should provide routine supplemental food safety inspections.	115	91	209
Maintain the status quo, all else held constant	-141	-47	-501

[a] The representative respondents had median level of affordability per person (150 yuan), averting behaviors (3) and education level (12 years/high school)
[b] Assumes have median level of averting behaviors and education level.
[c] Centered affordability is -110 yuan.
[d] Centered affordability is 183 yuan.

Table 2.7 Monthly individual-specific MWTPs for changes in food policy attributes and ASC_sq in yuan by percentiles

	1%	5%	10%	25%	50% (Median)	75%	90%	95%	99%
Model 2.3: RPL normal									
The government should require food producers to implement a food safety management system.	-255	-126	-83	47	165	306	505	685	1011
The percentage of traceable food in the market increases to 10% from less than 1%.	-84	-5	27	74	109	164	268	355	655
The government should publish food safety inspection results on a centralized website.	-344	-147	-86	-3	74	139	297	382	725
NGOs that focus on food safety should provide routine supplemental food safety inspections.	-34	6	25	60	88	151	207	284	633
Maintain the status quo, all else held constant	-729	-463	-359	-247	-174	-109	-36	5	68
Model 2.4.2: RPL normal with interactions									
The government should require food producers to implement a food safety management system.	-675	-53	-10	73	165	272	442	640	2083
The percentage of traceable food in the market increases to 10% from less than 1%.	-417	22	46	79	110	154	241	379	991
The government should publish food safety inspection results on a centralized website.	-425	-117	-75	4	69	126	260	370	872
NGOs that focus on food safety should provide routine supplemental food safety inspections.	-351	46	58	78	98	139	208	323	785
Maintain the status quo, all else held constant	-4986	-1251	-610	-260	-193	-132	-7	111	2316

The grey area on the left side has negative MWTPs for attributes. The grey area on the right side has positive MWTPs for the status quo.

CHAPTER 3: Cost or the Promise of Safety: Chinese Parents' Milk Choices

3.1 Introduction

The tradeoff between money and health/life risks is a common issue in our lives. For instance, people can choose between riskier jobs with higher wages and less risky jobs with lower wages, or between a high cost/low health risk living location and a low cost/high health risk living location, and expensive/safer food/water or cheaper/less safe food/water (Viscusi 1993; Viscusi, Magat, and Huber 1991; Grunert 2005; Andersson, Hole, and Svensson 2016). Different expected utility from money and health/life risks can lead to the choice of different money-risks combinations (Viscusi 1993). But the choice becomes more difficult when health/life risks are not necessarily reduced after money is paid, due to information asymmetry in the market. In this study, I examine Chinese parents' choice of milk for their children to investigate the general issue of tradeoffs when there is uncertainty about the level of health/life risks.

The "lemons principle" suggests that when information asymmetry exits and buyers cannot distinguish quality used cars from "lemons", they end up purchasing the lemons with lower prices and eventually drive quality used cars out of the market (Akerlof 1970). This is because the quality and price tend to be more consistent for the lemons than quality cars. Sellers are less likely to sell quality cars at the lower price level of the lemons, but are more likely to claim that a lemon is a quality car and sell a lemon at the higher price level of a quality car for more profit.

Empirical evidence for the existence of the lemons principle has been found in the used vehicle market, as well as the child care and coin markets (Bond 1984; Huston and

Spencer 2002; Mocan 2007). But some other markets do not follow the lemons principle due to their unique characteristics. These markets include but are not limited to the educational service market when schools can select students (buyers), the wholesale cherry market where buyers figure out signals to identify quality cherries, and eBay with its reputation system (MacLeod and Urquiola 2009; Resnick and Zeckhauser 2002; Rosenman and Wilson 1991).

It is not clear whether markets whose products differ in their safety levels rather than quality will follow the lemons principle. But in the Chinese milk market between 2004 and 2013, a series of safety incidents involving milk and milk products created a market with similar conditions described in the lemons principle: both high-quality (safe) and low-quality (unsafe) products exist but the actual safety levels are unknown to consumers.[13] This market allows me to explore people's tradeoff between money and health risks in an asymmetric information framework.

I conducted an anonymous valuation and attitudinal survey about food safety issues among urban parents of elementary-aged in two cities of China's Hunan province. I simulated the lemons principle by asking parents to choose between two hypothetical brands of milk for their children in Chinese milk market at the time of survey: Brand A has a lower price with no safety claim while Brand B has a higher price and is claimed to be safe by the producer.

A previous study found that consumers' mistrust of quality claims can lead to market failure in a food market as described in the lemons principle (Hennessy, Roosen,

[13] In those incidents, a variety of contaminants were found in milk products, including biological contaminations such as aflatoxin 140% higher than the food safety standard, and chemical contaminations from inedible additives such as melamine and leather-hydrolyzed protein. These contaminants can pose risks such as liver damage, heavy metal poisoning, cancer , and even death (J. Zhang 2011; Yau 2012).

and Jensen 2003). But when the food differs in terms of safety level rather than quality, my survey data reveals a different outcome than the one predicted by the lemons principle. For a question about parents' hypothetical choice of milk for their children, 80% of parents made an anti-lemons choice and chose the more expensive product with a safety claim (Brand B). The remaining 20 percent of parents chose the cheaper brand with no safety claim (Brand A). Therefore, my data suggests two important results. First, parents had heterogeneous preferences. Second, majority of parents made an anti-lemons choice.

This survey result is consistent with findings from previous studies: consumers were willing to pay more for milk with safety-related certifications and traceability (Ortega, Wang, Olynk, et al. 2011; Bai, Zhang, and Jiang 2013). It is also consistent with consumers' actual purchasing behavior: Chinese imports of milk and milk products have increased rapidly since 2008 and almost tripled between 2008 and 2013 (FAO 2014), given that consumers perceive imported milk to be safer.

Unlike the choice of lemons, the anti-lemon choice in my survey seems to prevent expensive safe products from being driven out of the market by cheap unsafe products. But in a market with information asymmetry, anti-lemon choice can cause a greater issue than the choice of lemons. The choice of lemons at least ensures the consistency between price and safety for products in the market, even though they are unsafe. The anti-lemon choice with information asymmetry provides producers both incentive and opportunity to sell unsafe products at higher prices by claiming they are safe. Market failure still exists with unsafe products in the market. But consumers can end up paying more for unsafe products that are claimed to be safe, compared to the choice of lemons.

Therefore, I need to further explore factors that influence parents' choice of milk to investigate the reason that the majority of Chinese parents made an anti-lemons choice. A better understanding of their choice can help policymakers obtain insight on market failure and implement policies to improve consumers' welfare. It can also help producers to find the best production strategies.

In this study, I empirically investigate factors that influence individual parent's milk choice using the unique survey data mentioned previously. I find that parents were more likely to choose Brand B with lower price and higher perceived safety level of Brand B. But I also find that the majority parents who somewhat did not trust the safety claim of Brand B chose Brand B, which seems irrational. I develop a theoretical model to explore parents' concerns in milk market and how milk price, safety level, and parents' risk aversion to the inconsistency between milk price and safety can jointly influence parents' choice of milk. I find that health concern provides parents the incentive to make an anti-lemon choice and may explain their seemingly irrational choice.

3.2 Model of Milk Choice by Individual Parent

The lemons principle focuses on choice at the aggregate level, without considering individual difference. However, people with different characteristics can have heterogeneous preferences. To capture influential factors on people's preferences and better understand the milk choice among parents, it is necessary to first model one parent's choice of milk.

When a parent chooses between two brands of milk, he/she compares the utility from each brand and chooses the one with higher utility. The utility from each brand of milk is determined by a utility maximization problem with constrained resources. In my study, each household's choice of milk may lead to different health status for children, which directly influences household utility. Therefore, this utility maximization problem should incorporate a household production function of health component for children (Becker 1965; Huffman 2011; Kutty 2008).

Assume household utility U depends on the child's current health status H, the consumption of a brand of milk M, the consumption of other nutrition N, the consumption of non-food goods (excluding medical care) C, and parents' leisure L. H^0 is the child's initial health status. X is a vector of other factors such as demographic variables. The utility function of a household is specified as

$$U = U(H, M, N, C, L, H^0, X)$$

which is assumed to be strictly concave. I assume f is the safety level of a brand of milk. A higher safety level means the brand has a higher probability to be safe and vise versa. I is the medical care for the child. φ is all the unobservable factors that influence the production of the child's health. The household production function for the child's health is specified as

$$H = H(M, N, f, I, H^0, X, \varphi)$$

which is also assumed to be strictly concave. Moreover, I assume P_M, P_N, P_I and P_C are the prices of milk, other nutrition, medical care and non-food goods (excluding medical care), respectively. h is hours of work and W is wage. V is non-labor income. T is the total amount of time the parents have. The utility maximization problem for a household can be written as

$$\max_{M,N,I,C,L,h} U = U(H(M, N, f, I, H^0, X, \varphi), M, N, C, L, H^0, X)$$

$$s.t.\ P_M M + P_N N + P_I I + P_C C = Wh + V$$

$$L + h = T$$

After solving the optimization problem, the indirect utility function can be written as

$$U^* = U(P_M, P_N, P_I, P_C, W, V, f, H^0, X, \varphi) \qquad (1)$$

which depends on prices, the wage and non-labor income, the safety level of milk, the initial health status of the child, and other observed and unobserved factors.

A linear function form of the indirect utility function (1) for respondent n with brand i ($i =$ A or B) can be written as the following:

$$U_{ni} = \beta_0 + \beta_1 MilkPrice_{ni} + \beta_2 MilkSafety_{ni} + \beta_3 Income_n + \beta_4 OtherPrices_n + \beta_5 InitialHealth_n + \beta_6 OtherFactors_n + \varepsilon_{ni}$$

where $MilkPrice$ represents milk price P_M in equation (1). $MilkSafety$ represents safety level f. $Income$ represents wage W and non-labor income V. $OtherPrices$ represents prices of other nutrition P_N, medical care P_I and non-food goods P_C. $InitialHealth$ represents child's initial health status H^0. $OtherFactors$ represents other factors X such as demographics. ε is a random component which represents all unobserved factors that influence utility and is assumed to follow an extreme value distribution.

Respondent n chooses Brand B over Brand A if Brand B brings a higher utility ($U_{nB} > U_{nA}$). Given the assumed distribution of the error term, the probability of respondent n choosing the expensive Brand B with a safety claim is

$$P_{nB} = Prob(U_{nB} > U_{nA}) = \frac{\exp(\beta_1 MilkPrice_{nB} + \beta_2 MilkSafety_{nB})}{\sum_{i=A,B} \exp(\beta_1 MilkPrice_{ni} + \beta_2 MilkSafety_{ni})}$$

Therefore, the empirical model to explore parents' choice of milk can be written as

$$\log\left(\frac{P_{nB}}{1-P_{nB}}\right) = \beta_0 + \beta_1 MilkPrice_n + \beta_2 MilkSafety_n + \beta_3 TotalIncome_n + \beta_4 OtherPrices_n + \beta_5 InitialHealth_n + \beta_6 OtherFactors_n + \varepsilon_n \quad (2)$$

In the next section, I will discuss details of the survey mentioned previously. I will also discuss variables and data that can be used in the empirical model to explore how potential influential factors can lead to the choice of Brand B.

3.3 Survey and Data

3.3.1 Survey Implementation

The data I use for the empirical model is collected from an anonymous valuation and attitudinal survey about food safety issues in China. I targeted urban parents of young children (approximately six and seven years old) in this survey because urban children are more likely to consume milk and be exposed to safety risks. Young children are also more vulnerable to safety risks. Therefore, their consumption of milk can have a larger impact in the market. They can also benefit more from the effective policies that ensure milk safety.

I randomly selected eight elementary schools from the two cities (Changsha and Huaihua) in Hunan province. The survey was implemented among parents of first- and second-year students.[14] I sent out 1,385 hard copies of the Chinese-version of the survey to parents via their children. Children were asked to return the completed surveys at their

[14] I did not focus on younger children from daycare or preschools because elementary school is free and mandatory, resulting in almost a 100% enrollment rate. In contrast, daycare/preschool is optional and parents must cover the cost. Thus, elementary school provides a more representative sample of households.

schools within two days. As this was an IRB-approved anonymous survey, parents were only contacted once. I received 1,205 responses, resulting in a response rate of 87%. After excluding respondents whose children did not drink milk and respondents with missing values, I have 1143 observations.

It is difficult to test the representativeness of this sample because there is no available demographic information for urban parents of elementary students in first and second year. I can only present a comparison between all residents of Changsha and Huaihua and my sample (see Table 3.2). Since the food expenditure data gathered through my survey is categorical, I use the lower and higher bounds of each category to calculate the lowest and highest possible average per capita food expenditure. The possible range of per capita food expenditure in my sample is lower than the population per capita food expenditure in Changsha. But the possible range of food expenditure per capita in my sample included the population per capita food expenditure in Huaihua. Therefore, my sample has lower per capita food expenditure in Changsha and comparable per capita food expenditure in Huaihua. Respondents in my sample also tend to have higher education than the population. One reason may be that my respondents are younger and have mostly finished their school.

3.3.2 Survey Instrument

The survey development process included focus group discussions, individual interviews, and a pretest. The final questionnaire consisted of four sections and a total of 33 questions, which took approximately 20 minutes to complete. Twenty of those questions are relevant to this study, which inquires parents' attitudes, knowledge and experiences with food safety issues, behaviors related to food choices, and demographic information (see Chapter 2 for more details about the survey).

This survey has four versions that differ in one question. Each school received a relatively equal number of surveys for each version. In this question, the choice in the "lemons principle" is simulated by providing two brands of milk for parents to choose for their children (see Figure 3.1 for a sample question). Parental choice becomes the dependent variable *ChoseBrandB* in the empirical model. Brand A is always 3 yuan per 250ml, which was the common price of milk in grocery stores. Brand B has different prices *MilkPrice* (6, 9, 12 or 15 yuan per 250ml) in different versions of the survey and is claimed to be safe by its producer (see Figure 3.1).[15]

In reality, both the actual safety level of milk and the chance of milk being safe may be unknown to consumers. But their perceived safety level can influence their choice (Grunert 2005). Therefore, after parents chose between milk brands A and B in the survey, a follow-up question asks how much they trusted the claim by the producer that Brand B was safe (*TrustLevelClaim*), within five categories from "not at all trust" to "very trusting". In reality, parents know neither the true safety level of milk nor the probability of milk being safe in this case. This trust level can be used to measure the perceived safety level of Brand B and represent *MilkSafety* in equation (2).[16] Parents also stated whether or not they consider the price as the most important characteristics to identify safe food (*PriceImportant*). The purpose of this question is to obtain additional information on parents' opinion to the relationship between price and safety.

[15] 15 yuan was the highest price I can find in the market at the time of the survey.
[16] The trust level of milk is the expected value of perceived safety level of brand B for the model in section 6.

This survey includes several questions relevant to *TotalIncome* in equation (2). Food expenditure and household size are collected to calculate food expenditure per capita (*FoodExp*). Per capita food expenditure provides an approximation of wage and non-labor income as wage and non-labor income are sensitive information that potentially would lead to fewer responses. The highest affordable increase in food expenditure (*AffordableExp*) and what other spending had to decrease if food became more expensive (*DecreaseExp*) reflect budget constraints that may influence the milk choice. The frequency of milk consumption (*MilkFrequency*) can also influence the financial situation of a household.

It is difficult to find detailed information about prices of non-milk goods and services, *OtherPrices* in equation (2). But school attended (*School*) provides an indicator for respondent location. Price levels in the same area tend to be similar but vary over locations. Different types of markets for grocery shopping (*ShoppingLocation*), such as supermarket and wet market, can also capture price differences. However, data on the initial health status of children is not available from the survey.

OtherFactors in equation (2) can include variables discussed and/or used in previous studies on risk, food safety and food choice, such as food safety concern, mass media, food safety knowledge, previous experience, and demographics such as gender (*Male*), *Age*, and *Education* (Sitkin and Pablo 1992; Baker 2003; Wilcock et al. 2004; Reilly 2006; Schroeder et al. 2007). I will discuss specific variables included in *OtherFactors* in the next few paragraphs.

Parents provided some information that can reflect their concern towards food safety in both subjective and objective ways. The information includes a stated concern level towards current food safety situation (*ConcernLevel*), whether their grocery stores or wet market publish food safety inspection results (*StorePublication*), how frequently they used mass media to check food safety (*CheckSafetyInfo*), and what and how many of their averting behaviors to avoid unsafe food were (*Averting*).

The influence of mass media can be reflected through whether parents heard any recent news on the food safety incidents that are provided in a survey question. The incidents were separated into two variables that represent the ones in and outside of Hunan province (*NumLocalNews* and *NonLocalNews*) because their influence may be different. Incidents closers to parents may have larger influences on their attitude towards food safety.

Parental knowledge of food safety management systems and food labels (*Knowledge*) is measured through their stated familiarity of those systems and labels. Those systems and labels can provide safety information of food. Parents may also obtain more safety information if they have friends or relatives work in food industry (*FoodJob*).

Consumer's previous experiences of dealing with food safety and quality issues (*Experience*) may influence their attitudes. This variable of previous experiences includes two parts of information. One is whether consumers took actions and the other one is how much time they spent and whether they are satisfied with the results if they took actions. Those who took actions and achieved satisfactory results with less time may be more optimistic about food safety and be less concerned about health risks compared to others.

3.3.3 Variables and Data

Fifty-six variables are generated from those survey questions (see Table 3.1 for definitions and descriptive statistics of variables). I received a relatively equal number of responses from each version of survey. According to the summary statistics of variables in Table 3.1, the majority of children drank milk almost every day. This confirms that milk is an important food in children's diets and it is crucial to understanding parents' choices of milk for policies to improve milk safety.

80% of respondents preferred Brand B (with a higher price and safety claim) as discussed previously. This is reasonable given that majority of respondents had heard recent news on food safety issues, especially on local issues. The fact that the majority chose Brand B is also reasonable given that 99% of respondents indicated they were more or less concerned about current food safety in Hunan province. The difference of safety levels tends to dominate the difference of price in this case.

Only 1% of respondents considered price as one of the most important characteristics to identify safe food. Many respondents probably realized that expensive milk was not necessarily safe milk. But even though the safety claim of Brand B was not completely reliable, only 25% of respondents completely or somewhat did not trust it.

Respondents put significant effort in improving the safety of food they consumed. They had an average of three averting behaviors to avoid unsafe food. It was common for them to use mass media to check safety information of food. 74% of respondents had experience taking actions to deal with food that has quality or safety issues, although many felt they spent too much time and energy without getting a satisfactory result. However, as important information to prevent unsafe food, respondents were not very familiar with food safety management systems and food labels, with only an average knowledge index of 4 out of 7.

Respondents averaged 37 of age and 13 years of education. 60% of respondents were female. This may because female are more involved in food decisions and grocery shopping in China. 38% of respondents had friends or relatives with a food related job. On average, the monthly food expenditure was 449 Chinese yuan per capita, and survey respondents thought they could afford a maximum increase of 167 Chinese yuan per capita on food, which was more likely to result in a cut in expenditure on leisure rather than saving and other expenditures.[17]

3.4 Marginal Effect of Influential Factors for Milk Choice

Even though my survey contains many potentially relevant variables, some of them are not explicitly suggested as independent variables by the theoretical model. The full model that contains all available variables is not necessarily the best fitting model for the data. To select a best fitting model, I use a stepwise model selection method to compare the AIC of multiple models that drop one variable at a time (Venables and Ripley 2002). The model with the lowest AIC is considered as the best fit. Table 3.3 presents the regression result of the full model (Model 1) and a selected model (Model 2).[18] The likelihood ratio test shows that the difference in fit between Models 1 and 2 is not significant; thus, the more restrictive model, Model 2, is the preferred model for this

[17] At the time of the survey, 1 yuan= 0.16 US dollar.

[18] Several variables are categorical variables. I create a dummy variable for each category. However, stepwise model selection method does not always select dummy variables of all categories for a categorical variable. In order to include full information from a categorical variable, if the dummy variable of at least one category is selected, I force the dummy variable of all categories of a categorical variable in Model 2.

study. Also, the Hosmer-Lemeshow chi-square test with 10 groups does not reject the null hypothesis that Model 2 is a good fit.

The marginal effect of independent variables on the probability of choosing Brand B is also presented in Table 3.3, in order to understand the influential factors for the choice of milk. The more a parent trusted the safety claim, the more likely he/she chose Brand B that has a safety claim. Compared to those who were neutral to the safety claim, parents who did not trust the safety claim at all had a 50% lower probability of choosing Brand B, while parents who were very trusting of the safety claim were 18% more likely to choose Brand B.

The price of Brand B also had some influence. There was 6-11% less probability of choosing Brand B when it was more expensive. However, when the price of Brand B was relatively low, a small increase in price, such as from 6 to 9 Chinese yuan, did not significantly influence parents' choice.

An increase of food expenditure per capita by one yuan led to a less than 0.1% higher probability of choosing Brand B. Higher food expenditures may indicate that the household was either richer or willing to spend more on food. Therefore, Brand B was more affordable to them and price was likely less of a concern compared to health risks.

The exposure to one more local food safety news item increased by 2% the probability of choosing Brand B. But among the 99% parents who claimed they were more or less concerned about the food safety situation in Hunan province, their concern level does not significantly influence their choice of milk.

A parent with one more averting behaviors to avoid unsafe food was more likely to choose Brand B by 2%. Since the choice of Brand B itself can be considered as an averting behavior, parents' choice was consistent with their behaviors.

The previous experience of dealing with food quality and safety issues had a weak influence on parents' choice. Compared to those who did not take any actions, parents with a positive experience (where they spent small amount of time and energy and got satisfactory results) were 5% less likely to choose Brand B (15% significance level). This may because parents with a positive experience had more confidence in their ability to solve safety issues if they happened, while other parents tried to avoid those issues through the choice of Brand B.

3.5 Aggregate Milk Choice by Prices and Perceived Safety Levels

The lemons principle focuses on qualitative analysis of people's choices considering the inconsistency, which is the joint effect, of quality and price of products. It only assumes high and low levels of quality and price, and does not further differentiate various magnitudes of high or low levels.

However, the marginal effect of influential factors for milk choice in section 4 shows that holding everything else constant, both different trust levels of the safety claim (perceived safety level) and different prices of Brand B (expensive with safety claim) influenced parents' choice of milk. Those differences cannot be captured by using the pooled data to directly count the percentage of parents choosing Brand B as the lemons principle. Therefore, I should further investigate the percentage of choosing Brand B at each price and perceived safety level of Brand B, after controlling other characteristics in Model 2 (see Table 3.4).

In Table 3.4, the lower left corner represents high inconsistency between price and perceived safety level of Brand B, while the upper right corner represents high consistency between price and perceived safety level. The probability of choosing Brand B increased from about 20% to 99% as the difference of perceived safety level increases and price difference decreases. This means when the price and perceived safety level of Brand B is highly inconsistent, parents' choice tend to follow the lemons principle. But when the price and perceived safety level become more consistent, the majority of parents made an anti-lemon choice at some point. Therefore, the magnitude of inconsistency for Brand B matters.

The turning point appears when parents somewhat did not trust the safety claim and the price is 12 yuan or less. Those parents, as well as parents who were neutral or trust the safety claim of Brand B at any given price, were consistently more likely to choose Brand B. It does not seem rational to choose a brand even when parents somewhat did not trust the safety claim of this brand. I am also curious about the reason for such high percentage of choosing Brand B when parents were neutral about the safety claim (70-86%).

It is worth noting that parents were significantly more likely to choose Brand B when its price and perceived safety level are both high (lower right corner of Table 3.4 with a probability of 97%), while they were less in favor of Brand B when its price and perceived safety level are both low (upper left corner with a probability of 38%). Perceived safety level seems to have a more dominant effect on parents' choice than the price. This may be relevant to the observation that more parents chose Brand B when they were neutral or even somewhat did not trust the safety claim of this brand. To address this, I build a theoretical model in the next section.

3.6 Risk Aversion to the Inconsistency of Price and Perceived Safety Level

One issue the lemons principle does not consider is people's risk aversion to the inconsistency of price and perceived safety level. Risk aversion may play an important role in parents' choice of milk in my survey due to a unique characteristic of food market.

A significant difference between food market, including milk market, and some other markets is that food relates to health. Even though the inconsistency between price and safety level provides an incentive to choose lemons, the inconsistency is not the only concern when health is involved. Cheap milk may in fact be more likely to have a greater safety risk. Health concerns can cause parents to make an anti-lemons choice for more expensive but possible safer milk. Therefore, parents may need to weigh the inconsistency concern and the health concern in making their milk choice.

The influence of health concern can be reflected by parents' risk aversion to the inconsistency between milk price and safety. If parents put more weight on health concern (health lovers), then they care less about the inconsistency and prefer possible safer products. Therefore, they are risk seekers. If parents put more weight on the inconsistency concern (consistency lovers), then they are risk averters.

To understand the influence of risk aversion, I need go back to individual parent's choice first. The price and perceived safety level of Brand B do not vary for an individual parent. Therefore, I assume there are two prices, high price P_M^h and low price P_M^l, and two safety levels, high safety level f^h and low safety level f^l for brands A and B.

Brand A has the low price P_M^l. Brand A is likely to have the low safety level f^l, which matches its low price. This is because the producer does not have incentive to charge a low price for milk with high safety level due to the additional cost to ensuring safety.

Brand B has the high price P_M^h. It is reasonable to believe that the producer may over-price unsafe milk and make more profit when there is a lack of supervision on the production of milk. Asymmetric information between producers and consumers creates uncertainty about whether Brand B has the high safety level that matches its high price for consumers. Therefore, I assume a probability π that Brand B has the high safety level f^h, and a probability of $1-\pi$ that Brand B has the low safety level f^l.

Assume an inconsistency index $A(f, P_M)$ can capture the joint influence of milk price and safety level on utility in the model for the discussion of individual milk choice. Utility should increase with the index $A(f, P_M)$ when a brand of milk is safer and decrease with the index $A(f, P_M)$ when this brand of milk is more expensive.

$A(f, P_M)$ can have many formats. Without losing generality, one possibility is for the index $A(f, P_M)$ to be the ratio of safety level and milk price ($\frac{f}{P_M}$). To include this inconsistency index in utility function (1), I can rewrite the utility function as

$$U^* = U\left(\frac{f}{P_M} \times P_M, P_M, P_N, P_I, P_C, W, V, H^0, X, \varphi\right) = U\left(\frac{f}{P_M}, P_M, P_N, P_I, P_C, W, V, H^0, X, \varphi\right)$$

Therefore, utility depends on the ratio of safety level and milk price, all prices, the wage and non-labor income, the initial health status of the child, and other factors. A smaller value of $\frac{f}{P_M}$ indicates less consistency between price and safety. Since parents are always opposed to inconsistency between price and safety, U^* is an increasing function of $\frac{f}{P_M}$. Therefore, $\frac{\partial U^*}{\partial \frac{f}{P_M}} > 0$, $\frac{\partial U^*}{\partial f} > 0$, and $\frac{\partial U^*}{\partial P_M} < 0$.

The indirect utility function of a parent choosing Brand A is

$$U_A^* = U\left(\frac{f^l}{P_M^l}, P_M^l, P_N, P_I, P_C, W, V, H^0, X, \varphi\right)$$

and the expected indirect utility function of a parent choosing Brand B is

$$E(U_B^*) = \pi U_{Bh}^* + (1-\pi)U_{Bl}^*$$

where π is the probability of Brand B having high safety level. $U_{Bh}^* = \left(\frac{f^h}{P_M^h}, P_M^h, P_N, P_I, P_C, W, V, H^0, X, \varphi\right)$ is the utility from Brand B with high safety level. $U_{Bl}^* = U\left(\frac{f^l}{P_M^h}, P_M^h, P_N, P_I, P_C, W, V, H^0, X, \varphi\right)$ is the utility from Brand B with low safety level. $U_{Bh}^* > U_{Bl}^*$.

Parents' choice of milk depends on the magnitude of U_A^* and $E(U_B^*)$. They will choose Brand B if $U_A^* < E(U_B^*)$, vise versa. When a parent makes the choice between any two given brands, many factors in the indirect utility function are the same for both brands, such as non-milk prices P_F, P_I, P_C and wage W. But two factors can influence his/her choice. The first factor is inconsistency index, $\frac{f}{P_M}$, for Brands A and B. The second factor is parents' risk aversion to $\frac{f}{P_M}$.

Inconsistency index $\frac{f^l}{P_M^l}$ (for Brand A) is always larger than $\frac{f^l}{P_M^h}$ (for Brand B with high price and low safety level). Therefore, the utility U_A^* for Brand A is larger than U_{Bl}^* for Brand B with high price and low safety level, holding everything else constant.

But the relationship between $\frac{f^h}{P_M^h}$ (for Brand B with high price and high safety level) and $\frac{f^l}{P_M^l}$ is not determined with two possible situations. When Brand B is much more expensive than Brand A or the safety level of Brand B is not much higher than Brand A, $\frac{f^h}{P_M^h} < \frac{f^l}{P_M^l}$ and $U_{Bh}^* < U_A^*$, holding everything else constant. No matter what risk aversion a parent has, he/she should always choose Brand A. Therefore, I will not focus on this case.

When Brand B is not much more expensive than Brand A or the safety level of Brand B is much higher than Brand A, $\frac{f^h}{P_M^h} > \frac{f^l}{P_M^l}$ and $U_{Bh}^* > U_A^*$, holding everything else constant. A parent should compare the expected utility of Brand B, $E(U_B^*)$, and the utility of Brand A, U_A^*. His/her choice of milk depends on the risk aversion and the magnitude of $\frac{f^l}{P_M^h}$, $\frac{f^h}{P_M^h}$ and $\frac{f^l}{P_M^l}$ as shown in Figure 3.2. The value of inconsistency index increases towards right, as the safety and price become more consistent.

It is worth mentioning that in my survey data, the low safety level f^l and price P_M^l are fixed, but the high safety level f^h and price P_M^h varies across parents. Graphs that reflect the variation of f^h and P_M^h can be complicated, give that both inconsistency indices of Brand B, $\frac{f^l}{P_M^h}$ and $\frac{f^h}{P_M^h}$, change. However, parents' choice should be influenced by the relative magnitude of the high and low values, rather than the absolute magnitude. Therefore, I fix the high safety level and price, and allow changes in the low safety level and price in all graphs. A larger difference of prices caused by a lower price of Brand A in the graphs is equivalent to a larger difference of prices caused by a higher price of Brand B from the survey data. The difference of safety level is similar.

According to previous discussion, Figure 3.2a presents the convex utility curve of a health lover (risk seeker to the inconsistency). This parent is willing to take the risk of inconsistency between price and safety of Brand B as long as Brand B has some chance to be safer. Therefore, the expected utility of Brand B, $E(U_B^*)$, is higher than the utility of expected inconsistency index:

$$U_B\big(E(f)/P_M^h\big) = U_B\left(\pi\frac{f^h}{P_M^h} + (1-\pi)\frac{f^l}{P_M^h}\right) = U_B\left(\frac{\pi f^h + (1-\pi)f^l}{P_M^h}\right)$$

Point T is at a level of inconsistency index where the corresponding utility is equal to $E(U_B^*)$. When the inconsistency index of Brand A $\frac{f^l}{P_M^l}$ is at point T, the utility of Brand A $U_A^* = E(U_B^*)$. The health lover is indifferent between brands A and B. When $\frac{f^l}{P_M^l}$ is smaller than the level at point T, $E(U_B^*) > U_A^*$, holding everything else constant. The health lover chooses Brand B with higher price and safety claim, vise versa.

As shown in Figure 3.2a, the point T is always on the right side of $E(f)/P_M^h$ in this situation. When $\frac{f^l}{P_M^l}$ is between $E(f)/P_M^h$ and point T, even though the expected inconsistency level of Brand B is lower than the inconsistency level of Brand A, the health lover still chooses Brand B due to the larger weight on health concern. He/she is relatively tolerant of the inconsistency of Brand B.

Only when $\frac{f^l}{P_M^l}$ is on the right side of point T, does the health lover choose Brand A. The inconsistency index $\frac{f^l}{P_M^l}$ is relatively far away from $\frac{f^l}{P_M^h}$ and is close to $\frac{f^h}{P_M^h}$. This means the high price of Brand B P_M^h is much larger than the low price of Brand A P_M^l, but difference between high safety level f^h and low safety level f^l is not large enough.

Brand A with slightly lower safety level and/or much cheaper price than Brand B can be very attractive, even the health lover with great health concern is willing to give up Brand B.

When Brand B has a higher probability to be safer (π increases), the expected utility of Brand B increases to $E'(U_B^*)$. The threshold point also increases from T to T'. Brand B becomes a better choice. Therefore, the health lover will need even higher safety level and/or lower price of Brand A than the situation at point T to switch to Brand A.

Moreover, the health lover can be heterogeneous, which leads to different thresholds (point T and T') to switch between brands A and B (see Figure 3.3). Figure 3.3 presents an example of a more extreme health lover and a more moderate health lover who are both risk seekers. Both of them have the same inconsistency index $\frac{f^h}{P_M^h}$ and $\frac{f^l}{P_M^h}$ for Brand B with high and low safety levels. They also have the same expected inconsistency index $\frac{E(f)}{P_M^h}$ for Brand B, which means the probability of Brand B to have a high safety level is the same. The utility curve of the extreme health lover is more convex than the moderate one.

In Figure 3.3, the difference between the expected inconsistency index $\frac{E(f)}{P_M^h}$ for Brand B and threshold point T for extreme health lover is larger than the difference between $\frac{E(f)}{P_M^h}$ and threshold point T' for a moderate health lover. A larger difference between $\frac{E(f)}{P_M^h}$ and threshold point T for $\frac{f^l}{P_M^l}$ in this situation means the difference between $E(f)$ and f^l is larger, and/or the difference between P_M^h and P_M^l is larger (i.e. the low safety level f^l is not much less than the high safety level f^h, and/or the low price P_M^l is much less than the high price P_M^h).

The indication of Figure 3.3 for the two health lovers is that to make the extreme health lover choose Brand A, $\frac{f^l}{P_M^l}$ has to be larger than point T; while to make the moderate health lover choose Brand A, $\frac{f^l}{P_M^l}$ only has to be larger than point T'.

For $\frac{f^l}{P_M^l}$ between points T' and T, only the moderate health lover chooses Brand A. This is because the low safety level f^l is not high enough comparing to the high safety level f^h, and/or the low price P_M^l is not low enough comparing to the high price P_M^h. In other words, the price difference does not significantly overwhelm the safety difference. The extreme health lover does not find it worth to give up his/her great health concern and switch to Brand A. On the other hand, the moderate health lover, who weighs the inconsistency concern slightly higher, may find f^l and P_M^l attractive enough comparing to f^h and P_M^h.

For a consistency lover who puts more weight on the concern of inconsistency between safety and price than health concern, his/her concave utility curve is shown in Figure 3.2b. Compared to the situation in Figure 3.2a, a much lower inconsistency index of Brand A $\frac{f^l}{P_M^l}$ can lead to the choice of Brand A. Even when $\frac{f^l}{P_M^l}$ is lower than the expected inconsistency index of Brand B $\frac{E(f)}{P_M^h}$, the consistency lover may still choose Brand A. When Brand B has a higher probability to be safer (π increases), the consistency lover can switch to Brand B at a slightly higher price and/or lower safety level, comparing to the situation before π increases. Brand B can be very attractive only when it has slight higher price and/or much safer level than Brand A. Even the consistency lover with great concern on inconsistency is willing to give up Brand A for this Brand B.

Parents' choice of milk is influenced by the relative magnitude of inconsistency indices of brands A and B. The relative magnitude of inconsistency is determined by the relative magnitude of price difference and safety difference. When the safety difference dominates the price difference, the difference of expected inconsistency index of Brand B $\frac{E(f)}{P_M^h}$ and inconsistency index of Brand A $\frac{f^l}{P_M^l}$ will increase, vise versa.

In Figure 3.4, I summarize the choice of milk by different types of parents with difference relationship of price difference and safety difference. Both health lovers and consistency lovers will choose Brand B with higher price and safety claim if the safety difference significantly overwhelms the price difference, vise versa. But when the safety difference does not significantly overwhelms the price difference, an extreme consistency lover switches to Brand A with lower price and no safety claim first, followed by moderate consistency lover, and vise versa.

From the aggregate level, when there are equal amount of identical moderate and extreme health and consistency lovers, and the probability of Brand B having high safe level is 50%, I would expect that half of parents choose Brand A and the other half choose Brand B. A larger share of health lovers will increase the amount of parents who choose Brand B. Safer Brand B can also make both risk seekers and risk averters more likely to choose Brand B. However, risk averters or seekers were not identical. The shape and location of utility curve can vary across parents, which lead to unique threshold T and different choices for each parent even when they face the same options.

In summary, I have found in previous sections that some components from utility function (1) (e.g., food expenditure, etc.) influence parents' choice of milk. But one important influence may come from the relative magnitude of safety difference and price difference between brands A and B, coupled with parents' risk aversion to the inconsistency between price and safety, that reflects how parents weigh health concern and inconsistency concern. Reasons for choosing Brand B include: (1) Assume Brand B has a 50% chances to be safe. There are the same amount of identical extreme and moderate health lovers and consistency lovers. Price difference and safety difference do not dominate each other. I would expect half of parents choose Brand A and the other half choose Brand B. A larger share of extreme and moderate health lovers will result in the choice of Brand B by a majority of parents; (2) When parents are not identical, for parents who are more extreme health lovers, they are more likely to choose Brand B even when the safety difference is very small and the price difference is very large between brands A and B; (3) An increase of safety difference and/or a decrease of price difference can cause more people to choose Brand B. When safety difference overwhelms price difference, even risk averters can switch to Brand B, especially the more moderate ones. Therefore, majority of parents will choose Brand B, regardless of their risk aversion to the inconsistency.

The result of this model provides some potential answers to questions raised in section 5. The majority of parents chose Brand B with higher price and safety claim, even those who somewhat did not trust the safety claim of Brand B. Given the food safety situation at the time of survey, it is highly possible that the majority of parents were health lovers and therefore were more likely to choose Brand B.

Also, when parents made their choice, they were considering the relative magnitude of price difference and safety difference. Therefore, the price difference for parents who somewhat did not trust the safety claim may not overwhelm the safety difference when the price of Brand B is 12 yuan and less, given their risk aversion and individual utility. It is possible that those parents belong to extreme health lover in the second column or even the third/fourth columns of Figure 3.4. When the price of Brand B rises to 15 yuan, the price difference does overwhelm the safety difference and majority of parents chose Brand A.

However, to empirically test this theoretical model with risk aversion, I need data on risk aversion to the inconsistency between price and safety. This data is not available from my survey and may also be difficult to collect. For future study, I may use clustering methods to group my observations into possible health lovers and consistency lovers, and then incorporate the group information into my empirical model for the choice of milk.

3.7 Discussion and Conclusion

Parents' hypothetical choice of milk found in this study shows they tended to make anti-lemons choice and demanded for safer milk in general. It provides some evidence to support the hypothesis that in markets where products differ in terms of safety level but the true safety levels are unknown to consumers, consumers' choice may not follow the lemons principle. This is because even though concern about inconsistency between price and safety level can lead to the choice of a lemon, the concern on safety risk provides an opposite incentive that can lead to the anti-lemons choice. Consumers' choice can be influenced by how they weigh these two concerns.

However, when the safety difference significantly dominates the price difference between two products, I would expect a stronger tendency of an anti-lemons choice, regardless of how consumers weigh the two concerns. My empirical result supports this and shows a higher probability of making anti-lemons choice when the perceived safety level increases and the price decreases for the expensive brand of milk with safety claim. Paying a relatively small additional cost for a relatively much safer product can be attractive even for some consistency lovers who have more concern about the inconsistency between price and safety.

As discussed previously, consumer choice in this type of market can cause issues. Information asymmetry allows some producers to make a higher profit by selling unsafe products with higher prices, which further distorts the market. This happened in China when safety risks were found in some imported milk products that used to be perceived safer by consumers. These producers not only put negative influence on consumers' welfare, but also make it difficult for producers of safe products to compete with them because producers of safe products have additional cost to ensure safety. Also, consumers' choice may lead to an increase of price, which may raise the burden especially for low-income households or lead some households to switch to cheap and unsafe substitutes.

Similar to the lemons principle, reducing information asymmetry is a possible solution for market failure in this type of market. However, this can be costly and difficult to achieve for every product especially when many small producers exist in the market.

There are some possible alternatives. If producers in a market have a negative reputation, the business of all producers will be influenced. Some producers may realize this and therefore are willing to provide safe products. Producers of safe products and consumers can have some mutual interest in this type of market. These producers can provide desired products for consumers, while consumers' demand and financial support can help these producers to survive in the market. To increase demand for their products, these producers only need to accumulate good reputation to increase perceived safety level of their products among consumers, such that the difference of perceived safety level between their products and other products can significantly dominate the price difference. Policymakers can also create some incentives to increase the long run benefit of producing safe products.

Even though safety is an important issue in this type of market, consumers' choice can lead to a segmented market where low-income households may not be able to afford expensive safer products and end up purchasing cheap and less safe products. Policymakers should also consider welfare of low-income households and implement policies to reduce safety risks for them.

The timing of this survey may be special. Parents were very concerned about food safety at the time of the survey, which may explain such a strong preference to expensive milk with safety claim. In a less extreme case, I would expect a smaller difference between the proportion of parents who choose brands A and B. Also, the purchase of food is not an expensive one-time choice consumers have to face in a long time period (i.e., a durable good such as a car). If they do find safety issues in those foods that are claimed to be safe, they can easily switch to a substitute. People’s behavior may change for an expensive one-time choice.

Table 3.1 Definitions and descriptive statistics of variables

Variable	Meaning	Mean	Std. Dev.	Min	Max
Dependent variable					
ChoseBrandB	A parent chose Brand B (claimed safe) milk [a]	0.80	0.40	0	1
Independent variables					
School					
School1	The first school in Changsha city	0.08	0.27	0	1
School2	The second school in Changsha city	0.11	0.31	0	1
School3	The third school in Changsha city	0.18	0.38	0	1
School4	The fourth school in Changsha city	0.11	0.31	0	1
School5	The first school in Huaihua city	0.14	0.35	0	1
School6	The second school in Huaihua city	0.14	0.35	0	1
School7	The third school in Huaihua city	0.12	0.32	0	1
School8	The fourth school in Huaihua city	0.13	0.34	0	1
ConcernLevel	**Concern level of current food quality and safety in Hunan**				
NotConcerned	Not at all concerned	0.01	0.11	0	1
SomewhatConcerned	Somewhat concerned	0.23	0.42	0	1
FairlyConcerned	Fairly concerned	0.39	0.49	0	1
VeryConcerned	Very concerned	0.36	0.48	0	1
NumLocalNews	The number of recent local news report food safety issues a respondent have heard about, which are listed in the survey question	1.46	0.68	0	2
NonLocalNews	Whether a respondent have heard about a recent non-local news report food safety issues, which is listed in the survey question	0.57	0.50	0	1
StorePublication	**Publication of food safety inspection results by store/market where you purchase food**				
PublishInspection	Store publishes food inspection results	0.13	0.34	0	1
NotPublishInspection	Store doesn’t publish food inspection results	0.60	0.49	0	1
NotSureInspection	Not sure if store publishes food inspection results	0.27	0.44	0	1
Knowledge	A knowledge index on food labels and food safety management systems. The	3.58	1.46	0	7

	survey provides three food safety management systems (HACCP, ISO9000, ISO22000) and five food labels (pollution-free agricultural product, green food, quality safety, organic food and a fake one). Those systems and labels are supposed to help improving food safety and guide people's choice of food brands. The survey asked parents if they had heard of/seen or even know the meaning of those labels and systems. For each system or label, heard of/seen it or even know the meaning represents 1 point, 0 point otherwise. Parents can get up to 7 points in total. But they lose half of the points if they had heard of/seen or even knew the meaning of the fake label.				
CheckSafetyInfo	**Frequency of using mass media to check food safety information**				
NeverCheckInfo	Never	0.08	0.27	0	1
SometimesCheckInfo	Sometimes	0.30	0.46	0	1
FairlyOftenCheckInfo	Fairly often	0.45	0.50	0	1
VeryOftenCheckInfo	Very often	0.16	0.37	0	1
PriceImportant	Respondent agreed that "price is one of the most important characteristics to identify safe food"	0.01	0.12	0	1
FoodExp	Monthly food expenditure per capita in yuan	449.35	177.39	41.67	1000
AffordableExp	Affordable increase in food expenditure per capita in yuan	166.86	119.82	4.17	750
DecreaseExp	**Additional food expenditure would decrease…**				
DecreaseSaving	Saving	0.32	0.47	0	1
DecreaseLeisure	Leisure	0.59	0.49	0	1
DereaseOther	Other	0.09	0.28	0	1
MilkFrequency	**Frequency of children drinking milk**				
DrinkLessThan1	Less than once a week	0.10	0.29	0	1
DrinkAtLeast1	At least once a week	0.24	0.43	0	1
DrinkAlmostDaily	Almost every day	0.67	0.47	0	1
MilkPrice	**Milk price of Brand B in yuan per 250ml**				
Price6	6 yuan	0.24	0.43	0	1
Price9	9 yuan	0.26	0.44	0	1
Price12	12 yuan	0.25	0.43	0	1

Price15	15 yuan	0.26	0.44	0	1
TrustLevelClaim	**Trust level of the special safety claim by the producer of Brand B milk**				
NotTrust	Not at all trust	0.04	0.19	0	1
SomewhatNotTrust	Somewhat not trust	0.21	0.41	0	1
Neutral	Neutral	0.29	0.46	0	1
SomewhatTrust	Somewhat trust	0.42	0.49	0	1
Trust	Completely trust	0.04	0.19	0	1
ShoppingLocation	**Location of grocery shopping**				
ShopWetMarket	Wet market or other	0.17	0.38	0	1
ShopSupermarket	Supermarket	0.83	0.38	0	1
Averting	The number of averting behaviors to avoid unsafe food. Those behaviors include avoid food with high safety risk, only choose brands you trust, use tricks to choose relatively safer food, make processed food at home, grow vegetables or raise poultry by yourself, get agricultural products from you farmer relatives, purchase imported foods, other	3.06	1.40	0	7
Experience	**Result from previous experience of dealing with food that has a quality or safety problem**				
SatisfiedSpentLittle	Satisfied & spent a little time and energy	0.19	0.39	0	1
SatisfiedSpentMuch	Satisfied & spent too much time and energy	0.18	0.38	0	1
NotSatisfiedSpentLittle	Not satisfied & spent a little time and energy	0.21	0.41	0	1
NotSatisfiedSpentMuch	Not satisfied & spent too much time and energy	0.17	0.38	0	1
NoAction	Not take action	0.25	0.44	0	1
Male	Male	0.40	0.49	0	1
FoodJob	Have friends or relatives with food related job	0.38	0.48	0	1
Age	Age	37.31	6.29	24	74
Education	Years of education	13.27	2.62	0	22

[a] The number of observation is 1,143.
[b]All indicator variables in this table take 1 if it is true, 0 otherwise.

Table 3.2 Comparison between sample and city population

	Sample		City Population	
	Changsha	Huaihua	Changsha	Huaihua
Annual food expenditure per capita [a,b,c]	[4870,6496]	[4391, 5992]	7366	4446
Years of education [d]	13.1	13.5	12.5	8.5

[a] Since the food expenditure data gathered through my survey is categorical, I use the lower and higher bounds of each category to calculate the lowest and highest possible average per capita food expenditure, which is the range in sample.

[b] Population data source: Statistical Bureau of Hunan Province

[c] Since Hunan Statistical Yearbook 2014 does not include food expenditure data from 2013, I use food expenditure data from 2012 with adjustment of inflation.

[d] Population years of education in Huaihua is 2010 data.

Currently there are two brands of milk (milk A and milk B) in domestic market. They look the same except the price and safety claim. Which brand would you choose for your children?

	Milk A	Milk B
Price:	￥3/250ml	￥6/250ml
Safety claim:	There is no special safety claim from the producer.	The producer claims that they guarantee the safety of this milk.
I choose ⟶	A	B

Figure 3.1 Sample question that simulates the choice in the “lemons principle”

Table 3.3 Estimated result of logistic regression and marginal effect of the final model

	Model 1: Full Model			Model 2: Selected Model			Model 2: Marginal Effect of Independent Variables at Mean		
ChoseBrandB	Coef.	Std. Err.	P>z	Coef.	Std. Err.	P>z	dy/dx	Delta-method Std. Err.	P>z
MilkPrice									
Price9	-0.082	0.270	0.762	-0.063	0.267	0.814	-0.005	0.022	0.813
Price12	-0.559	0.258	0.031	-0.551	0.255	0.030	-0.056	0.026	0.031
Price15	-0.986	0.258	<0.001	-0.931	0.253	<0.001	-0.110	0.030	<0.001
TrustLevelClaim									
NotTrust	-2.316	0.415	<0.001	-2.251	0.406	<0.001	-0.504	0.082	<0.001
SomewhatNotTrust	-1.076	0.207	<0.001	-1.002	0.200	<0.001	-0.205	0.041	<0.001
SomewhatTrust	1.683	0.253	<0.001	1.741	0.251	<0.001	0.158	0.024	<0.001
Trust	2.668	1.047	0.011	2.728	1.039	0.009	0.184	0.028	<0.001
PriceImportant	2.158	1.141	0.059	2.391	1.132	0.035	0.265	0.125	0.033
FoodExp	0.001	0.001	0.050	0.002	0.001	0.003	<0.001	<0.001	0.003
AffordableExp	0.002	0.001	0.103						
DecreaseExp									
DecreaseSaving	-0.181	0.192	0.345						
DecreaseOther	0.267	0.338	0.430						
MilkFrequency									
DrinkLessThan1	-0.047	0.285	0.869	-0.076	0.277	0.785	-0.009	0.034	0.789
DrinkAtLeast1	0.335	0.222	0.131	0.334	0.218	0.126	0.035	0.021	0.104
School									
School1	0.578	0.413	0.161	0.654	0.400	0.102	0.081	0.047	0.084
School2	0.198	0.357	0.578	0.341	0.341	0.316	0.047	0.047	0.312
School3	0.295	0.311	0.343	0.364	0.300	0.225	0.050	0.042	0.235
School4	0.302	0.349	0.387	0.359	0.337	0.287	0.049	0.046	0.283
School5	0.634	0.327	0.052	0.588	0.320	0.066	0.075	0.041	0.071

School6	0.400	0.335	0.233	0.477	0.327	0.145	0.063	0.043	0.147
School7	1.200	0.369	0.001	1.139	0.361	0.002	0.120	0.039	0.002
ShopWetMarket	-0.234	0.220	0.286						
Male	0.147	0.187	0.430						
Age	0.003	0.015	0.858						
Education	-0.001	0.039	0.988						
ConcernLevel									
NotConcerned	1.939	1.140	0.089	1.964	1.134	0.083	0.102	0.027	<0.001
SomewhatConcerned	-0.358	0.247	0.148	-0.361	0.239	0.131	-0.044	0.030	0.142
FairlyConcerned	-0.017	0.214	0.935	-0.002	0.209	0.993	<0.001	0.022	0.993
StorePublication									
PublishInspection	0.290	0.282	0.304						
NotSureInspection	0.078	0.204	0.703						
CheckSafetyInfo									
NeverCheckInfo	0.226	0.387	0.559						
SometimesCheckInfo	-0.111	0.285	0.697						
FairlyOftenCheckInfo	0.106	0.268	0.693						
Averting	0.191	0.069	0.006	0.175	0.066	0.008	0.019	0.007	0.008
NumLocalNews	0.199	0.138	0.149	0.217	0.132	0.100	0.024	0.015	0.101
NonLocalNews	0.187	0.187	0.317						
Knowledge	-0.091	0.068	0.178						
FoodJob	-0.295	0.182	0.105	-0.265	0.177	0.135	-0.029	0.020	0.134
Experience									
SatisfiedSpentLittle	-0.411	0.271	0.130	-0.419	0.264	0.112	-0.050	0.032	0.124
SatisfiedSpentMuch	-0.154	0.286	0.589	-0.135	0.279	0.628	-0.014	0.030	0.632
NotSatisfiedSpentLittle	-0.134	0.260	0.605	-0.134	0.255	0.597	-0.014	0.027	0.599
NotSatisfiedSpentMuch	0.026	0.289	0.929	0.042	0.282	0.882	0.004	0.028	0.881
Constant	0.003	0.953	0.997	-0.102	0.488	0.835			

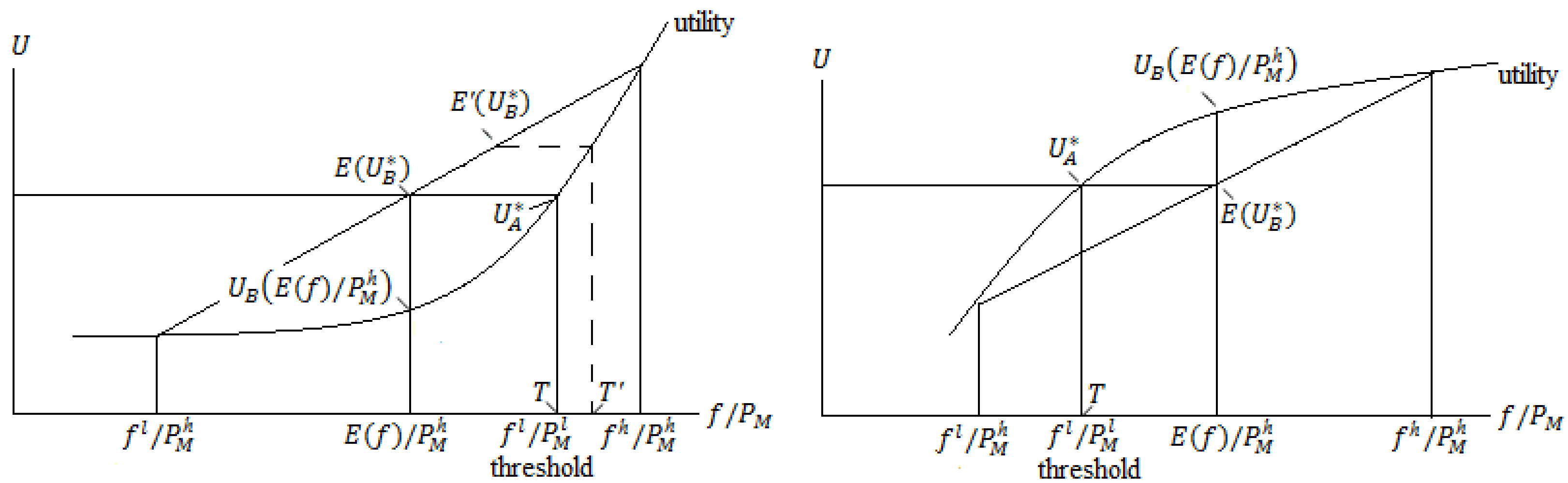
N	1143	1143
Log likelihood	-428.908	-435.381

[a] The dependent variable is a parent choosing Brand B (claimed safe) milk.

Table 3.4 Probability of choosing Brand B (more expensive with safety claim) at different prices and trust levels[a]

	Trust level of safety claim for Brand B				
Price of Brand B	Not at all trust	Somewhat not trust	Neutral	Somewhat trust	Completely trust
6 yuan	38%	69%	86%	97%	99%
9 yuan	37%	67%	85%	97%	99%
12 yuan	26%	56%	77%	95%	98%
15 yuan	20%	46%	70%	93%	97%

[a] Remaining independent variables are set to their mean value.



a. Risk seeker/health lover

b. Risk averter/consistency lover

Notes: f^l/P_M^l: inconsistency index for Brand A

f^l/P_M^h: inconsistency index for Brand B with high price and low safety level

f^h/P_M^h: inconsistency index for Brand B with high price and high safety level

$E(f)/P_M^h$: expected inconsistency index for Brand B

Figure 3.2 Choice of milk by health lover and consistency lover

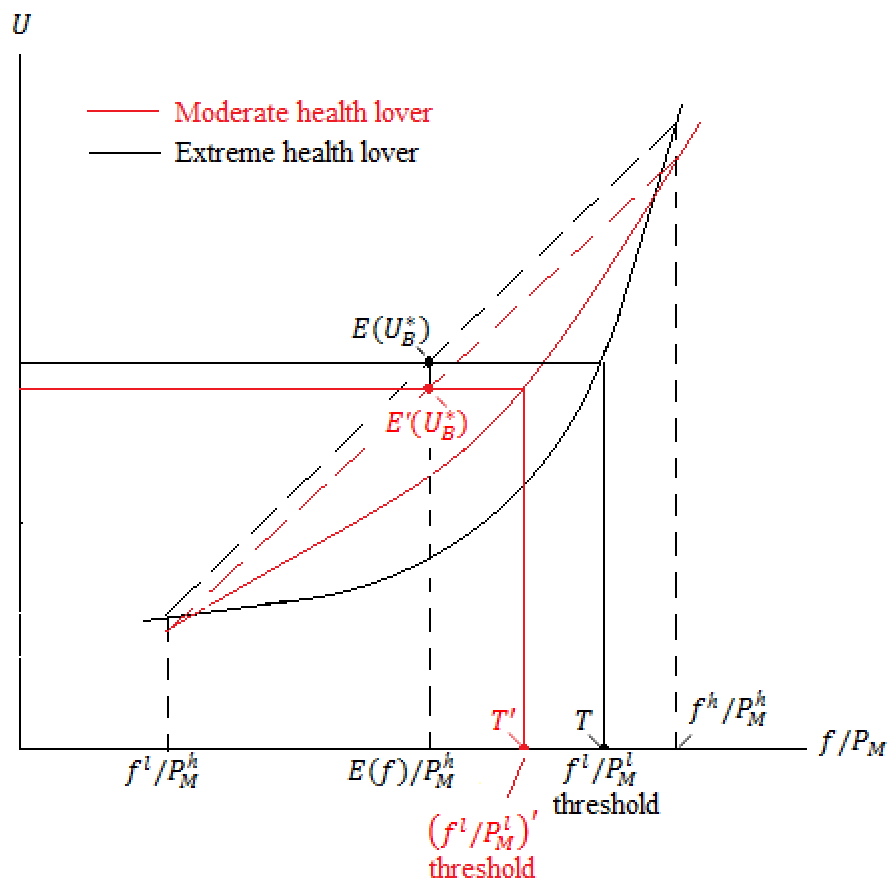


Figure 3.3 Extreme health lover vs. moderate health lover based on Figure 3.2a

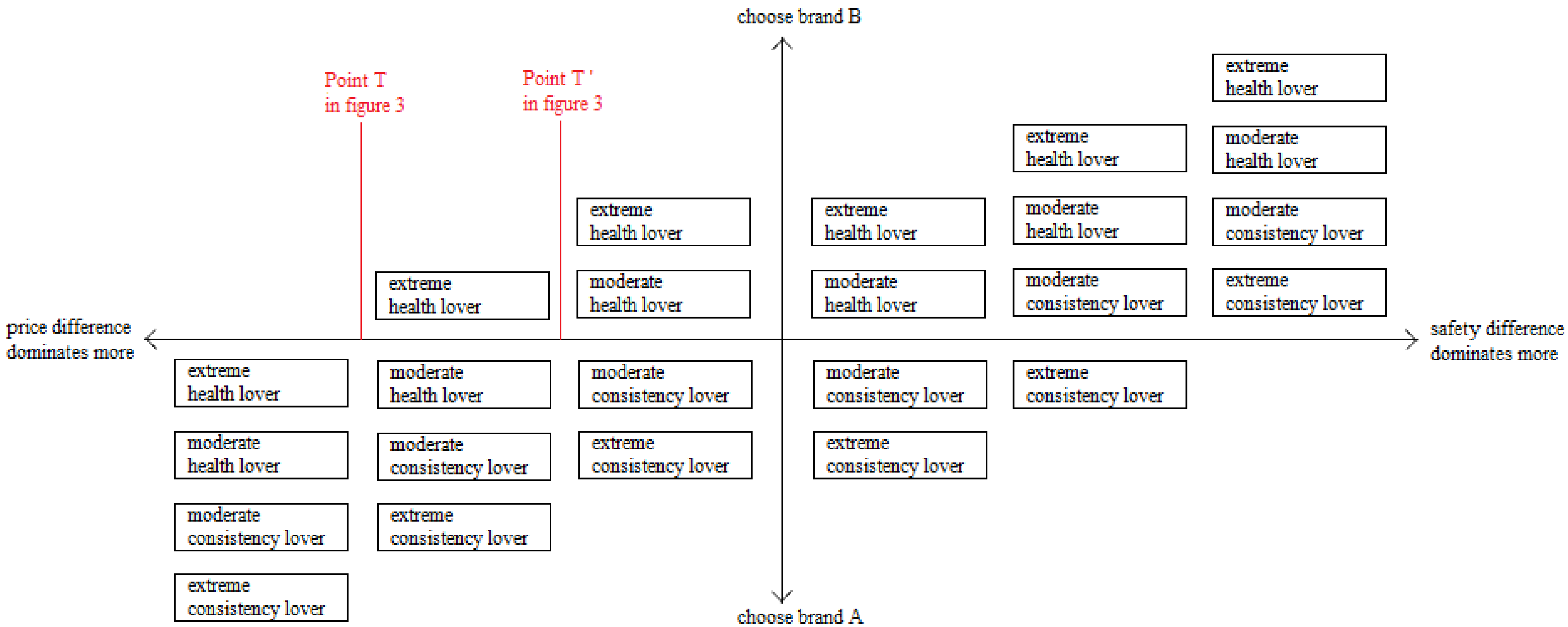


Figure 3.4 Choice of milk by different groups

CHAPTER 4: A Dynamic Game of Pollution Emissions and Resource Extraction

4.1 Introduction

Climate change is a serious global concern, due to negative externalities and the uncertainty of the impact on, for example, food security and human health (McMichael 2013; Wheeler and von Braun 2013). Human activities are a significant factor in climate change. In this study I explore the dynamic interaction of human activity, which influence climate over time. A better understanding of these interactions can provide insight into strategies for responding to climate change.

Climate change, the long-term change in prevailing weather conditions, is partially manifested through changing temperatures. The world average temperature level increased by 1.5°F over the past century and is forecast to increase even further in the future. However, there is a great deal of uncertainty and variation in projected temperatures ranging from 0.5 to 8.6°F over the next century (EPA 2017a). Human activities, especially the use of fossil fuel, contribute to climate change by generating greenhouse gases (GHG). As a major component of GHG, global emissions of CO_2 have increased by 90% since 1970 (EPA 2017b). The rapid increase in emissions leads to higher concentrations of GHG in the atmosphere that trap heat and change the climate.

Fossil fuel is an important source of energy for economic development and people's daily lives. At the current time, fossil fuel use will generate more GHGs. Sustainable development requires finding a balance between uses of fossil fuel and mitigation of climate change. Moreover, GHG are stock pollutants. Even GHG emissions from one region can increase GHG concentrations and lead to global impact.

Climate change policies should be implemented to mitigate climate change. Command-and-control, as a direct regulation, sets pollution reduction targets for firms. However, it may not be efficient if firms have the same pollution reduction target but different marginal reduction cost. Therefore, market approaches, such as cap-and-trade, are increasingly popular.

Cap-and-trade sets a total emissions cap for all agents and allows them to purchase pollution permits, based on permit price and pollution reduction costs. Currently, there are several international and regional cap-and-trade systems in the world. The European Union's Emissions Trading System (EU ETS) is the world's first major carbon market based on the cap-and-trade approach. It covers 45% of CO_2 emissions in the EU and is targeting a reduction of 40% of GHGs by 2030 compared with 1990 levels. The allocation of permits is mostly free and by auctioning. In Phase II (2008 to 2012) of the EU ETS, total emissions were less than the allocated permits allowed for all years except 2008, and price decreased due to an imbalance of supply and demand for permits (IETA 2015). As the largest CO_2 emitter in the world, China has begun to develop its own regional ETS in 2013, which includes five cities and two provinces, using free allocation of permits (IETA 2016).

Understanding the interactions of societies can provide insight for economic and environmental policies. In this study, I develop a model for a differential game to explore how two agents react to the other player's polluting behavior and how they balance the use of fossil fuel and mitigation of climate change under a cap-and-trade system. This study contributes to the dynamic pollution game literature by simultaneously considering resource extraction, the use of clean technology and carbon trade in the model. It also uses general functional forms and, therefore, allows for a more complete consideration of outcomes than the extant literature, where linear functional forms are the norm.

In section two, I summarize previous studies on dynamic pollution games. In section three, I present a dynamic game of resource extraction and GHG emissions for two agents under a cap-and-trade system using a general functional form, and discuss the optimal time path of resource extraction and GHG emissions under different scenarios. In section four, I discuss conclusions about the model.

4.2 Literature Review

There is a large literature focused on dynamic analysis of pollution and resources. A comprehensive review summarizes studies of pollution games with different control instruments and different interactions among agents in the game (Jørgensen, Martín-Herrán, and Zaccour 2010). A common set up of the model is to optimize welfare/benefit or cost for each agent in a non-cooperative game and for all agents in a cooperative game, with a dynamic pollution stock constraint that is influenced by emissions from all agents. Studies may add other components into the basic model, such as a dynamic capital stocks constraint (Jørgensen and Zaccour 2001).

Among the control instruments, a Pigouvian tax and cap-and-trade system are better than a command-and-control approach in terms of minimizing the total cost (Bertrand 2013). But non-constant emission permits from cap-and-trade can have even lower expected costs than non-constant taxes (Yates 2012).

Cap-and-trade sets a ceiling for emissions and allows for the trade of emission permits among different agents in a market. It can be considered as a market solution to market failure caused by externality. The “Coase Theorem” (Coase 1960) provides a theoretical foundation for a cap-and-trade policy intervention. Unless circumstances such as non-constant marginal transaction costs, significant market power in a permit market, etc. appear, the initial allocation of tradable emission permits does not influence the market equilibrium and the total cost of emission reduction is minimized under a cap-and-trade system (Hahn and Stavins 2011). Permit trade can also be temporally flexible. Time-dependent inter-temporal trade of permits may lead to socially optimal emission levels (Legras and Zaccour 2011).

The empirical results are somewhat contradictory. Weak evidence of independence between emissions and the allocation of permits for nitrogen oxide is found in Southern California’s Regional Clean Air Incentives Market (Fowlie and Perloff 2013). But the data from the Acid Rain Program in the U.S. shows the aggregate emission rate of sulfur dioxide vary between scenarios where closing plants or new entrants obtain initial permits (Dardati 2014).

There are different approaches to the allocation of permits, including grandfathering (based on historic emissions) and auctioning and benchmarking (based on output and sector common benchmarks). While an auctioning approach is most efficient in the long run, the cost makes firms in the cap-and-trade system less competitive than firms outside the system. The benchmarking approach compensates firms and maintains the incentive for pollution abatement compared with the grandfathering approach (Zetterberg et al. 2012).

Some studies focus on the quantity of permits and investigate the use of a market stability reserve (MSR). MSR adjusts the number of permits auctioned based on the previous surplus of permits. MSR is well-equipped to handle the issue of overly supplied permits that causes a lack of incentives for the investment of clean technologies (Perino and Willner 2015). This adjustment can improve the overall cost effectiveness (Kollenberg and Taschini 2016). But it may increase price volatility (Perino and Willner 2015). Other studies focus on the price of permits. Inter-temporal tradable permits allows firms to adjust permit portfolio allocations across time and the corresponding price dynamics can be applied to CO_2 option pricing (Chesney and Taschini 2012).

The emissions cap places a limit on the level of pollution and, therefore, controls the damage from pollution. Firms' profits or decisions to enter/exit the market are not relevant to the emission cap (Anouliès 2017). However, for one agent, when two resources are available with one cleaner than the other, the dirtier resource may be used first to take advantage of natural decay when emissions are below the cap, and then switch to the cleaner resource and then back to the dirtier resource again (Chakravorty, Moreaux, and Tidball 2008).

There is substitution between the purchase of permits and the abatement of pollution. The tradeoff between these two approaches to handle pollution can be addressed in the dynamic model (Liski and Montero 2011). The decision to adopt cleaner technologies for countries that do not cooperate is not influenced by their neighbors' behaviors (Boucekkine, Krawczyk, and Vallée 2011). Cleaner technologies also have issues associated with free-riding (Harstad 2012).

But other changes of an agent's behaviors can influence other agents. A decrease in damage costs for one country can put pressure to reduce emissions on other countries (Benchekroun and Taherkhani 2014). Uncertainties about future payoffs also influence emissions. An agent with more optimistic beliefs about the risk of pollution will increase his/her emissions while other agents decrease their emissions. This is associated with an increase in total emissions and vise versa (Masoudi, Santugini, and Zaccour 2016).

Other studies focus on tax as the control instrument for pollution. Discussions include the influence of different taxes, the optimal tax plan, etc. (Canton, Soubeyran, and Stahn 2008; Liski and Tahvonen 2004; Vossler, Suter, and Poe 2013).

Due to the lack of a central planner for international trans-boundary pollution issues, countries may form coalitions such as an international environmental agreement. Some study topics are related to international environmental regimes/agreements, such as the dynamic decision to join or leave such a coalition and effectiveness of such a coalition (Rubio and Ulph 2007; Young 2011).

Others explore the dynamic game of resource trade with consideration of pollution. There is also a comprehensive review of those studies (Long 2011).

In this paper, I develop a non-cooperative dynamic game model of GHG emissions and the extraction of polluting nonrenewable resource. This model allows for two agents who maximize social welfare with constraints on resource extraction, pollution stock and emission cap. I discuss the optimal resource extraction and pollution emissions for both identical and heterogenous agents.

4.3 A Dynamic Game of Pollution and Resource

4.3.1 Theoretical Model

To present a simple model, I assume there are only two agents. They do not know each other’s strategy or the state of the differential game of pollution and resource. Both agents implement open loop strategies with control variables depending only on time. They each extract one single polluting nonrenewable resource independently. There is no trade of this resource between the two agents. When they use this resource to produce energy, they also generate GHG, which has a negative impact on both the other agent and themselves through the GHG stock in the air. In order to emit GHG, they need to buy emissions permits from a third party. The third party has a limited number of permits to offer at each time interval and the number can decrease over time.

For the nonrenewable resource, assume x_i is the quantity of the extraction at time t for agent i ($i = 1,2$). U_i is the utility of the extracted resource for agent i. I assume that $\frac{dU_i}{dx_i} > 0$ and $\frac{d^2U_i}{dx_i{}^2} < 0$ (Chakravorty, Magné, and Moreaux 2003). This means that the agent derives utility from the resource, but the more resource it extracts, the less utility it obtains from an extra unit of the resource. C_i is the total cost of extraction for agent i. To simplify the model, I assume the cost of extraction is only related to the level of extraction. Extraction raises the cost through increasing marginal cost. Therefore, $\frac{dC_i}{dx_i} > 0$ and $\frac{d^2C_i}{dx_i{}^2} > 0$. X_i is the stock of the nonrenewable resource for agent i.

For pollution, assume E_i is the quantity of the pollution generated by x_i units of the resource under the current technology for agent i. I assume E_i and x_i have a positive linear relationship, which is $\frac{dE_i}{dx_i} > 0$ and $\frac{d^2E_i}{dx_i{}^2} = 0$. q_i is the number of emissions permits bought by agent i. q_j is the number of emissions permit bought by agent j ($j = 1,2. i \neq j$). I assume that one unit of the permits is the same as one unit of the pollutant emissions. So q_i and q_j are the permitted emissions for agent i and j. R_i is the total cost of the new technology that keeps the emissions level at q_i for agent i and depends on E_i and q_i. I assume $\frac{dR_i}{dq_i} < 0$ and $\frac{d^2R_i}{dq_i^2} > 0$ (Germain et al. 2003). This means that if an agent is permitted to increase pollution emitted, the agent can spend less on technology to eliminate the rest part of pollution. The marginal cost of technology will decrease as the amount of permitted pollution rises because it becomes easier to eliminate pollution when more pollution is emitted. E_i, the total pollution generated by using the resource, should be similar to q_i with the opposite impact on R_i. Similarly, the cost of technology is also assumed to increase as the amount of total pollution increases at an increasing rate, which means $\frac{dR_i}{dE_i} > 0$ and $\frac{d^2R_i}{dE_i^2} > 0$. Also, when permitted emissions increase, the positive marginal cost of technology from total pollution should decrease. Therefore, $\frac{d^2R_i}{dq_i\,dE_i} < 0$. $\bar{q}$ is an emissions cap set by a third party. p is the per unit price of emissions permits and assumed to depend on the total permitted emissions demanded by the two agents in a permit auction (Lopomo et al. 2011). The price increases with more permits demanded. To simplify the model, I assume a linear relationship between price and the permitted pollution. Therefore, $\frac{dp}{dq_i} > 0$ and $\frac{d^2p}{dq_i^2} = 0$. Z is the stock of the pollution. D_i is the damage from the pollution stock for agent i. The damage increases with the pollution stock at an increasing rate, which means $\frac{dD_i}{dZ} > 0$ and $\frac{d^2D_i}{dZ^2} > 0$ (Toman and Withagen 2000). f is the change in the pollution stock and depends on the permitted emissions of both agents and the pollution stock. Most studies assume there is natural abatement of pollution as a proportion of the pollution stock. The change of the pollution stock is the difference between total permitted emissions and pollution abatement. Therefore, $\frac{df}{dq_i} > 0$, $\frac{df}{dq_j} > 0$, $\frac{df}{dZ} < 0$, and $\frac{d^2f}{dq_i^2} = \frac{d^2f}{dq_j^2} = \frac{d^2f}{dq_i\,dq_j} = \frac{d^2f}{dq_i\,dZ} = 0$.

The goal of agent i is to maximize social welfare while considering dynamic resource and pollution constraints and the emissions cap as follows:

$$\max_{x_i(t),\, q_i(t)} \int_0^\infty e^{-\rho t}\{U_i[x_i\,(t)] - C_i[x_i\,(t)] - R_i\big[E_i\big(x_i(t)\big), q_i(t)\big] - p\big[q_i(t) + q_j(t)\big]$$

$$\cdot\, q_i(t) - D_i[Z(t)]\big\}dt \qquad (4.1)$$

$$s.t. \quad \dot{X}_i(t) = -x_i(t), \;\; X_i(0) = X_{i0}\; given \qquad (4.2)$$

$$\dot{Z}(t) = f\big[q_i(t), q_j(t), Z(t)\big], \;\; Z(0) = Z_0\; given \qquad (4.3)$$

$$x_i(t) \geq 0 \qquad (4.4)$$

$$q_i(t) \geq 0 \qquad (4.5)$$

$$q_i(t) + q_j(t) \leq \bar{q}(t) \qquad (4.6)$$

The generalized Lagrangian is written as

$$\mathcal{L} = e^{-\rho t}\{U_i[x_i\,(t)] - C_i[x_i\,(t)] - R_i\big[E_i\big(x_i(t)\big), q_i(t)\big] - p\big[q_i(t) + q_j(t)\big] \cdot q_i(t)$$

$$- D_i[Z(t)]\big\} + \mu_i(t) \cdot [-x_i(t)] + \lambda_i(t) \cdot f\big[q_i(t), q_j(t), Z(t)\big] + \theta_i(t) x_i(t)$$

$$+ \varphi_i(t) q_i(t) + \gamma_i(t) \cdot \big[\bar{q}(t) - q_i(t) - q_j(t)\big]$$

where $\mu_i(t)$ is the marginal user cost of resource. $\mu_i(t) \geq 0$. $\lambda_i(t)$ is the marginal value of the pollutant stock. Given that the pollution stock is a bad, $\lambda_i(t) \leq 0$. $\theta_i(t)$, $\varphi_i(t)$, and $\gamma_i(t)$ are shadow values for resource, emissions and the emissions cap respectively.

The first order conditions include

$$\frac{\partial \mathcal{L}}{\partial x_i} = e^{-\rho t}\left(U_i^{'} - C_i^{'} - \frac{\partial R_i}{\partial E_i} E_i^{'}\right) - \mu_i + \theta_i = 0 \qquad (4.7)$$

$$\frac{\partial H}{\partial q_i} = e^{-\rho t}\left(-\frac{\partial R_i}{\partial q_i} - p - \frac{\partial p}{\partial q_i} q_i\right) + \lambda_i \frac{\partial f}{\partial q_i} + \varphi_i - \gamma_i = 0 \qquad (4.8)$$

Equation (4.7) shows that the discounted marginal net benefit of the resource should be equal to its marginal user cost, which reflects the opportunity cost of resource extraction.

This is consistent with the Hotelling model. Equation (4.8) shows that the discounted marginal cost of emissions should be equal to the marginal value of change in the pollution stock and the marginal value of emissions.

The adjoint conditions are

$$\frac{\partial H}{\partial X_i} = 0 = -\dot{\mu}_i(t) \qquad (4.9)$$

$$\frac{\partial H}{\partial Z} = -e^{-\rho t} D_i' + \lambda_i(t) \frac{\partial f}{\partial Z} = -\dot{\lambda}_i(t) \qquad (4.10)$$

Equation (4.9) shows that the marginal user cost of the resource does not change over time. This is a simplified situation under the model assumption that the extraction cost does not depend on the resource stock. Equation (4.10) shows that the change in the marginal value of the pollutant stock is equal to the difference between the discounted marginal damage of the pollution stock and the marginal value of decay of the pollution stock.

Equation (4.10) can be used to solve for $\lambda_i(t)$. Rewrite equation (4.10) as

$$\dot{\lambda}_i(t) + \lambda_i(t) \frac{\partial f}{\partial Z} = e^{-\rho t} D_i' \qquad (4.10')$$

Multiplying both sides of equation (4.10') by $\exp\left(\int \frac{\partial f}{\partial Z} dt\right)$ I obtain

$$\frac{d\lambda_i(t)}{dt} \exp\left(\int \frac{\partial f}{\partial Z} dt\right) + \lambda_i(t) \frac{\partial f}{\partial Z} \exp\left(\int \frac{\partial f}{\partial Z} dt\right) = e^{-\rho t} D_i' \exp\left(\int \frac{\partial f}{\partial Z} dt\right)$$

$$\Rightarrow \frac{d\left(\lambda_i(t) \exp\left(\int \frac{\partial f}{\partial Z} dt\right)\right)}{dt} = e^{-\rho t} D_i' \exp\left(\int \frac{\partial f}{\partial Z} dt\right)$$

Integrating both sides yields

$$\lambda_i(t) \exp\left(\int \frac{\partial f}{\partial Z} dt\right) = \int \left(e^{-\rho t} D_i' \exp\left(\int \frac{\partial f}{\partial Z} dt\right)\right) dt + constant$$

$$\Rightarrow \lambda_i(t) = \frac{\int \left(e^{-\rho t} D_i' \exp\left(\int \frac{\partial f}{\partial Z} dt \right) \right) dt}{\exp\left(\int \frac{\partial f}{\partial Z} dt \right)} + C \qquad (4.10'')$$

where C is any constant. Taking the time derivative of equation (4.10”) yields

$$\dot{\lambda}_i(t) = -\frac{\partial f}{\partial Z} \exp\left(-\int \frac{\partial f}{\partial Z} dt \right) \int \left(e^{-\rho t} D_i' \exp\left(\int \frac{\partial f}{\partial Z} dt \right) \right) dt$$

$$+ \exp\left(-\int \frac{\partial f}{\partial Z} dt \right) e^{-\rho t} D_i' \exp\left(\int \frac{\partial f}{\partial Z} dt \right)$$

$$= -\frac{\partial f}{\partial Z} \frac{\int \left(e^{-\rho t} D_i' \exp\left(\int \frac{\partial f}{\partial Z} dt \right) \right) dt}{\exp\left(\int \frac{\partial f}{\partial Z} dt \right)} + e^{-\rho t} D_i' \qquad (4.11)$$

The complementary slackness conditions are

$$\theta_i(t) \geq 0, \qquad \theta_i(t) x_i(t) = 0 \qquad (4.12)$$

$$\varphi_i(t) \geq 0, \qquad \varphi_i(t) q_i(t) = 0 \qquad (4.13)$$

$$\gamma_i(t) \geq 0, \qquad \gamma_i(t) \left(\bar{q}(t) - q_i(t) - q_j(t) \right) = 0 \qquad (4.14)$$

Equations (4.12) and (4.13) mean the shadow values are zero as long as there are resource extraction and pollution emissions. Otherwise these are positive shadow values. Equation (4.14) means that only when the total emissions of two agents reach the emissions cap, the emission cap has a positive marginal value. If the total emissions do not reach the emissions cap, the emissions cap does not have a marginal value.

Taking the time derivative on equation (4.7) yields

$$e^{-\rho t} \left(U_i'' \dot{x}_i - C_i'' \dot{x}_i - \left(\frac{\partial^2 R_i}{\partial E_i \partial q_i} \dot{q}_i E_i' + \frac{\partial R_i}{\partial E_i} E_i'' \dot{x}_i \right) \right) - \rho e^{-\rho t} \left(U_i' - C_i' - \frac{\partial R_i}{\partial E_i} E_i' \right) - \dot{\mu}_i + \dot{\theta}_i$$

$$= 0 \qquad (4.15)$$

The linear assumption of the emissions function can simplify equation (4.15) as

$$e^{-\rho t}\left(U_i^{''}\dot{x}_i - C_i^{''}\dot{x}_i - \frac{\partial^2 R_i}{\partial E_i \partial q_i}\dot{q}_i E_i^{'}\right) - \rho e^{-\rho t}\left(U_i^{'} - C_i^{'} - \frac{\partial R_i}{\partial E_i}E_i^{'}\right) - \dot{\mu}_i + \dot{\theta}_i$$

$$= 0 \qquad (4.15')$$

Plugging equation (4.9) into equation (4.15') and solving for $\dot{x}_i$ I obtain

$$e^{-\rho t}\left(U_i^{''}\dot{x}_i - C_i^{''}\dot{x}_i - \frac{\partial^2 R_i}{\partial E_i \partial q_i}\dot{q}_i E_i^{'}\right) - \rho e^{-\rho t}\left(U_i^{'} - C_i^{'} - \frac{\partial R_i}{\partial E_i}E_i^{'}\right) + \dot{\theta}_i = 0$$

$$\Rightarrow \dot{x}_i = \frac{\rho\left(U_i^{'} - C_i^{'} - \frac{\partial R_i}{\partial E_i}E_i^{'}\right) - e^{-\rho t}\dot{\theta}_i}{U_i^{''} - C_i^{''}} + \frac{\frac{\partial^2 R_i}{\partial E_i \partial q_i}E_i^{'}}{U_i^{''} - C_i^{''}}\,\dot{q}_i \qquad (4.16)$$

According to the assumption of the signs of derivatives, $\frac{\frac{\partial^2 R_i}{\partial E_i \partial q_i}E_i^{'}}{U_i^{''} - C_i^{''}} > 0$. This means resource extraction and pollution emissions change in the same direction, which is reasonable.

Taking the time derivative on equation (4.8) yields

$$e^{-\rho t}\left(-\frac{\partial^2 R_i}{\partial {q_i}^2}\dot{q}_i - \frac{\partial^2 R_i}{\partial E_i \partial q_i}E_i^{'}\dot{x}_i - \frac{\partial p}{\partial q_i}\left(\dot{q}_i + \dot{q}_j\right) - \left(\frac{\partial^2 p}{\partial {q_i}^2}\dot{q}_i q_i + \frac{\partial^2 p}{\partial q_i \partial q_j}\dot{q}_j q_i + \frac{\partial p}{\partial q_i}\dot{q}_i\right)\right)$$

$$- \rho e^{-\rho t}\left(-\frac{\partial R_i}{\partial q_i} - p - \frac{\partial p}{\partial q_i}q_i\right) + \lambda_i\left(\frac{\partial^2 f}{\partial {q_i}^2}\dot{q}_i + \frac{\partial^2 f}{\partial q_i \partial q_j}\dot{q}_j + \frac{\partial^2 f}{\partial q_i \partial Z}\dot{Z}\right)$$

$$+ \dot{\lambda}_i\frac{\partial f}{\partial q_i} + \dot{\varphi}_i - \dot{\gamma}_i = 0 \quad (4.17)$$

The linear assumptions for the permit price p and the change of pollution stock f discussed in section 4.3.1 can simplify equation (4.17) as

$$e^{-\rho t}\left(-\frac{\partial^2 R_i}{\partial {q_i}^2}\dot{q}_i - \frac{\partial^2 R_i}{\partial E_i \partial q_i}E_i^{'}\dot{x}_i - \frac{\partial p}{\partial q_i}\left(\dot{q}_i + \dot{q}_j\right) - \frac{\partial p}{\partial q_i}\dot{q}_i\right) - \rho e^{-\rho t}\left(-\frac{\partial R_i}{\partial q_i} - p - \frac{\partial p}{\partial q_i}q_i\right)$$

$$+ \dot{\lambda}_i\frac{\partial f}{\partial q_i} + \dot{\varphi}_i - \dot{\gamma}_i = 0 \quad (4.17')$$

Plugging equation (4.11) into equation (4.17') and solving for $\dot{q}_i$ as a function of both $\dot{q}_j$ and $\dot{x}_i$ I obtain

$$e^{-\rho t}\left(-\frac{\partial^2 R_i}{\partial {q_i}^2}\dot{q}_i - \frac{\partial^2 R_i}{\partial E_i \partial q_i}E_i^{'}\dot{x}_i - \frac{\partial p}{\partial q_i}\left(\dot{q}_i + \dot{q}_j\right) - \frac{\partial p}{\partial q_i}\dot{q}_i\right) - \rho e^{-\rho t}\left(-\frac{\partial R_i}{\partial q_i} - p - \frac{\partial p}{\partial q_i}q_i\right)$$

$$+\left(-\frac{\partial f}{\partial Z}\frac{\int\left(e^{-\rho t}D_i^{'}\exp\left(\int\frac{\partial f}{\partial Z}dt\right)\right)dt}{\exp\left(\int\frac{\partial f}{\partial Z}dt\right)} + e^{-\rho t}D_i^{'}\right)\frac{\partial f}{\partial q_i} + \dot{\varphi}_i - \dot{\gamma}_i = 0$$

$$\Rightarrow e^{-\rho t}\left(-\frac{\partial^2 R_i}{\partial {q_i}^2}\dot{q}_i - 2\frac{\partial p}{\partial q_i}\dot{q}_i\right) - e^{-\rho t}\frac{\partial p}{\partial q_i}\dot{q}_j - e^{-\rho t}\frac{\partial^2 R_i}{\partial E_i \partial q_i}E_i^{'}\dot{x}_i$$

$$+\rho e^{-\rho t}\left(\frac{\partial R_i}{\partial q_i} + p + \frac{\partial p}{\partial q_i}q_i\right)$$

$$+\left(-\frac{\partial f}{\partial Z}\frac{\int\left(e^{-\rho t}D_i^{'}\exp\left(\int\frac{\partial f}{\partial Z}dt\right)\right)dt}{\exp\left(\int\frac{\partial f}{\partial Z}dt\right)} + e^{-\rho t}D_i^{'}\right)\frac{\partial f}{\partial q_i} + \dot{\varphi}_i - \dot{\gamma}_i = 0$$

$$\dot{q}_i$$

$$= -\frac{\frac{\partial p}{\partial q_i}}{\frac{\partial^2 R_i}{\partial {q_i}^2} + 2\frac{\partial p}{\partial q_i}}\dot{q}_j - \frac{\frac{\partial^2 R_i}{\partial E_i \partial q_i}E_i^{'}}{\frac{\partial^2 R_i}{\partial {q_i}^2} + 2\frac{\partial p}{\partial q_i}}\dot{x}_i$$

$$+\frac{\rho e^{-\rho t}\left(\frac{\partial R_i}{\partial q_i} + p + \frac{\partial p}{\partial q_i}q_i\right) + \left(-\frac{\partial f}{\partial Z}\frac{\int\left(e^{-\rho t}D_i^{'}\exp\left(\int\frac{\partial f}{\partial Z}dt\right)\right)dt}{\exp\left(\int\frac{\partial f}{\partial Z}dt\right)} + e^{-\rho t}D_i^{'}\right)\frac{\partial f}{\partial q_i} + \dot{\varphi}_i - \dot{\gamma}_i}{e^{-\rho t}\left(\frac{\partial^2 R_i}{\partial {q_i}^2} + 2\frac{\partial p}{\partial q_i}\right)}$$

(4.18)

Plugging equation (4.16) into equation (4.18) and solving for $\dot{q}_i$ as a function of $\dot{q}_j$ without $\dot{x}_i$ I obtain

$\dot{q}_i$

$$= -\frac{\frac{\partial p}{\partial q_i}}{\frac{\partial^2 R_i}{\partial {q_i}^2} + 2\frac{\partial p}{\partial q_i}}\dot{q}_j - \frac{\frac{\partial^2 R_i}{\partial E_i \partial q_i}E_i^{'}}{\frac{\partial^2 R_i}{\partial {q_i}^2} + 2\frac{\partial p}{\partial q_i}}\left(\frac{\rho\left(U_i^{'} - C_i^{'} - \frac{\partial R_i}{\partial E_i}E_i^{'}\right) - e^{-\rho t}\dot{\theta}_i}{U_i^{''} - C_i^{''}} + \frac{\frac{\partial^2 R_i}{\partial E_i \partial q_i}E_i^{'}}{U_i^{''} - C_i^{''}}\ \dot{q}_i\right)$$

$$+ \frac{\rho e^{-\rho t}\left(\frac{\partial R_i}{\partial q_i} + p + \frac{\partial p}{\partial q_i}q_i\right) + \left(-\frac{\partial f}{\partial Z}\frac{\int\left(e^{-\rho t}D_i^{'}\exp\left(\int\frac{\partial f}{\partial Z}dt\right)\right)dt}{\exp\left(\int\frac{\partial f}{\partial Z}dt\right)} + e^{-\rho t}D_i^{'}\right)\frac{\partial f}{\partial q_i} + \dot{\varphi}_i - \dot{\gamma}_i}{e^{-\rho t}\left(\frac{\partial^2 R_i}{\partial {q_i}^2} + 2\frac{\partial p}{\partial q_i}\right)}$$

$\Rightarrow \dot{q}_i$

$$= -\frac{\frac{\partial p}{\partial q_i}}{\frac{\partial^2 R_i}{\partial {q_i}^2} + 2\frac{\partial p}{\partial q_i}}\dot{q}_j - \frac{\left(\frac{\partial^2 R_i}{\partial E_i \partial q_i}E_i^{'}\right)\left(\rho\left(U_i^{'} - C_i^{'} - \frac{\partial R_i}{\partial E_i}E_i^{'}\right) - e^{-\rho t}\dot{\theta}_i\right)}{\left(\frac{\partial^2 R_i}{\partial {q_i}^2} + 2\frac{\partial p}{\partial q_i}\right)\left(U_i^{''} - C_i^{''}\right)}$$

$$- \frac{\left(\frac{\partial^2 R_i}{\partial E_i \partial q_i}E_i^{'}\right)^2}{\left(\frac{\partial^2 R_i}{\partial {q_i}^2} + 2\frac{\partial p}{\partial q_i}\right)\left(U_i^{''} - C_i^{''}\right)}\ \dot{q}_i$$

$$+ \frac{\rho e^{-\rho t}\left(\frac{\partial R_i}{\partial q_i} + p + \frac{\partial p}{\partial q_i}q_i\right) + \left(-\frac{\partial f}{\partial Z}\frac{\int\left(e^{-\rho t}D_i^{'}\exp\left(\int\frac{\partial f}{\partial Z}dt\right)\right)dt}{\exp\left(\int\frac{\partial f}{\partial Z}dt\right)} + e^{-\rho t}D_i^{'}\right)\frac{\partial f}{\partial q_i} + \dot{\varphi}_i - \dot{\gamma}_i}{e^{-\rho t}\left(\frac{\partial^2 R_i}{\partial {q_i}^2} + 2\frac{\partial p}{\partial q_i}\right)}$$

$$\Rightarrow \dot{q}_i$$

$$= -\left(1+\frac{\left(\frac{\partial^2 R_i}{\partial E_i \partial q_i}E_i^{'}\right)^2}{\left(\frac{\partial^2 R_i}{\partial {q_i}^2}+2\frac{\partial p}{\partial q_i}\right)\left(U_i^{''}-C_i^{''}\right)}\right)^{-1}\left(\frac{\frac{\partial p}{\partial q_i}}{\frac{\partial^2 R_i}{\partial {q_i}^2}+2\frac{\partial p}{\partial q_i}}\right)\dot{q}_j$$

$$-\left(1+\frac{\left(\frac{\partial^2 R_i}{\partial E_i \partial q_i}E_i^{'}\right)^2}{\left(\frac{\partial^2 R_i}{\partial {q_i}^2}+2\frac{\partial p}{\partial q_i}\right)\left(U_i^{''}-C_i^{''}\right)}\right)^{-1}\left(\frac{\left(\frac{\partial^2 R_i}{\partial E_i \partial q_i}E_i^{'}\right)\left(\rho\left(U_i^{'}-C_i^{'}-\frac{\partial R_i}{\partial E_i}E_i^{'}\right)-e^{-\rho t}\dot{\theta}_i\right)}{\left(\frac{\partial^2 R_i}{\partial {q_i}^2}+2\frac{\partial p}{\partial q_i}\right)\left(U_i^{''}-C_i^{''}\right)}\right)$$

$$+\left(1+\frac{\left(\frac{\partial^2 R_i}{\partial E_i \partial q_i}E_i^{'}\right)^2}{\left(\frac{\partial^2 R_i}{\partial {q_i}^2}+2\frac{\partial p}{\partial q_i}\right)\left(U_i^{''}-C_i^{''}\right)}\right)^{-1}$$

$$\cdot\left(\rho e^{-\rho t}\left(\frac{\partial R_i}{\partial q_i}+p+\frac{\partial p}{\partial q_i}q_i\right)+\left(-\frac{\partial f}{\partial Z}\frac{\int\left(e^{-\rho t}D_i^{'}\exp\left(\int\frac{\partial f}{\partial Z}dt\right)\right)dt}{\exp\left(\int\frac{\partial f}{\partial Z}dt\right)}+e^{-\rho t}D_i^{'}\right)\frac{\partial f}{\partial q_i}\right.$$

$$\left.+\dot{\varphi}_i-\dot{\gamma}_i\right)\frac{1}{e^{-\rho t}\left(\frac{\partial^2 R_i}{\partial {q_i}^2}+2\frac{\partial p}{\partial q_i}\right)} \qquad (4.19)$$

where $\dot{\theta}_i = 0$ if there is resource extraction. $\dot{\varphi}_i = 0$ if there are resource extraction and pollution emissions. $\dot{\gamma}_i = 0$ if the emissions cap is not binding.

Equation (4.19) reflects the relationship of the pollution emissions change between the two agents. However, the sign of $-\left(1+\frac{\left(\frac{\partial^2 R_i}{\partial E_i \partial q_i}E_i^{'}\right)^2}{\left(\frac{\partial^2 R_i}{\partial {q_i}^2}+2\frac{\partial p}{\partial q_i}\right)\left(U_i^{''}-C_i^{''}\right)}\right)^{-1}\left(\frac{\frac{\partial p}{\partial q_i}}{\frac{\partial^2 R_i}{\partial {q_i}^2}+2\frac{\partial p}{\partial q_i}}\right)$ is unknown. If

$$\left(\frac{\partial^2 R_i}{\partial E_i \partial q_i}E_i^{'}\right)^2 > \left(\frac{\partial^2 R_i}{\partial {q_i}^2}+2\frac{\partial p}{\partial q_i}\right)\left(U_i^{''}-C_i^{''}\right)$$

Then

$$-\left(1+\frac{\left(\frac{\partial^2 R_i}{\partial E_i \partial q_i}E_i^{'}\right)^2}{\left(\frac{\partial^2 R_i}{\partial {q_i}^2}+2\frac{\partial p}{\partial q_i}\right)\left(U_i^{''}-C_i^{''}\right)}\right)^{-1}\left(\frac{\frac{\partial p}{\partial q_i}}{\frac{\partial^2 R_i}{\partial {q_i}^2}+2\frac{\partial p}{\partial q_i}}\right)>0$$

and the two pollution emissions will increase or decrease at the same time. If

$$\left(\frac{\partial^2 R_i}{\partial E_i \partial q_i}E_i^{'}\right)^2<\left(\frac{\partial^2 R_i}{\partial {q_i}^2}+2\frac{\partial p}{\partial q_i}\right)\left(U_i^{''}-C_i^{''}\right)$$

then the two pollution emissions change in the opposite direction. In the real world, many societies realize the impact of climate change and start to put forth mutual effort to reduce emissions. Therefore, I may expect emissions of different societies decrease at the same time in the long run.

4.3.2 MATHEMATICAL APPROACH FOR A GENERAL FORM OF SOLUTION

By asymmetry, there is also an equation for pollution emissions of agent *j* that depends on pollution emissions of agent i. When the specific functional forms and parameters are available, these two equations allow me to solve for $\dot{q}_i(t)$ and $\dot{q}_j(t)$ and obtain a system of non-linear differential equations of emissions for the two agents in the following form

$$\begin{cases}\dot{q}_i(t)=F\left(q_i(t),q_j(t)\right)\\ \dot{q}_j(t)=G\left(q_i(t),q_j(t)\right)\end{cases}\qquad(4.20)$$

then I can use the following Taylor series expansion to approximate the non-linear system around point $\left({q_i}^*(t),{q_j}^*(t)\right)$, where $F\left({q_i}^*(t),{q_j}^*(t)\right)=G\left({q_i}^*(t),{q_j}^*(t)\right)=0$

$$\begin{cases} \dot{q}_i(t) \approx F\left(q_i{}^*(t), q_j{}^*(t)\right) + \dfrac{\partial F\left(q_i{}^*(t), q_j{}^*(t)\right)}{\partial q_i(t)}\left(q_i(t) - q_i{}^*(t)\right) \\ \qquad + \dfrac{\partial F\left(q_i{}^*(t), q_j{}^*(t)\right)}{\partial q_j(t)}\left(q_j(t) - q_j{}^*(t)\right) \\ \dot{q}_j(t) \approx G\left(q_i{}^*(t), q_j{}^*(t)\right) + \dfrac{\partial G\left(q_i{}^*(t), q_j{}^*(t)\right)}{\partial q_i(t)}\left(q_i(t) - q_i{}^*(t)\right) \\ \qquad + \dfrac{\partial G\left(q_i{}^*(t), q_j{}^*(t)\right)}{\partial q_j(t)}\left(q_j(t) - q_j{}^*(t)\right) \end{cases}$$

$$\Rightarrow \begin{cases} \dot{q}_i(t) \approx \dfrac{\partial F\left(q_i{}^*(t), q_j{}^*(t)\right)}{\partial q_i(t)}\left(q_i(t) - q_i{}^*(t)\right) + \dfrac{\partial F\left(q_i{}^*(t), q_j{}^*(t)\right)}{\partial q_j(t)}\left(q_j(t) - q_j{}^*(t)\right) \\ \dot{q}_j(t) \approx \dfrac{\partial G\left(q_i{}^*(t), q_j{}^*(t)\right)}{\partial q_i(t)}\left(q_i(t) - q_i{}^*(t)\right) + \dfrac{\partial G\left(q_i{}^*(t), q_j{}^*(t)\right)}{\partial q_j(t)}\left(q_j(t) - q_j{}^*(t)\right) \end{cases}$$

$$\Rightarrow \begin{pmatrix} \dot{q}_i(t) \\ \dot{q}_j(t) \end{pmatrix} \approx \begin{pmatrix} \dfrac{\partial F\left(q_i{}^*(t), q_j{}^*(t)\right)}{\partial q_i(t)} & \dfrac{\partial F\left(q_i{}^*(t), q_j{}^*(t)\right)}{\partial q_j(t)} \\ \dfrac{\partial G\left(q_i{}^*(t), q_j{}^*(t)\right)}{\partial q_i(t)} & \dfrac{\partial G\left(q_i{}^*(t), q_j{}^*(t)\right)}{\partial q_j(t)} \end{pmatrix} \begin{pmatrix} q_i(t) - q_i{}^*(t) \\ q_j(t) - q_j{}^*(t) \end{pmatrix}$$

Let

$$Tr = \frac{\partial F\left(q_i{}^*(t), q_j{}^*(t)\right)}{\partial q_i(t)} + \frac{\partial G\left(q_i{}^*(t), q_j{}^*(t)\right)}{\partial q_j(t)}$$

$$Det = \frac{\partial F\left(q_i{}^*(t), q_j{}^*(t)\right)}{\partial q_i(t)} \frac{\partial G\left(q_i{}^*(t), q_j{}^*(t)\right)}{\partial q_j(t)} - \frac{\partial F\left(q_i{}^*(t), q_j{}^*(t)\right)}{\partial q_j(t)} \frac{\partial G\left(q_i{}^*(t), q_j{}^*(t)\right)}{\partial q_i(t)}$$

$$P(\pi) = \pi^2 - Tr \cdot \pi + Det$$

When $Tr^2 - 4Det > 0$, the two distinct real eigenvalues are

$$\pi_1 = \frac{Tr + \sqrt{Tr^2 - 4Det}}{2}, \pi_2 = \frac{\left(Tr - \sqrt{Tr^2 - 4Det}\right)}{2}$$

If $Det > 0$ and $Tr < 0$, then $\pi_2 < \pi_1 < 0$. All trajectories pass through $\left(q_i{}^*(t), q_j{}^*(t)\right)$ and this equilibrium point is an asymptotically stable node. If $Det > 0$ and $Tr > 0$, then

$\pi_1 > \pi_2 > 0$. All trajectories pass through $\left(q_i{}^*(t), q_j{}^*(t)\right)$ and this equilibrium point is an unstable node. If $Det < 0$, then $\pi_1 > 0 > \pi_2$. Only some trajectories pass through $\left(q_i{}^*(t), q_j{}^*(t)\right)$ and this equilibrium point is a saddle point.

When $Tr^2 - 4Det < 0$, the two complex eigenvalues are

$$\pi_1 = \frac{Tr + i\sqrt{4Det - Tr^2}}{2}, \pi_2 = \frac{Tr - i\sqrt{4Det - Tr^2}}{2}$$

If $Tr < 0$, then the real part is negative. All trajectories approach $\left(q_i{}^*(t), q_j{}^*(t)\right)$ and this equilibrium point is an asymptotically stable spiral. If $Tr > 0$, then the real part is positive. All trajectories depart from $\left(q_i{}^*(t), q_j{}^*(t)\right)$ and this equilibrium point is an unstable spiral. If $Tr = 0$, then all trajectories are closed curves around $\left(q_i{}^*(t), q_j{}^*(t)\right)$ and this equilibrium point is a center point.

When $Tr^2 - 4Det = 0$, the repeated eigenvalue is

$$\pi = \frac{Tr}{2}$$

If $Tr < 0$, then $\pi < 0$. All trajectories pass through $\left(q_i{}^*(t), q_j{}^*(t)\right)$ and this equilibrium point is likely to be an asymptotically stable improper node. If $Tr > 0$, then $\pi > 0$. All trajectories pass through $\left(q_i{}^*(t), q_j{}^*(t)\right)$ and this equilibrium point is likely to be an unstable improper node.

Equation (4.19) is a complicated equation with possible uncertainty on the signs in each part. The system equations (4.20) for the model in this study are even more complicated because they should be solved using equation (4.19) and its symmetric equation for $\dot{q}_j$. The complexity of the system is the reason that most previous studies assume linear functional form in their models. Rather than using a specific functional form, I take the general form with assumed derivative signs and describe some possible optimal paths of resource extraction and emissions that could occur. Different functional forms may influence the magnitude of paths but have similar trends.

4.3.3 POSSIBLE TIME PATH

Before I discuss the results, I want to summarize the important characteristics of the model.

- Based on the assumptions of the theoretical model, each unit of resource extracted by an agent generates pollution.
- An agent can either use technology to eliminate the pollution, or purchase permit to emit the pollution and take the damage from more pollution stock.
- A change of resource extraction can but does not necessarily change emissions in the same direction.
- The optimal levels of resource extraction and emissions should maximize social welfare over time.

Figure 4.1 shows the relationship between the four components of social welfare in equation (4.1) (net benefit of resource $U_i(x_i) - C_i(x_i)$, technology cost $R_i(E_i(x_i), q_i)$, cost of permits $p(q_i + q_j) \cdot q_i$, and damage $D_i(Z)$) and resource extraction x_i, pollution emissions q_i, and pollution stock Z for agent i. The slopes of the curves in figure 4.1 reflect the marginal net benefit of resource, marginal technology cost of eliminating the unpermitted part of emissions (with respect to resource and emissions separately), marginal cost of emissions permits, and marginal damage of pollution stock.

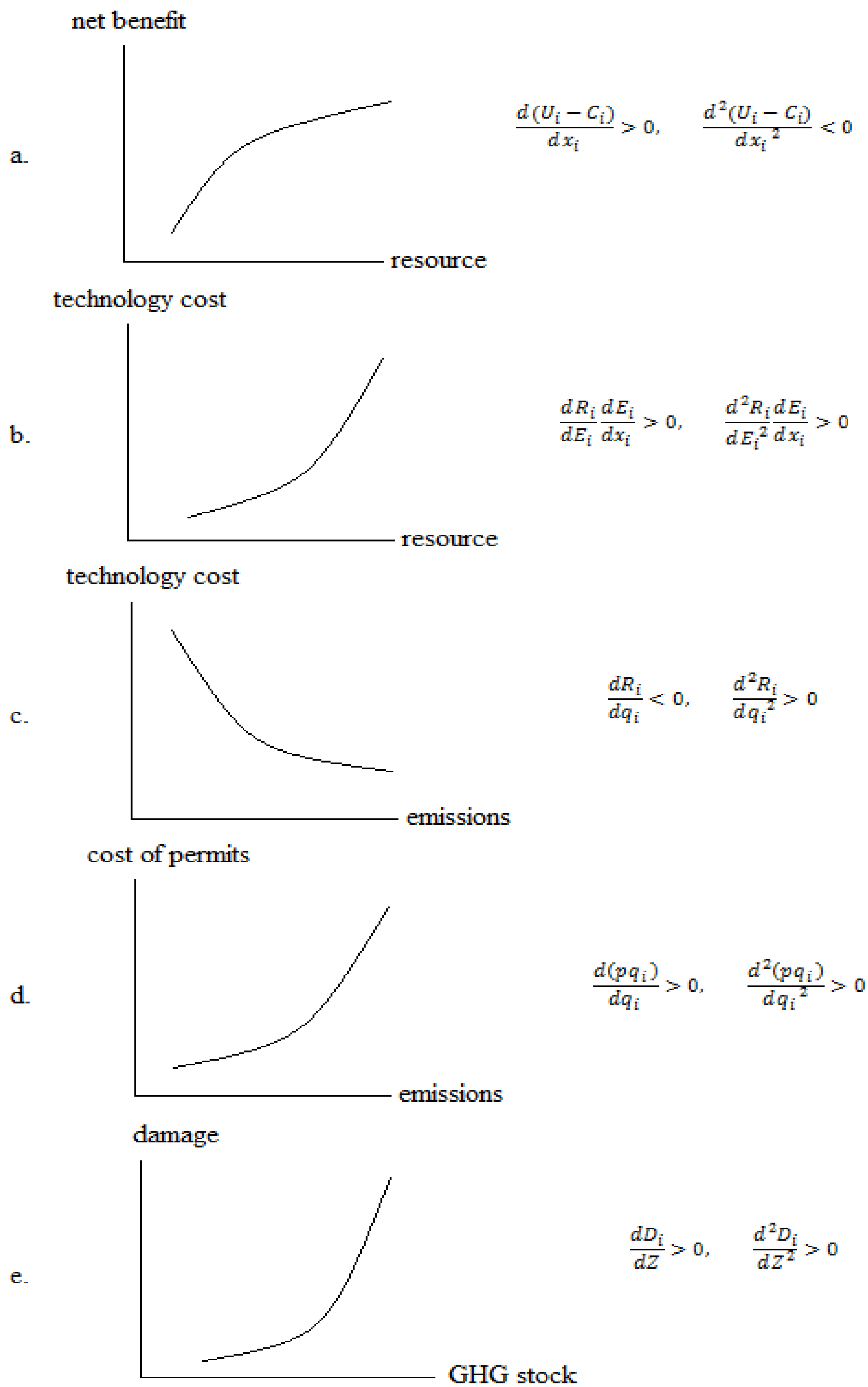


Figure 4.1 Relationship between benefit/cost and resource extraction/emissions/GHG stock

The relative magnitude of the marginal values determines the optimal resource extraction and emissions. The optimal resource extraction and emissions are reached when a one-unit change in resource extraction and/or emissions from the optimal levels adds a negative value to the social welfare. In other words, the optimal levels are reached when any change in resource extraction or emissions is associate with a negative marginal social welfare. There are several possible changes in resource extraction and/or emissions. In the following sections, I will discuss the static behaviors for an independent agent. Then I will discuss the dynamics of two agents with interactions.

The basic idea is that at each time period, an agent has two choices to eliminate one unit of GHG generated from resource, either use technology to eliminate it with a marginal cost $\frac{dR_i}{dq_i}$, or purchase permits to emit pollution with a marginal cost and damage of $\frac{d(pq_i)}{dq_i} + \frac{dD_i}{dq_i}$. After determining the optimal combination for all generated GHGs, which reflects optimal emissions levels, the agent compares the marginal net benefit $\frac{d(U_i - C_i)}{dx_i}$ with the marginal total costs $\frac{d(R_i + pq_i + D_i)}{dx_i}$ to determine the resource extraction. But resource extraction also influences emissions through the technology component $R_i\left[E_i\left(x_i(t)\right), q_i(t)\right]$.

4.3.3.1 ONE AGENT'S BEHAVIOR

Assume the emissions of the other agent are fixed. To find the optimal emissions at one time period, I assume the resource extraction stays at the optimal level. Therefore, I can ignore the net benefit of resource extraction $U_i[x_i\,(t)] - C_i[x_i\,(t)]$ from the welfare function for now

$$U_i[x_i\,(t)] - C_i[x_i\,(t)] - R_i\big[E_i\big(x_i(t)\big), q_i(t)\big] - p\big[q_i(t) + q_j(t)\big] \cdot q_i(t) - D_i[Z(t)]$$

and focus on the costs and damage related to pollution emitted:

$$R_i\big[E_i\big(x_i(t)\big), q_i(t)\big] + p\big[q_i(t) + q_j(t)\big] \cdot q_i(t) + D_i[Z(t)]$$

This allows me to explore the tradeoff between the two approaches to manage pollution: eliminate or emit it.

A one unit increase from a certain level of emissions leads to a decrease in technology cost (see Figure 4.1.c) and an increase in both the cost of permits (see Figure 4.1.d) and the damage from the pollution stock (see Figure 4.1.e).[19] If this decrease in technology cost $\frac{dR_i}{dq_i}$ is larger than the sum of the increase in the cost of permits $\frac{d(pq_i)}{dq_i}$ and damage from the pollution stock $\frac{dD_i}{dq_i}$, then this emissions level is not optimal. Technology is relatively more expensive than the sum of the cost of permits and damage. Therefore, the agent should eliminate less pollution with technology and increase emissions to lower the cost. If this decrease in technology cost is smaller, then the agent should decrease emissions. Similarly, a one-unit decrease related to a certain level of emissions leads to the opposite result.

Therefore, as long as the total emissions does not exceed the emissions cap, the optimal level of emissions occurs when the change in technology cost is equal to the sum of changes in the cost of permits and damage from the pollution stock $\left(-\frac{dR_i}{dq_i} = \frac{d(pq_i)}{dq_i} + \right.$ $dDidqi$, given the optimal resource extraction (see Figure 4.2.a).

If the marginal technology cost always dominates in a relatively long period of time, then the agent should only purchase permits until the total emissions reach the cap

[19] Damage of pollution stock is not directly related to emissions. But when emissions increase, pollution stock will increase and therefore damage will increase.

(see Figure 4.2.b). In this case, the third party, which may be the government, plays an important role in determining the cap and the time path of emissions. If the marginal technology cost never dominates in a relatively long period of time, then the agent should always use technology to eliminate the pollution (see Figure 4.2.c). In this case, the carbon market does not exist. The scenario in Figure 4.2.a is the most complicated but realistic in the long run, because according to my assumption, the slopes of the two curves in Figures 4.2b and 4.2c will eventually equal when the time period is long enough. Therefore, I focus the discussion on the scenario depicted in Figure 4.2.a.

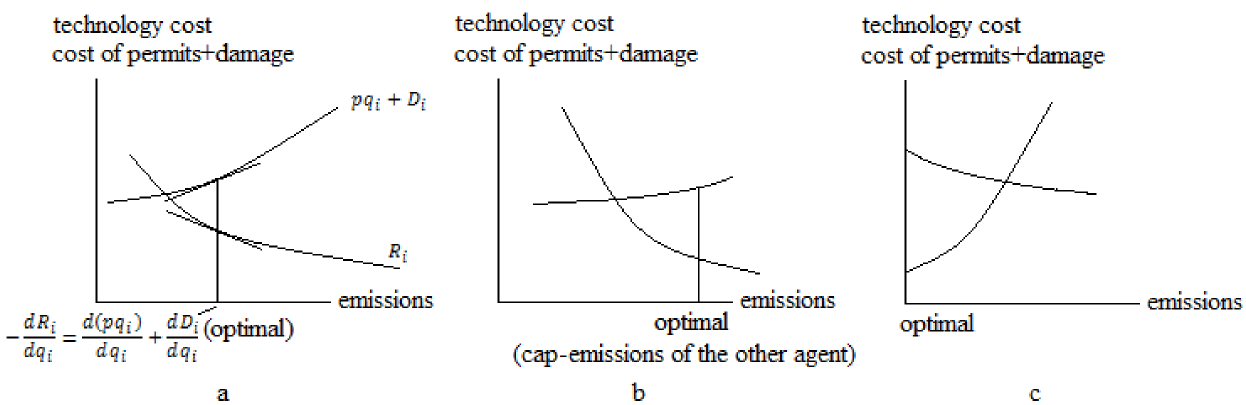


Figure 4.2 Optimal emissions for a fixed level of pollution generated by resource

The next step is to find the optimal resource extraction. When resource extraction changes, say increases, additional GHGs are generated. At any fixed emissions level, the agent needs to eliminate more GHGs and pay a higher technology cost $\left(\frac{dR_i}{dE_i}\frac{dE_i}{dx_i} > 0\right)$. Therefore, compared to Figure 4.2.a, the technology cost curve shifts up (see Figure 4.3). The increase of resource extraction increases the optimal emissions. This is because at the old optimal emissions level, the negative slope of the new technology cost curve R_i is larger than the slope of the sum of cost of permits and damage $pq_i + D_i$. The former slope decreases and the latter slope increases with the increase in the level of emissions. Therefore, they eventually reach equality at the new optimal emissions level that is higher than the old one.

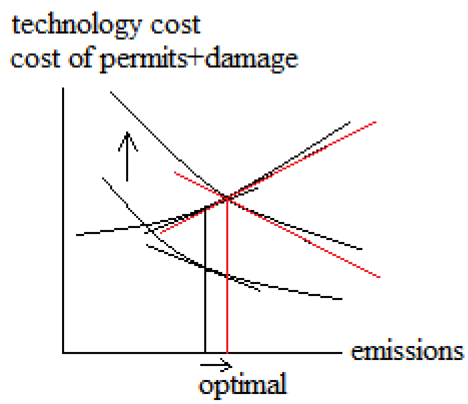


Figure 4.3 Change of optimal emissions with an increase in pollution generated by resource

For each level of resource extraction, there is an optimal emissions level. When resource extraction is at a higher level, the optimal emissions level increases at an increasing rate (see Figure 4.4). The reason is the costs associated with generating GHG: the technology cost to reduce GHG, and the sum of the emissions permits cost and damage from GHG stock for more emissions, increases with a rise in generated GHG at an increasing rate.

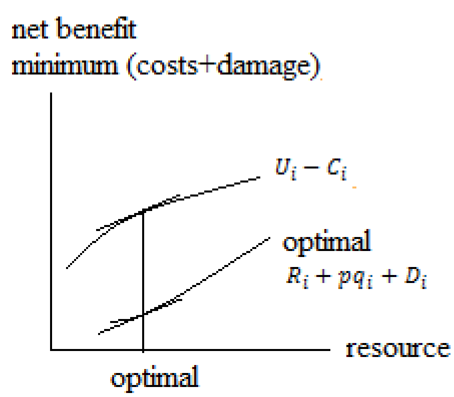


Figure 4.4 Optimal resource extraction when emissions are also optimized

The optimal level of resource extraction is determined by the relationship between the marginal net benefit of resource extraction $\frac{d(U_i - C_i)}{dx_i}$ and the marginal optimized costs and damage $\frac{d(R_i + pq_i + D_i)}{dx_i}$. Assume the resource extraction increases one unit from the optimal level at any time period. The net benefit of resources increases (see Figure 4.1.a) and more pollution is generated.

For a one-unit increase in resource extraction from the optimal level, the magnitude of the increase in net benefits from increased resource extraction is smaller than the increase of the sum of costs and damage at the optimal emissions point. Negative marginal social welfare occurs. Similarly, a one-unit decrease in resource extraction from the optimal level leads to the opposite result. Therefore, the optimal resource extraction occurs at the level where the marginal net benefit of resource extraction is equal to the sum of changes in costs and damage caused by one unit change in resource extraction, where the combination of approaches minimizes the sum of costs and damage (see Figure 4.4).

4.3.3.2 INTERACTIONS OF TWO AGENTS

In the previous section, I explored behaviors of one agent independently. However, two agents in the model interact through the purchase of permits and the pollution stock. In this section, I will explore the interaction between two agents over time under different conditions for the two agents.

4.3.3.2.1 IDENTICAL AGENTS

If the two agents are identical, then they should have the same time path for emissions and resource extraction. Given that the emissions cap decreases over time, I would expect the emissions of both agents have the same decreasing trend in the long run. I assume the emissions cap is set by a third party. There are three possible scenarios: the total emissions never reach the cap, emissions always reach the cap or emissions reach the cap during certain periods. To simplify the discussion, I want to start with the scenario where that the cap is not restricted and the total emissions never reach the cap.

4.3.3.2.1.1 THE TOTAL EMISSIONS NEVER REACH THE CAP

For different time periods, it is realistic to assume that the pollution stock will increase at least for a certain period initially. Similar to the idea in Figure 4.3, the damage from the pollution stock is higher at any emissions level when the pollution stock is at a higher level because $\frac{dD_i}{dZ} > 0$. Therefore, the curve for the sum of the cost of permits and damage shifts up compared with the scenario in Figure 4.2.a (see Figure 4.5).

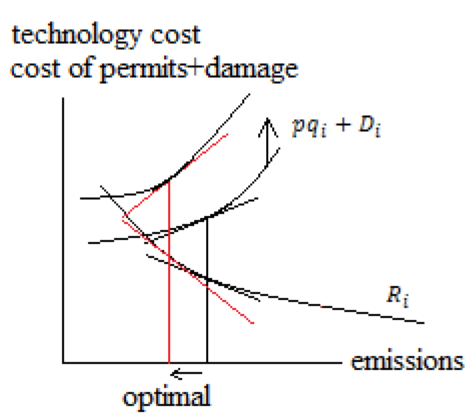


Figure 4.5 Change of emissions with an increase in damage (holding everything else constant)

There are two observations from Figure 4.5. First, holding everything else constant, the optimal emissions decrease with a higher pollution stock. Second, the sum of costs and damage at the optimal emissions level is also higher.

For the optimal resource extraction, compared with Figure 4.4, the increase in damage shifts the minimum sum of costs and damage curve up according to Figure 4.5. This leads to a decrease in resource extraction over time (see Figure 4.6).

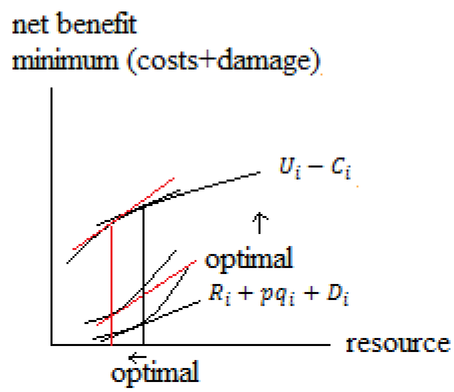


Figure 4.6 Change of "optimal" resource extraction with an increase in damage

However, there is interdependency between Figures 4.5 and 4.6 over time. Figure 4.5 is incomplete and the true optimal emissions cannot be determined. The decrease in optimal resource extraction shown in Figure 4.6 can influence Figure 4.5 by shifting the technology cost curve down over time (similar to Figure 4.3, but the opposite direction). This also contributes to a decrease of optimal emissions. But this may not be the only case and will discuss it later.

The shape and magnitude of the shift of curves in Figures 4.5 and 4.6 determines the rate of change for optimal resource extraction and emissions. I will use Figure 4.7 to explore it. In Figure 4.7, L1 and L4 are the initial curves of the sum of the cost of permits and damage curve and the initial technology cost curve. Point A on L1 and point B on L2 have the same absolute values of slope, and therefore are at the optimal emissions level. In the second period, L1 and L4 shift to L2 and L5 respectively. In the third period, L2 and L5 shift to L3 and L6 respectively.

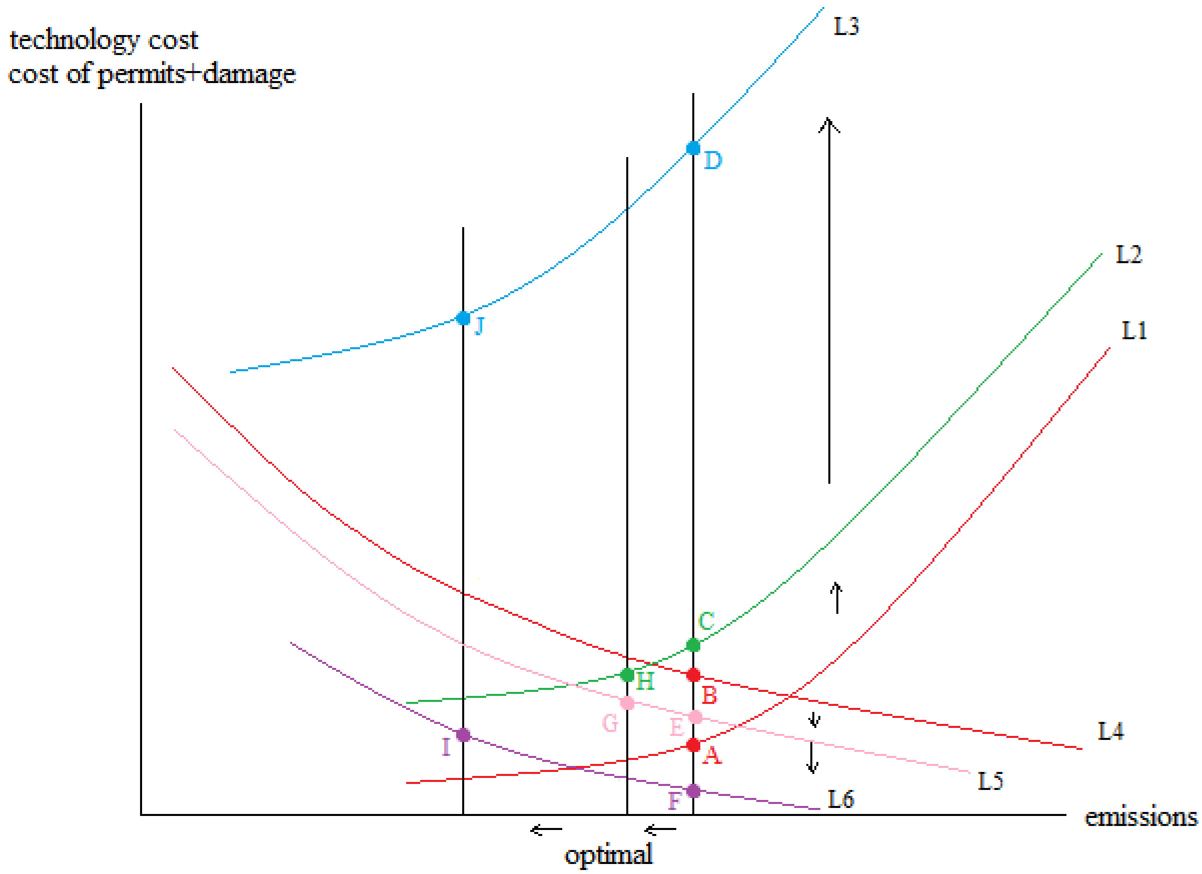


Figure 4.7 Change of optimal emissions over time

First, I fix L4 and consider only shifts for L1. The damage increases with the pollution stock at an increasing rate $\left(\frac{dD_i}{dZ} > 0,\ \frac{d^2D_i}{dZ^2} > 0\right)$. Therefore, there is a larger jump from L2 to L3 than from L1 to L2. Points C and D are at the initial optimal emissions level as points A and B. But the slope of point C is larger than the negative slope of point B, while the slope of point D is larger than both points B and C.

Given the shape of the curves, L2 should have the same negative slope as L4 when the emissions level decreases from the initial optimal level, which is determined by L1 and L4 at points A and B. The emissions level needs to decrease even further for L3. In other words, the "optimal" emissions level decreases with shifts from L1 to L3 (ignore the shift of L4 for now).

The rate of decrease for the "optimal" emissions level is influenced by the shape of L1 and L4, and the magnitude of the shift of L1 over time. Assume the marginal damage increases slowly with a higher emissions level. L1 is relatively flat and experiences a relatively small jump to L2 and L3. The slope of points A, C, and D are relatively close. Meanwhile, the marginal technology cost increases fast with a lower emissions level. L4 is very steep. When the emissions level is lower, the same decrease in emissions leads to a larger increase in the negative slope of L4.

In this case where, L1 increases to L2, the emissions level needs to decrease more to achieve a slope that is large enough as the negative slope of L4. But from L2 to L3, the emissions level only needs to decrease slightly further to reach a slope that is large enough as the negative slope of L4, given the rapid increase of L4 at the lower end of the emissions level. Because the difference of "optimal" emissions level between L1 and L2 is larger than the difference between L2 and L3, the "optimal" emissions level decreases at a decreasing rate.

This result means if additional damage increases slowly with more emissions, while the additional technology cost to reduce pollution increases more rapidly, emissions would decrease. But it is not worth using more expensive technology to eliminate more pollution per period over time, compared to slowly increased damage.

The opposite case happens when the marginal damage increases fast with a higher emissions level, and the marginal technology cost increases slowly with a lower emissions level. The "optimal" emissions level decreases at an increasing rate. This means that if the additional damage increases fast with more emissions, while the additional cost of technology to reduce more pollution increases slowly, emissions would also decrease. In this case, the better solution is to spend on slowly increased technology costs to eliminate additional pollution over time as opposed to allowing increased damage from pollution emissions.

Second, holding L1 fixed and allowing shifts in L4, the direction and magnitude of the shifts are uncertain under this scenario. This is because the change in minimum cost over time is uncertain. Therefore, the change in optimal resource extraction, which directly influences L4, is uncertain. I will leave a more detailed discussion for the next scenario where both L1 and L4 shift. But when L4 decreases, the "optimal" emissions decreases as well (ignoring the shift of L1 for now) and vise versa.

Finally, I consider shifts in L1 and L4 simultaneously. There are three possible scenarios:

A. L1 increases. L4 decreases at an increasing rate

The changes in L1 and L4 are shown in Figure 4.7. L2 and L5 slopes have the same absolute value at points G and H in the second period. L3 and L6 slopes have the same absolute value at points I and J in the third period. When L1 increases to L3 and L4 decreases to L6, the optimal emissions levels will always decrease at an increasing rate. But the change in minimum cost is uncertain.

A.1 Assume there is a relatively large increase from L1 to L2 to L3 and a relatively small decrease from L4 to L5 to L6 as shown in Figure 4.7. The minimum costs are the heights of point A plus point B in the first period, the heights of point G plus point H in the second period, and the heights of point I plus point J in the third period. The minimum cost increases over time at an increasing rate in this case.

Therefore, in Figure 4.6, the minimum cost curve increases at an increasing rate over time. But the optimal resource extraction decreases at an uncertain rate. When the minimum cost curve makes a relatively larger jump after each period, and the net benefit curve is relatively flat, the optimal resource extraction decreases at an increasing rate. Even though the decrease in pollution makes the technology cost curve decrease at a decreasing rate due to the convex damage function, the increasing rate of pollution reduction from the optimal resource extraction decrease creates an opposite effect on the technology cost curve and may dominate to make L4 decreases at an increasing rate in Figure 4.7.

This indicates that when the damage from the pollution stock places a greater threat on society in the long run, technology costs to reduce pollution are much less of a burden when less pollution is generated, and the decrease in resource extraction has a relatively small influence on economic development, then emissions should decrease faster over time to control the damage, while resource extraction should also decrease faster to reach the goal in emissions reduction and may help reduce the burden of technology costs without sacrificing too much economic development (see Figure 4.8 for time paths).

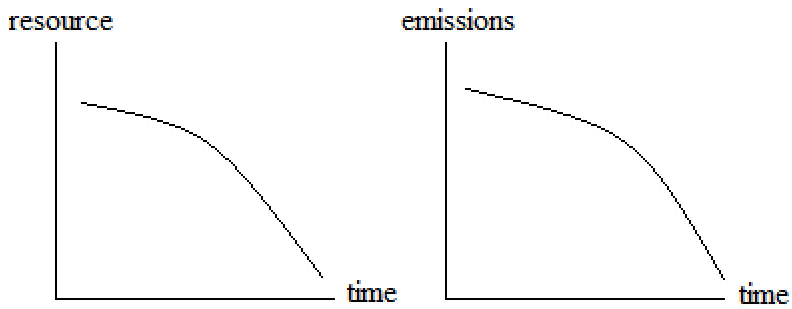


Figure 4.8 Time path of resource extraction and emissions

When the minimum cost curve makes a relatively smaller jump after each period, and the net benefit curve is relatively steep, the optimal resource extraction decreases at a decreasing rate. This makes L4 decreases at a decreasing rate in Figure 4.7, which conflicts with the scenario I started with and, therefore, is not valid for the discussion in section A.

A.2 When there is a relatively small increase from L1 to L2 to L3 and a relatively large decrease from L4 to L5 to L6, I obtain the opposite result of A.1. The minimum cost decreases over time at an increasing rate. In Figure 4.6, the minimum cost curve increases at a decreasing rate over time. The optimal resource extraction decreases at a decreasing rate. Similar to the discussion in situation A.1, this is not valid.

<u>B. L1 increases. L4 decreases at a decreasing rate</u>

Similar to the scenario in A, the optimal emissions level will always decrease under this scenario. But the decreasing rate of the optimal emissions level and the change in minimum costs are uncertain.

B.1 Assume there is a relatively large increase from L1 to L2 to L3 and a relatively small decrease from L4 to L5 to L6 in Figure 4.7. The minimum cost increases over time at an increasing rate in this case.

Therefore, in Figure 4.6, the minimum cost curve increases at an increasing rate over time. But the optimal resource extraction level decreases at an uncertain rate. When the minimum cost curve experiences a relatively large increase after each period and the net benefit curve is relatively flat, the optimal resource extraction level decreases at an increasing rate. Similar to the discussion in A.1, this may make L4 decreases at a decreasing rate in Figure 4.7 if the effect from the convex damage function dominates the effect from the increasing rate of pollution reduction.

This indicates that when the damage from the pollution stock places a greater threat on society in the long run, technology costs to reduce pollution are a relatively heavier burden even with less pollution generated, and the decrease in resource extraction has a relatively small influence on economic development, it may be more difficult for the decrease in resource extraction to offset the burden of technology costs due to the large increase in its marginal cost. But resource extraction should still decrease faster to help reduce at least part of the burden of increased technology costs without sacrificing too much economic development. But given the situation of technology costs, the decreasing rate of emissions is uncertain (see Figure 4.9 for time paths).

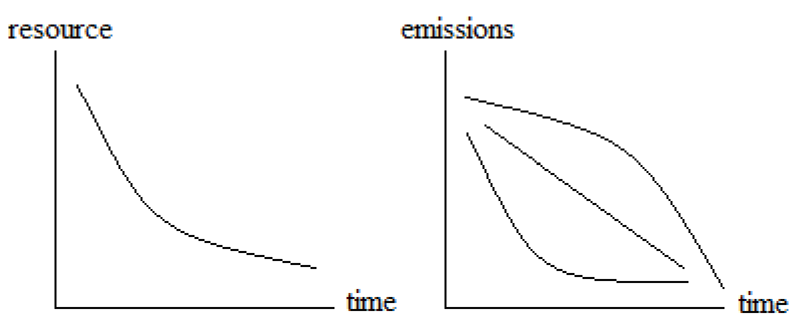


Figure 4.9 Time path of resource extraction and possible time paths of emissions

When the minimum cost curve makes a relatively small jump after each period, and the net benefit curve is relatively steep, the optimal resource extraction level decreases at a decreasing rate. L4 also decreases at a decreasing rate in Figure 4.7.

Similar to the discussion for Figure 4.9, when the damage from the pollution stock places a greater threat on society in the long run, and the decreasing rate of emissions is uncertain, the decrease in resource extraction has a relatively large influence on economic development and, therefore, cannot be reduced to decrease technology costs and influence emissions without sacrificing economic development (see Figure 4.10 for time paths).

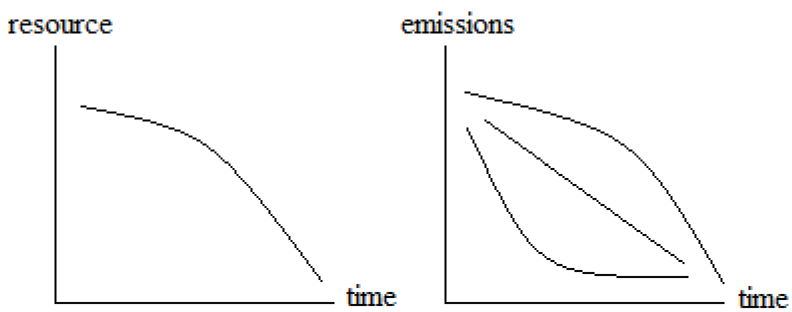


Figure 4.10 Time path of resource extraction and possible time paths of emissions

The scenarios depicted in Figures 4.9 and 4.10 may happen on one net benefit curve and shift the minimum cost curve. The net benefit from resource extraction increases significantly at a lower level of resource extraction, while increases are much slower at higher levels of resource extraction (see Figure 4.11). The time path of resource extraction decreases at an increasing rate and then at a decreasing rate.

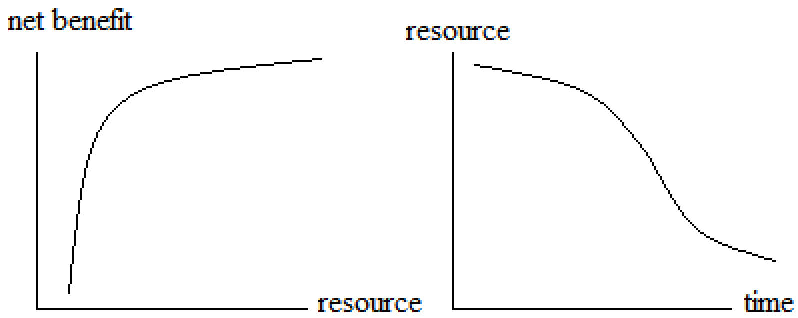


Figure 4.11 Net benefit curve and time path of resource extraction

B.2 When there is a relatively small increase from L1 to L2 to L3 and a relatively large decrease from L4 to L5 to L6 in Figure 4.7, the minimum cost decreases at an unknown rate. Therefore, in Figure 4.6, the minimum cost curve moves down over time. The optimal resource extraction and emissions levels increase initially. But eventually they will be restricted by the emissions cap.

C. L1 increases. L4 increases

Under this scenario, L1 increases to L2 and then to L3, while L4 increases to L5 and then to L6 in Figure 4.7. The minimum cost will always increase and lead to a decrease in resource extraction. In this case, L4 cannot increase. Therefore, this is not valid.

4.3.3.2.1.2 THE TOTAL EMISSIONS REACH THE CAP AT SOME PERIODS

When the emissions cap is relatively restrictive and total emissions reach the cap at some time interval, actual emissions may be lower than the optimal emissions found in section 4.3.3.2.1.1 during those periods. The actual cost is higher than the minimum cost, which leads to a lower actual resource extraction level than the optimum. The lower actual resource extraction level leads to a lower technology cost curve and lower emissions level. This may or may not lead to total emissions lower than the cap in the next period, depending on the level of the emissions cap.

When total emissions always reach the cap, the emissions level of one agent is always half of the cap. The resource extraction level is also influenced by the specific path of the emissions cap.

4.3.3.2.2 DIFFERENT NET BENEFIT OF RESOURCE

Assume agent j is the same as in scenario 4.3.3.2.1 (identical agents). Assume other characteristics for agent i are also the same, except that agent i has a higher net benefit of resources than agent j. The optimal resource extraction for agent i is higher than for agent j.

Compared with scenario 4.3.3.2.1, agent i produces additional pollution that is partially reduced by technology and partially emitted. This directly shifts L1 up faster for both agents in Figure 4.7. It also directly shifts L4 up for agent i. Agent j has a lower resource extraction level than under scenario 4.3.3.2.1 due to the change in L1. L4 is also lower because less pollution is generated.

Based on the previous discussion in scenario 4.3.3.2.1, agent i derives more benefit from resource extraction and, therefore, their resource extraction may decrease slower than that of agent j. The faster decrease in resource extraction also allows agent j to reduce a relatively larger proportion of pollution. Therefore, the emissions level for agent j decreases faster than that of agent i. This can be the reason that some developing countries have difficulty to reduce pollution emissions faster.

4.3.3.2.3 DIFFERENT TECHNOLOGY COSTS

Assume agent j is the same as under scenario 4.3.3.2.1 (identical agents). Assume other characteristics for agent i are also the same, except that agent i has lower technology costs than agent j. Lower technology costs allow agent i to enjoy a lower optimal emissions level and higher optimal resource extraction level than agent j.

Compared with scenario 4.3.3.2.1, lower optimal emissions shift L1 up slower for both agents in Figure 4.7. Agent j has higher resource extraction and emissions levels than under scenario 4.3.3.2.1.

Due to lower technology costs, it is easier for agent i to reduce emissions and, therefore, their emissions decrease faster than those of agent j. The minimum total cost for agent i increases slower. Therefore, the resource extraction level for agent i decreases slower than that of agent j. When agent i invests on clean technology, free riding from agent j may occur, given that agent j can benefit from agent i's behavior without cost.

4.3.3.2.4 DIFFERENT DAMAGE OF POLLUTION STOCK

Assume agent j is the same as under scenario 4.3.3.2.1 (identical agents). Assume other characteristics for agent i are also the same, except that agent i has larger damage from pollution stock than agent j. The optimal resource extraction and emissions levels for agent i are lower than those of agent j.

Compared with scenario 4.3.3.2.1, the lower emissions for agent i shift L1 up at a slower rate than for agent j. The minimum total cost for agent j is lower and the optimal resource extraction level is higher than the scenario 4.3.3.2.1. The optimal emissions level for agent j is also higher.

Damage is a more serious issue for agent i. Therefore, the resource extraction and emissions levels decrease faster for agent i compared to agent j. A more accurate measure of damage from the pollution stock can lead to the optimal level of reduction in pollution emissions.

In summary, the optimal time path for resource extraction and emissions levels for each agent is related to the specific functional forms in the model, the relative magnitude of both agents' marginal net benefit of resource extraction, marginal technology cost of eliminating the unpermitted portion of the pollution, marginal cost of emissions permits, and marginal damage from the pollution stock, as well as the emissions cap. In the long run, resource extraction and emissions levels for both agents should decrease at different rates under different scenarios, depending on the functional forms of equations 4.1-4.6 and the relative magnitude of marginal values in each components of social welfare.

4.4 CONCLUSION

Climate change caused by GHG emissions is a common issue for all societies. This study builds a theoretical model to explore optimal paths of GHG emissions and resource extraction levels for different agents while allowing for the interaction between two agents under a cap-and-trade policy. Compared to many other studies that assume a linear functional form, this study uses a general functional form with specific signs on derivatives to allow for some flexibility for the optimal time paths of resource extraction and emissions levels. Different functional forms lead to different time paths. But the trend in the long run should be very similar and consistent with what will happen in the real world. This study also allows for carbon trade and the use of technology simultaneously, which is consistent with the real world.

To mitigate climate change without sacrificing economic development, each society should carefully evaluate its own net benefit from resource extraction for production related to industry and the well-being of its citizens, costs related to emissions and damage from the pollution stock. It should also consider behaviors of other societies to determine optimal levels.

A society may reduce the use of resources to generate less pollution, or purchase more emissions permits to use more resources to meet the demand for economic development. But these approaches may not be sustainable and always be feasible. Economic development may slow down. The number of emissions permits is limited, so a society may not purchase as many permits as they want. Moreover, a society's optimal resource extraction and emissions level may largely rely on other societies' decisions.

On the other hand, a society could use cleaner resources and/or develop new technology to reduce pollution emissions from each unit of resource extraction at a lower cost. These approaches may help to reach goals of economic development and pollution reduction simultaneously. They also allow a society to rely less on other societies' decisions and, therefore, have more control over its own optimal choice of resource extraction and emissions levels.

The model in this study does not allow for technological change over time. It also assumes independent resource extraction and does not capture any uncertainty across time. These issues can be addressed in future studies. Future studies can also adopt scientific functional form and parameters for this model that simulate optimal time paths.

CHAPTER 5 CONCLUSION

Market failure can lead to the production of substandard products and serious and long-lasting negative impacts on the earth and human welfare. Several issues can cause market failure, including information asymmetry and externality. This research uses the Chinese food market and a carbon market as examples to explore approaches to reduce market failure from different perspectives. It investigates different consumers' reactions to market failure for the design of possible approaches, and reactions to several potential policy interventions for the selection of preferred approaches; it also investigates different societies' reactions once a policy has been implemented.

This research contributes to the literature by extending the use of choice experiment method to explore individual parent's preference toward different types of policy changes that target market failure. This research also explores the lemon principle in the food market and finds that parents' choices contradict the lemon principle due to specific characteristics of the food market. Finally, this research uses a more general model to discuss the optimal resource extraction and pollution emissions, with consideration of carbon trade and the use of technology to deal with pollution simultaneously.

The first study in chapter 2 estimates respondents' MWTP for four changes related to overall food safety: (1) a government requirement that food producers implement a food safety management system (*Management*); (2) an increase in the percentage of traceable food (*Traceability*); (3) publication of all food safety inspection results on a centralized governmental website (*CentralizedWeb*); and (4) provision of routine supplemental food safety inspection by non-governmental organizations (*NGO*). On average, parents were willing to pay up to 165 yuan/month for those changes, with the highest MWTP for *Management*, followed by *Traceability*, *NGO*, and *CentralizedWeb*. The heterogeneity in individual-specific MWTPs for these policies also shows more than 95% of respondents supported *Traceability* and *CentralizedWeb*. In selecting the appropriate food safety policy, decision makers may want to consider whether the goal is to maximize funding for improving food safety or to have greater consumer support for a policy change. Improving food traceability represents a good mechanism for improving food safety in China, as there is relatively high average MWTP and support from more than 95% of respondents in this survey.

The second study in chapter 3 investigates parents' tradeoff between money and safety risks in the food market when there is uncertainty about the true level of food safety. The data show that parents tend to choose a brand of milk with a higher price and safety claim (Brand B), rather than a brand with a lower price and no safety claim (Brand A). This is true even when factors such as food expenditure, concern level of food safety, etc. are held constant, unless the perceived safety level of Brand B is low and the relative price of Brand B is much higher than Brand A. A possible explanation for these results is that parents' health concerns and the inconsistency between price and safety levels provide opposite incentives for parent choice. Their final choice depends on how they weigh the two concerns, which is reflected by their risk aversion to the inconsistency between price and safety, and the relative magnitude of price difference and safety difference between Brands A and B.

The last study in chapter 4 explores the optimal time path of resource extraction and GHG emissions in a dynamic game between two agents. Both time paths decrease in the long run, but the decreasing rates vary depending on the net benefit of resource extraction, costs of technology and emission permits, and damage from pollution stock. Relative to the other agent, larger net benefit from resource extraction for one agent leads to slower decreases in both optimal resource extraction and emissions for this agent; lower technology cost leads to faster decreases in optimal emissions and slower decrease in resource extraction; larger damage from pollution stock leads to faster decrease in both optimal resource extraction and emissions.

Overall, safety issues caused by information asymmetry in food market can have immediate and serious consequences on human health and lives. Parents' willingness-to-pay reflects the demand for strong tools with multiple functions to solve market failure in the food market. The preferred approach has both direct government regulation and incentive, such as traceability information that helps consumers' purchasing decision, for the market to solve the problem. Parents' choice of milk also reflects that consumers and some producers may have mutual interest. Consumers' concern and willingness-to-pay for food safety may enable producers of food with high safety level to survive in the long run. If producers of safe food can devise a way to signals this desirable safety level in the food market, then this market approach may solve the problem without the need for government intervention. While government approach is desirable, a market solution to market failure in the food market without any form of government intervention may also exist. Given the difficulty and high cost for direct regulation or providing incentives to the tremendous number of small-scaled food producers in China, market solutions without government intervention may be a good supplemental approach for policies that involves both government and market approaches.

For climate change, when the damage from pollution stock is large enough, there will be a decrease in emissions. However, to prevent irreversible damage, policy intervention is necessary. As a market based incentive approach, the cap-and-trade policy can ensure the decreasing trend of total emissions by adjusting the cap over time, in a cost efficient manner. Societies can adjust their resource extraction, use of clean technology, and purchase of emission permits to meet the emissions cap while optimizing social welfare. In some cases, the cap can also provide an incentive for the use of clean resources and the investment of clean technology. For climate change, instead of direct regulation on individual pollution emitters such as in command-and-control, it is better for the government to carefully design a cap-and-trade system and allow the market to solve the market failure.

Both the food market and the environmental sector desire market approaches, probably because market solutions leave more choices for consumers or societies. For instance, societies can purchase a reasonable amount of permits according to their specific situation to emit pollutions under a cap-and-trade system; Consumers can use safety information to select food with different levels of safety risks based on their preferences and income. Some low-income consumers do not have to bear a heavy burden from expensive safer food. But the choice of government approaches is also reasonable. It is likely that consumers can not constantly search for safety information on all food they consume. The existence of food with a low safety level is a great concern for consumers. Therefore, they also want the government to ensure food safety for them.

Findings from this dissertation provide information and raise some questions for future studies. A cost benefit analysis can use the estimated MWTP in Chapter 2 to evaluate the feasibility of these changes suggested to select the most beneficial change for implementation.

Chapter 3 builds a theoretical model to explain the choice of milk while allowing for risk aversion. This model is not limited for the food market. It may be used to explain consumers' choice for safety related products and provides a theoretical foundation for empirical analysis in other markets. Future studies may use empirical data from markets where safety is a concern to test this theoretical model. They may also provide discussion on effective signaling from producers of safe products.

In chapter 4, technology is assumed to remain the same over time. Also, trade of resources is not possible. Future studies may relax these assumptions. They may also address uncertainty in the model to show more realistic time paths.

APPENDIX A: Additional Survey Questions

1. What is your current level of concern about food quality and safety in Hunan? *Circle one.*

Not at all concerned	Somewhat concerned	Fairly Concerned	Very concerned
(1)	(2)	(3)	(4)

2. Which of the following news did you hear or see recently? *Check all that apply.*

1	Ginger with Shennongdan
2	Fake lamb
3	Two people sold 40 tons of pork that die from sick
4	None of the above

3. Do any of the grocery stores or wet market at which you typically shop publish daily food inspection results for their agricultural products to consumers? *Check one.*

1	Yes
2	No
3	Not sure

4. In the following systems and food safety labels, have you previously heard of/seen any of them? Do you know their meaning? *Check all that apply.*

	I have heard of/seen it	I know it	I have never heard of/seen and do not know it
ISO 9000	1	2	3
ISO 22000	1	2	3
HACCP	1	2	3
质量安全	1	2	3
无公害农产品	1	2	3
绿色食品 GreenFood	1	2	3
健康食品	1	2	3
有机食品 CERTIFIED ORGANIC COFCC	1	2	3

5. Have frequently, if at all, do you use internet, TV, newspaper and other mass media to check whether a brand of food is safe? *Circle one.*

Never	Sometimes	Fairly often	Very often
(1)	(2)	(3)	(4)

6. Choose the 2 most important and the 2 least important characteristics that help you to identify whether a food is safe. *Check two for each.*

	Most important	Least important
Reputation of the brand	1	1
Appearance and taste of food	2	2
Price	3	3
Where the food is produced	4	4
Where the food is sold	5	5
Ingredients on the package	6	6
Manufacturing and expiration dates	7	7
Safety certification label on the package	8	8

7. What is your average monthly food expenditure? *Check one.*

1	Less than ￥499	5	￥2000 – 2499
2	￥500 - 999	6	￥2500 – 2999
3	￥1000 - 1499	7	More than￥3000
4	￥1500 - 1999		

8. According to the financial situation of your household, what is the highest affordable increase in your monthly food expenditure?

1	Less than ￥25	8	Less than ￥700
2	Less than ￥100	9	Less than ￥800
3	Less than ￥200	10	Less than ￥1000
4	Less than ￥300	11	Less than ￥1200
5	Less than ￥400	12	Less than ￥1500
6	Less than ￥500	13	More than ￥1500
7	Less than ￥600		

9. Which category of spending would you have to decrease first in order to afford a higher food expenditure? *Check one.*

1	Savings
2	Leisure
3	Other (Please write it down)________________________________

10. On average, how frequently does your child drink milk? *Check one.*

1	Never **(⟶Go to question 13)**
2	Less than once a week
3	At least once a week
4	Almost every day

11. Currently there are two brands of milk (milk A and milk B) in domestic market. They look the same except the price and safety claim. Which brand would you choose for your children?

	Milk A	Milk B
Price:	￥3/250ml	￥6/250ml
Safety claim:	There is no special safety claim from the producer.	The producer claims that they guarantee the safety of this milk.
I choose ⟶	A	B

12. How much do you trust the safety claims of milk B in the above question? *Circle one.*

Do not trust at all	Somewhat not trust	Indifferent	Somewhat trust	Completely trust
(1)	(2)	(3)	(4)	(5)

13. Where do you usually buy groceries? *Check all that apply.*

1	Wet market
2	Supermarket
3	Other (Please write it down) ________________________________

14. Have you ever taken any of the following actions to avoid food safety issues? *Check all that apply.*

1	Avoid eating certain foods with a high food safety risk
2	Only choose the brands of food that you trust.
3	Use tricks you learnt from some sources to choose relatively safer food, such as observe appearance of food.
4	Make your own processed food, such as soy milk, sweet wine, etc.
5	Grow vegetables or raise poultry by yourself.
6	Get agricultural products from your farmer relatives.
7	Purchase imported foods instead of domestic foods in store and/or online.
8	Other (Please write it down)____________________________________
9	No. I have never done anything special to deal with food safety issues.

15. If you ever take any actions to deal with a food that has a quality or safety problem, what was the result in most cases? *Check one.*

1	I was satisfied with the final result, and I only spent a little time and energy.
2	I was satisfied with the final result, but I spent too much time and energy.
3	I was not satisfied with the final result, but I only spent a little time and energy.
4	I was not satisfied with the final result, and I spent too much time and energy.
5	I have never taken any actions.

16. What is your gender? *Check one.*

1	Male
2	Female

17. How many people live in this household including yourself? ________

18. Does anyone in your family work in food related industry, such as food processing, restaurant, grocery store, food inspection, etc? *Check one.*

1	Yes
2	No

19. What is your age? ____________________

20. What is the highest degree or level of school you have completed? *Check one.*

1	None	5	Junior college
2	Elementary school	6	Bachelor's degree
3	Junior high school	7	Master's degree
4	Senior high school	8	Doctorate degree

APPENDIX B: Models for Chapter 2

Random utility models are used to analyze parents' choices (). Base on the random utility theory, respondent n intends to maximize utility U_{nki} by choosing alternative i over other alternatives in a choice set (choice experiment question) k. The utility has two components:

$$U_{nki} = V_{nki} + \varepsilon_{nki}$$

where $V_{nki} = \beta' X_{nki}$ is the indirect utility from a vector of all attributes X_{ki} of alternative i (i=1,2,3) in choice set k (k=1,2,3,4). β' is a vector of parameters of attributes. ε_{nki} is a random component and includes all unobserved factors that impact utility.

Respondent n will choose alternative i over other alternatives if $U_{nki} > U_{nkj}, \forall i \neq j$. Therefore, the probability of respondent n choosing alternative i in choice set k is

$$P_{nki} = Prob\left(V_{nki} + \varepsilon_{nki} > V_{nkj} + \varepsilon_{nkj}, \forall i \neq j\right)$$
$$= Prob\left(V_{nki} - V_{nkj} + \varepsilon_{nki} > \varepsilon_{nkj}, \forall i \neq j\right)$$

Different assumptions allow me to use different econometric models to estimate the parameters. The following sections will discuss the four groups of econometric models used in this study.

Model 2.1: Multinomial logit without interaction

Multinomial logit (MNL) model without any interaction terms is my base model. It assumes homogeneous taste across respondents. The indirect utility function of respondent n choosing alternative i in a choice set k is

$$V_{nki} = ASC\_sq_{nki} + \beta_1 \times Management_{nki} + \beta_2 \times Traceability_{nki} + \beta_3 \times CentralizedWeb_{nki} + \beta_4 \times NGO_{nki} + \beta_5 \times Cost_{nki} \quad (B.1)$$

where ASC_sq is an alternative specific constant that equals to 1 if status quo is chosen and 0 otherwise. It captures potential status quo bias.

The random component ε_{nki} is independent and homogeneous across respondents and follows an extreme value distribution. Therefore,

$$P_{nki}|\varepsilon_{nki} = \prod_{i \neq j} e^{-e^{-\left(V_{nki}-V_{nkj}+\varepsilon_{nki}\right)}}$$

The probability P_{nki}

$$P_{nki} = \int \left(\prod_{i \neq j} e^{-e^{V_{nki}-V_{nkj}+\varepsilon_{nki}}} \right) e^{-\varepsilon_{nki}} e^{-e^{-\varepsilon_{nki}}} d\varepsilon_{nki} = \frac{\exp\left(V_{nki}\right)}{\sum_{j=1,2,3} \exp\left(V_{nkj}\right)} \quad (B.2)$$

which has the logit form.

The coefficients are estimated using maximum likelihood estimation (MLE) method, which maximize the probability of respondents choosing the plan that they are observed to choose. The log-likelihood function is

$$\ln L(\beta) = \sum_{nk} \sum_{i} y_{nki} \ln P_{nki}$$

where $y_{nki} = 1$ if plan i or status quo is chosen and $y_{nki} = 0$ otherwise. The estimates of βs maximize the log-likelihood function and therefore satisfy the first order condition $\frac{\mathrm{d} \ln L(\beta)}{\mathrm{d}\beta} = 0$.

Model 2.2: Multinomial logit with interaction

The assumption of homogeneous taste is a limitation of MNL without interactions because in reality, respondents are more likely to have different attitudes towards attribute and the status quo. Some factors can influence or reflect respondents' tastes, including their financial situations, behaviors, and demographics. To capture the influence of those factors, I want to add interactions between those factors and attributes or *ASC_sq* into the indirect utility function as the following:

$$V_{nki} = ASC\_sq_{nki} + ASC\_sq_{nki} \times Affordability_n + ASC\_sq_{nki} \times Averting_n + ASC\_sq_{nki} \times Education_n + \beta_1 \times Management_{nki} + \beta_2 \times Traceability_{nki} + \beta_3 \times CentralizedWeb_{nki} + \beta_4 \times NGO_{nki} + \beta_5 \times Cost_{nki} + \beta_6 \times Cost_{nki} \times Affordability_n \qquad (B.3)$$

The probability of respondent n choosing alternative i in choice set k remains B.2 in this situation.

Model 2.3: Random parameter logit without interaction

Random parameter logit also allows for heterogeneous tastes across respondents (McFadden and Train, 2000). It does not identify the influence of other factors as the

MNL with interactions does. But it finds out individual parameters for each respondent. The probability in the random parameter logit model is

$$P_{nki}(\theta) = \int \frac{\exp(V_{nki})}{\sum_j \exp(V_{nkj})} f(\beta|\theta) d\beta \qquad (B.4)$$

Where $f(\cdot)$ is the density function of random parameters β. θ represents the mean and covariance of β that need to be estimated. $P_{nki}(\theta)$ is the weighted average of multinomial logit probabilities and the weights depend on the density function $f(\cdot)$.

There are different assumptions for the distributions of β, such as normal distribution and lognormal distribution. The normal distribution allows for flexible signs for β, while the lognormal distribution may be more reasonable when I am confident that β should take a certain sign. In this study, I will make two different assumptions for the distribution of β. One assumes normal distribution for all βs. The other one assumes lognormal distribution for β of *Cost* and *ASC_sq*. I find the model with all normal distribution has lower AIC and therefore is better.

To estimate a random parameter logit model, I need to draw a value of β^r from the density function $f(\beta|\theta)$ and use this value of β to calculate $\frac{\exp(V_{nki}^r)}{\sum_j \exp(V_{nkj}^r)}$ for R times. Then I calculate the average simulated probability

$$\breve{P}_{nki} = \frac{1}{R} \sum_{r=1}^{R} \frac{\exp(V_{nki}^r)}{\sum_j \exp(V_{nkj}^r)}$$

Similar to the multinomial logit model, the simulated log likelihood function for the random parameter model is

$$SLL = \sum_{nk} \sum_{i} y_{nki} \ln \breve{P}_{nki}$$

The estimates of θ maximize the simulated log likelihood function.

Models 2.4.1 and 2.4.2: Random parameter logit without interactions

Even though random parameters in the random parameter logit models capture heterogeneous preferences among respondents, some factors may have a strong influence on the respondents' attitudes towards attributes or ASC_sq that need to be specified in the model. Therefore, these two models assume indirect utility function (B.3) and probability (B.4).

In Model 2.4.1, the standard errors of $Cost$, ASC_sq, $ASC\_sq \times Averting$, and $ASC\_sq \times Education$ are insignificant. Therefore, I assume the coefficients of those variables are fixed in Model 2.4.2 as the final model.

References:

Akerlof, George. 1970. "The Market for ' Lemons ': Quality Uncertainty and the Market Mechanism." *The Quarterly Journal of Economics* 84 (3): 488–500.

Andersson, Henrik, Arne Risa Hole, and Mikael Svensson. 2016. "Valuation of Small and Multiple Health Risks: A Critical Analysis of SP Data Applied to Food and Water Safety." *Journal of Environmental Economics and Management* 75: 41–53.

Anouliès, Lisa. 2017. "Heterogeneous Firms and the Environment : A Cap-and-Trade Program." *Journal of Environmental Economics and Management* 84: 84–101.

Bai, Junfei, Caiping Zhang, and Jing Jiang. 2013. "The Role of Certificate Issuer on Consumers' Willingness-to-Pay for Milk Traceability in China." *Agricultural Economics* 44 (4–5): 537–44. doi:10.1111/agec.12037.

Baker, Gregory A. 2003. "Food Safety and Fear : Factors Affecting Consumer Response to Food Safety Risk." *International Food and Agribusiness Management Review* 6 (1): 1–11.

Becker, Gary S. 1965. "A Theory of the Allocation of Time." *The Economic Journal* 75 (299): 493–517.

Benchekroun, Hassan, and Farnaz Taherkhani. 2014. "Adaptation and the Allocation of Pollution Reduction Costs." *Dynamic Games and Applications* 4 (1): 32–57.

Bertrand, Vincent. 2013. "Modeling of Emission Allowance Markets : A Literature Review." 1304. Chaire Economie Du Climat.

Bond, Eric W. 1984. "Test of the Lemons Model : Reply." *American Economic Review* 74 (4): 801–4.

Boucekkine, Raouf, Jacek B. Krawczyk, and Thomas Vallée. 2011. "Environmental Quality versus Economic Performance: A Dynamic Game Approach." *Optimal Control Applications and Methods* 32 (1): 29–46. doi:10.1002/oca.927.

Canton, Joan, Antoine Soubeyran, and Hubert Stahn. 2008. "Environmental Taxation and Vertical Cournot Oligopolies: How Eco-Industries Matter." *Environmental and Resource Economics* 40 (3): 369–382.

Chakravorty, Ujjayant, Bertrand Magné, and Michel Moreaux. 2003. "From Coal to Clean Energy : Hotelling with a Limit on the Stock of Externalities." 229. IDEI Working Papers. Toulouse.

Chakravorty, Ujjayant, Michel Moreaux, and Mabel Tidball. 2008. "Ordering the Extraction of Polluting Nonrenewable Resources." *American Economic Review* 98 (3): 1128–44.

Chesney, Marc, and Luca Taschini. 2012. "The Endogenous Price Dynamics of Emission Allowances: An Application to CO2 Option Pricing." *Applied Mathematical Finance* 19 (5): 447–75.

China Internet Network Information Center. 2013. "The 33rd Statistical Report on Internet Development in China." https://www.iis.se/docs/CNNIC_report.pdf.

China National Accreditation Service for Conformity Assessment. 2015. "The Thirteenth National HACCP Application And Certification Conference Is Held In Beijing." https://www.cnas.org.cn/rdzt/sjrkr2015n/fhbd/2015/06/869325.shtml.

China Quality Certification Centre. 2016. "Introduction of Certification." *China Quality Certification Centre*. Accessed August 11.

http://www.cqc.com.cn/www/chinese/c/2015-04-30/512481.shtml.
Coase, Ronald H. 1960. “The Problem of Social Cost.” *Journal of Law and Economics* 3: 1–44.
Codex. 1997. *Hazard Analysis and Critical Control Point (HACCP) System and Guidelines for Its Application. Annex to CAC/RCP 1-1969, Rev. 3.* Rome: Codex. http://www.fao.org/docrep/005/y1579e/y1579e03.htm.
Combris, Pierre, Alexandra Seabra Pinto, António Fragata, and Eric Giraud-Héraud. 2009. “Does Taste Beat Food Safety? Evidence From the ‘Pêra Rocha’ Case in Portugal.” *Journal of Food Products Marketing* 16 (1): 60–78. doi:10.1080/10454440903415667.
Dardati, Evangelina. 2014. “Pollution Permit Systems and Firm Dynamics: How Does the Allocation Scheme Matter ?” *International Economic Review* 57 (1): 305–328.
Doherty, Edel, and Danny Campbell. 2014. “Demand for Safety and Regional Certification of Food.” *British Food Journal* 116 (4): 676–89. doi:10.1108/BFJ-10-2011-0266.
EPA. 2017a. “C-FERST Issue Profile: Climate Change.” https://www.epa.gov/c-ferst/c-ferst-issue-profile-climate-change.
———. 2017b. “Global Greenhouse Gas Emissions Data.” https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data.
FAO. 2014. “Milk and Milk Products Price and Trade Update: April 2014.” http://www.fao.org/fileadmin/templates/est/COMM_MARKETS_MONITORING/Dairy/Documents/Milk_and_Milk_Products.pdf.
FAO and WHO. 2003. *Assuring Food Safety and Quality: Guidelines for National Food Control Systems*. Rome: FAO and WHO. http://www.wpro.who.int/foodsafety/documents/docs/English_Guidelines_Food_control.pdf.
FDA. 2015. “Hazard Analysis Critical Control Point (HACCP).” *http://www.fda.gov/Food/GuidanceRegulation/HACCP/*.
Food Safety Information. 2016. “What We Should Know About ‘Gutter Oil.’” Accessed August 11. https://www.foodsafety.gov.mo/e/sense/detail.aspx?id=617f44e4-62ff-4db5-a718-b9ac2cecc2fc.
FORHEAD. 2014. “Food Safety in China : A Mapping of Problems , Governance.” *Social Science Research Council*. http://webarchive.ssrc.org/cehi/PDFs/Food-Safety-in-China-Web.pdf.
Fowlie, Meredith, and Jeffrey M. Perloff. 2013. “Distributing Pollution Rights in Cap-and-Trade Programs: Are Outcomes Independent of Allocation?” *Review of Economics and Statistics* 95 (5): 1640–52.
Gale, Fred, and Kuo Huang. 2007. “Demand for Food Quantity and Quality in China.” *Quality*, no. 32: 69–115. http://www.ers.usda.gov/Publications/ERR32/.
Germain, Marc, Philippe Toint, Henry Tulkens, and Aart De Zeeuw. 2003. “Transfers to Sustain Dynamic Core-Theoretic Cooperation in International Stock Pollutant Control.” *Journal of Economic Dynamics & Control* 28 (1): 79–99.
Greene, William. 2012. “Discrete Choice Modeling.” http://pages.stern.nyu.edu/~wgreene/DiscreteChoice/Lectures/GTPart3-BinaryChoiceInference.pptx.
Grunert, Klaus G. 2005. “Food Quality and Safety : Consumer Perception and Demand.”

European Review of Agricultural Economics 32 (3): 369–91. doi:10.1093/eurrag/jbi011.
Hahn, Robert W., and Robert N Stavins. 2011. "The Effect of Allowance Allocations on Cap-and-Trade System Performance." *The Journal of Law & Economics* 54 (4): 267–94.
Harstad, Bård. 2012. "Climate Contracts: A Game of Emissions, Investments, Negotiations, and Renegotiations." *Review of Economic Studies* 79: 1527–57. doi:10.1093/restud/rds011.
He, Pinghua, and Peisi Chen. 2014. "Study on Causes of Slow Progress in Promoting the Application of Food Traceability System in China." *Asian Agricultural Research* 6 (6): 87–93.
Hennessy, David A., Jutta Roosen, and Helen H. Jensen. 2003. "Systemic Failure in the Provision of Safe Food." *Food Policy* 28 (1): 77–96.
Huffman, Wallace E. 2011. "Household Production Theory and Models." In *The Oxford Handbook of the Economics of Food Consumption and Policy*, edited by Jayson L. Lusk, Jutta Roosen, and Jason F. Shogren, 35–74. Oxford: Oxford University Press.
Huston, John H., and Roger W. Spencer. 2002. "Quality, Uncertainty and the Internet: The Market for Cyber Lemons." *The American Economist* 46 (1): 50–60.
IAASTD. 2009. *IAASTD International Assessment of Agricultural Knowledge, Science and Technology for Development: Global Report*. Edited by Beverly D. McIntyre, Hans R. Herren, Judi Wakhungu, and Robert T. Watson. 2nded. Island Press. http://www.unep.org/dewa/agassessment/reports/IAASTD/EN/Agriculture at a Crossroads_Global Report (English).pdf.
IETA. 2015. "European Union : An Emissions Trading Case Study." http://www.ieta.org/resources/Resources/Case_Studies_Worlds_Carbon_Markets/euets_case_study_may2015.pdf.
———. 2016. "China: An Emissions Trading Case Study." http://www.ieta.org/resources/2016 Case Studies/China case study.pdf.
Jiang, Mingjun, Dezhao Chen, Zhehui Peng, and Huiling Xu. 2011. "Food Safety: How Should China Solve The Problems." *Ecological Safety Research* 10: 1–23. http://www.iesco-iesco.org/Writable/Resource/books/ResearchonEcology/2011/10.pdf.
Jin, Shaosheng, Jiehong Zhou, and Juntao Ye. 2008. "Adoption of HACCP System in the Chinese Food Industry: A Comparative Analysis." *Food Control* 19: 823–28. doi:10.1016/j.foodcont.2008.01.008.
Jørgensen, Steffen, Guiomar Martín-Herrán, and Georges Zaccour. 2010. "Dynamic Games in the Economics and Management of Pollution." *Environmental Modeling & Assessment* 15 (6): 433–67. doi:10.1007/s10666-010-9221-7.
Jørgensen, Steffen, and Georges Zaccour. 2001. "Time Consistent Side Payments in a Dynamic Game of Downstream Pollution." *Journal of Economic Dynamics & Control* 25: 1973–87. doi:10.1016/S0165-1889(00)00013-0.
Kollenberg, Sascha, and Luca Taschini. 2016. "Emissions Trading Systems with Cap Adjustments." *Journal of Environmental Economics and Management* 80. Elsevier: 20–36. doi:10.1016/j.jeem.2016.09.003.
Kuhfeld, Warren F. 2001. "Multinomial Logit, Discrete Choice Modeling." *An Introduction to Designing Choice Experiments, and Collecting, Processing and*

Analyzing Choice Data with SAS. SAS Institute TS-643. http://dina2000.gotoip2.com/news/UploadFiles/t9.pdf.
Kutty, Nandinee K. 2008. "A Household Production Function Model of the Production of Child Health and Education—The Role of Housing-Related Inputs." https://ssrn.com/abstract=1232602.
Kwok, Joey, and Arthur Yau. 2006. "Sudan Dyes in Food." *Food Safety Focus* 5. http://www.cfs.gov.hk/english/multimedia/multimedia_pub/multimedia_pub_fsf_05_01.html.
Lagos, Joshua E, Ryan R Scott, Kristen Rasmussen, Wu Bugang, and Ursula Chen. 2010. "China Organics Report." http://gain.fas.usda.gov/Recent GAIN Publications/Organics Annual_Beijing_China - Peoples Republic of_10-14-2010.pdf.
Legal Daily. 2015. "Where Is the Tough Part of New Food Safety Law?" *Xinhuanet.com*, May 4. http://news.xinhuanet.com/food/2015-05/04/c_127760564.htm.
Legras, Sophie, and Georges Zaccour. 2011. "Temporal Flexibility of Permit Trading When Pollutants Are Correlated." *Automatica* 47 (5). Elsevier Ltd: 909–19. doi:10.1016/j.automatica.2011.01.057.
Li, Xianjun. n.d. "The Current Status and Prospects for Organic Agriculture in China." http://www.law.osaka-u.ac.jp/~c-forum/box5/vol8/lixianjun(c).pdf.
Lim, Kar H., Wuyang Hu, Leigh J Maynard, and Ellen Goddard. 2013. "U.S. Consumers' Preference and Willingness to Pay for Country-of-Origin-Labeled Beef Steak and Food Safety Enhancements." *Canadian Journal of Agricultural Economics/Revue Canadienne D'agroeconomie* 61 (1): 93–118. doi:10.1111/j.1744-7976.2012.01260.x.
Lin, Yao-Yu, Hui Zeng, Gui-Cai Li, and Hong-Gang Ni. 2010. "Economic Development Is Ultimate Determinant of Food Safety: A Case Study of China." *Environmental Pollution (Barking, Essex : 1987)* 158 (5): 1185–88. doi:10.1016/j.envpol.2009.11.014.
Liski, Matti, and Juan-pablo Montero. 2011. "Market Power in an Exhaustible Resource Market : The Case of Storable Pollution Permits." *The Economic Journal* 121 (551): 116–44.
Liski, Matti, and Olli Tahvonen. 2004. "Can Carbon Tax Eat OPEC's Rents?" *Journal of Environmental Economics and Management* 47 (1): 1–12.
Liu, Jieping. 2016. "Changsha Will Implement Traceability System For Meat and Vegetable This Year. People Can Use Receipt To Check Producation Informtaion." *Changsha Evening News*, June 19. http://hn.rednet.cn/c/2016/06/19/4011860.htm.
Long, Ngo Van. 2011. "Dynamic Games in the Economics of Natural Resources: A Survey." *Dynamic Games and Applications* 1 (1): 115–48. doi:10.1007/s13235-010-0003-2.
Lopomo, Giuseppe, Leslie M. Marx, David McAdams, and Brian Murray. 2011. "Carbon Allowance Auction Design: An Assessment of Options for the United States." *Review of Environmental Economics and Policy* 5 (1): 25–43.
Loureiro, Maria L., and Wendy J. Umberger. 2007. "A Choice Experiment Model for Beef: What US Consumer Responses Tell Us about Relative Preferences for Food Safety, Country-of-Origin Labeling and Traceability." *Food Policy* 32 (4): 496–514. doi:10.1016/j.foodpol.2006.11.006.

MacLeod, Bentley, and Miguel Urquiola. 2009. “Anti-Lemons : School Reputation and Educational Quality.” 15112. National Bureau of Economic Research.

Masoudi, Nahid, Marc Santugini, and Georges Zaccour. 2016. “A Dynamic Game of Emissions Pollution with Uncertainty and Learning.” *Environmental and Resource Economics* 64 (3): 349–372.

McFadden, Daniel. 1974. “Condition Logit Analysis of Qualitative Choice Behavior.” In *Frontiers in Econometrics*, edited by P. Zarembka, 1:105–42. Acedemic Press.

McFadden, Daniel, and Kenneth Train. 2000. “Mixed MNL Models for Discrete Response.” *Journal of Applied Econometrics* 15 (5): 447–70. doi:10.1002/1099-1255(200009/10)15:5<447::AID-JAE570>3.0.CO;2-1.

McMichael, Anthony J. 2013. “Globalization, Climate Change, and Human Health.” *The New England Journal of Medicine* 368: 1335–43. doi:10.1056/NEJMra1109341.

Mocan, Naci. 2007. “Can Consumers Detect Lemons? An Empirical Analysis of Information Asymmetry in the Market for Child Care.” *Journal of Population Economics* 20 (4): 743–80. doi:10.1007/s00148-006-0087-6.

National Bureau of Statistics Survey Office in Hunan. n.d. “National Bureau of Statistics Survey Data of Hunan Province.” *http://www.hndc.gov.cn/hndc/hndcdata/2013/index.htm*. http://www.hndc.gov.cn/hndc/hndcdata/2013/index.htm.

NBC News. 2008. “China: 6 Babies Likely Died from Toxic Milk.” *Nbcnews.com*, December 2. http://www.nbcnews.com/id/28004966/ns/health-food_safety/t/china-babies-likely-died-toxic-milk/#.VollyvkrLIU.

Ortega, David L., H. Holly Wang, Nicole J. Olynk, Laping Wu, and Junfei Bai. 2011. “Chinese Consumers’ Demand for Food Safety Attributes: A Push for Government and Industry Regulations.” *American Journal of Agricultural Economics* 94 (2): 489–95. doi:10.1093/ajae/aar074.

Ortega, David L., H. Holly Wang, Laping Wu, and Nicole J. Olynk. 2011. “Modeling Heterogeneity in Consumer Preferences for Select Food Safety Attributes in China.” *Food Policy* 36 (2): 318–24. doi:10.1016/j.foodpol.2010.11.030.

Perino, Grischa, and Maximilian Willner. 2015. “The Price and Emission Effects of a Market Stability Reserve in a Competitive Allowance Market.” 28. WiSo-HH Working Paper Series.

Population Census Office under the State Council, and Department of Population and Employment Statistics National Bureau of Statistics. 2012. *Tabulation On The 2010 Population Census of The People’s Republic of China*. Beijing: China Statistics Press. http://www.stats.gov.cn/tjsj/pcsj/rkpc/6rp/indexch.htm.

Probst, Lorenz, Elysée Houedjofonon, Hayford Mensah Ayerakwa, and Rainer Haas. 2012. “Will They Buy It? The Potential for Marketing Organic Vegetables in the Food Vending Sector to Strengthen Vegetable Safety: A Choice Experiment Study in Three West African Cities.” *Food Policy* 37 (3). Elsevier Ltd: 296–308. doi:10.1016/j.foodpol.2012.02.014.

Qiu, Yuming. 2011. “The Causes of Food Safety Issues.” *315online.com*. http://315online.com/action/reports/132220.html.

Reilly, Jacquie. 2006. “The Impact of the Media on Food Choice.” In *The Psychology of Food Choice*, edited by Richard Shepherd and Monique Raats, 201–25. Wallingford, Oxfordshire, UK: CABI.

Resnick, Paul, and Richard Zeckhauser. 2002. "Trust among Strangers in Internet Transactions : Empirical Analysis of eBay ' S Reputation System." In *The Economics of the Internet and E-Commerce,* edited by Michael R. Baye, 127–57. Amsterdam: Elsevier Science.
Revision Committee on the Handbook for Introduction of Food Traceability Systems. 2007. *Handbook for Introduction of Food Traceability Systems: Guidelines for Food Traceability*. Tokyo: Food Marketing Research and Information Center. http://www.maff.go.jp/j/syouan/seisaku/trace/pdf/handbook_en.pdf.
Rosenman, Robert E., and Wesley W. Wilson. 1991. "Quality Differentials and Prices Are Cherries Lemons." *The Journal of Industrial Economics* 39 (6): 649–58.
Rubio, Santiago J, and Alistair Ulph. 2007. "An Infinite-Horizon Model of Dynamic Membership of International Environmental Agreements." *Journal of Environmental Economics and Management* 54: 296–310. doi:10.1016/j.jeem.2007.02.004.
Sanxiang Metro News. 2012. "Changsha Will Implement Traceability System for Meat and Vegetable." *Ministry of Commerce People's Republic of China*. http://traceability.mofcom.gov.cn/static/zy_shehuijujiao/page/2013/1/1358839319977.html.
Scarpa, Riccardo, Mara Thiene, and Kenneth Train. 2008. "Utility in Willingness to Pay Space: A Tool to Address Confounding Random Scale Effects in Destination Choice to the Alps." *American Journal of Agricultural Economics* 90 (4): 994–1010. doi:10.1111/j.1467-8276.2008.01155.x.
Schroeder, Ted C., Glynn T. Tonsor, Joost M.E. Pennings, and James Mintert. 2007. "Consumer Food Safety Risk Perceptions and Attitudes : Impacts on Beef Consumption across Countries." *The B.E. Journal of Economic Analysis & Policy* 7 (1): 1–29.
Shanghai World Expo Exhibition & Convertion Center. n.d. "Welcome to BIOFACH CHINA 2017." *Shanghai World Expo Exhibition & Convertion Center, China*. http://www.biofachchina.com/en/home.php.
Sitkin, Sim B., and Amy L. Pablo. 1992. "Reconceptualizing the Determinants of Risk Behavior." *The Academy of Management Review* 17 (1): 9–38.
Solheim, Anne Lyche, Kari Austnes, Tor Erik Eriksen, Isabel Seifert, and Silje Holen. 2010. "Climate Change Impacts on Water Quality and Biodiversity." Prague.
Stern, Nicholas. 2007. "Stern Review on the Economics of Climate Change." Cambridge, UK: Cambridge University Press.
Stiglitz, Joseph E. 2008. "Government Failure vs. Market Failure: Principles of Regulation." *Columbia University Academic Commons*. doi:https://doi.org/10.7916/D82F7V5C.
The State Council Information Office. 2007. "The Quality and Safety of Food in China." http://www.foodprocessing.com/assets/Media/MediaManager/chinese_food_safety.pdf.
The World Bank. 2016. "China Overview." *The World Bank*. http://www.worldbank.org/en/country/china/overview.
Toman, M. A., and C. Withagen. 2000. "Accumulative Pollution, 'Clean Technology', and Policy Design." *Resource and Energy Economics* 22 (4): 367–84.
Tonsor, Glynn T., Ted C. Schroeder, Joost M E Pennings, and James Mintert. 2009.

“Consumer Valuations of Beef Steak Food Safety Enhancement in Canada, Japan, Mexico, and the United States.” *Canadian Journal of Agricultural Economics* 57 (3): 395–416. doi:10.1111/j.1744-7976.2009.01158.x.

Train, Kenneth. 2003. *Discrete Choice Methods with Simulation*. Cambridge, UK: Cambridge University Press.

USDA. 2015. “Percent of Consumer Expenditures Spent on Food, Alcoholic Beverages, and Tobacco That Were Consumed at Home, by Selected Countries, 2013.” http://www.ers.usda.gov/datafiles/Food_Expenditures/Expenditures_on_food_and_alcoholic_beverages_that_were_consumed_at_home_by_selected_countries/table97_2013.xlsx.

Van Loo, Ellen J., Vincenzina Caputo, Rodolfo M. Nayga, Jean Francois Meullenet, and Steven C. Ricke. 2011. “Consumers’ Willingness to Pay for Organic Chicken Breast: Evidence from Choice Experiment.” *Food Quality and Preference* 22 (7). Elsevier Ltd: 603–13. doi:10.1016/j.foodqual.2011.02.003.

Venables, William N., and Brian D. Ripley. 2002. *Modern Applied Statistics with S*. 4thed. New York: Springer.

Verbeke, Wim. 2005. “Agriculture and the Food Industry in the Information Age.” *European Review of Agricultural Economics* 32 (3): 347–68. doi:10.1093/eurrag/jbi017.

Viscusi, W. Kip. 1993. “The Value of Risks to Life and Health.” *Journal of Economic Literature* 31: 1912–46.

Viscusi, W. Kip, Wesley A. Magat, and Joel Huber. 1991. “Pricing Environmental Health Risks: Survey Assessments of Risk-Risk and Risk-Dollar Trade-Offs for Chronic Bronchitis.” *Journal of Environmental Economics and Management* 21: 32–51.

Vossler, Christian A, Jordan F Suter, and Gregory L Poe. 2013. “Experimental Evidence on Dynamic Pollution Tax Policies.” *Journal of Economic Behavior & Organization* 93. Elsevier B.V.: 101–15. doi:10.1016/j.jebo.2013.07.017.

Wang, Lixia, Zhaohui Guo, Xiyuan Xiao, Tongbin Chen, Xiaoyong Liao, Jie Song, and Bin Wu. 2008. “Heavy Metal Pollution of Soils and Vegetables in the Midstream and Downstream of the Xiangjiang River, Hunan Province.” *Journal of Geographical Sciences* 18 (3): 353–62. doi:10.1007/s11442-008-0353-5.

Wang, Shuo, Xiaojun Liu, Fei Wang, Zhencai Liang, and Jie Guan. 2014. “Research on the Current Situation of Chinese Food Traceability System.” *Ministry of Commerce People’s Republic of China*. http://traceability.mofcom.gov.cn/static/zy_hangyeyanju/page/2014/1/1389685356530.html.

Wang, Zhigang, Yanna Mao, and Fred Gale. 2008. “Chinese Consumer Demand for Food Safety Attributes in Milk Products.” *Food Policy*. doi:10.1016/j.foodpol.2007.05.006.

Weber Shandwick. 2014. “China Food Forward Trends Report 2014.”

Wheeler, Tim, and Joachim von Braun. 2013. “Climate Change Impacts on Global Food Security.” *Science* 341: 508–13. doi:10.1126/science.1239402.

WHO. 2016. “Questions and Answers on Melamine.” *Who.int*. Accessed August 11. http://www.who.int/csr/media/faq/QAmelamine/en/.

———. 1999. “Strategies for Implementing HACCP in Small and / or Less Developed Businesses.”

http://apps.who.int/iris/bitstream/10665/66690/1/WHO_SDE_PHE_FOS_99.7.pdf?ua=1.
———. 2012. “10 Facts on Climate Change and Health.” http://www.who.int/features/factfiles/climate_change/facts/en/.
———. 2015a. “Food Safety Key Facts.” http://www.who.int/mediacentre/factsheets/fs399/en/.
———. 2015b. “WHO Estimates of The Global Burden of Foodborne Diseases.” Geneva. http://apps.who.int/iris/bitstream/10665/199350/1/9789241565165_eng.pdf?ua=1.
Wilcock, Anne, Maria Pun, Joseph Khanona, and May Aung. 2004. “Consumer Attitudes, Knowledge and Behavior: A Review of Food Safety Issues.” *Trends in Food Science & Technology* 15: 56–66. doi:10.1016/j.tifs.2003.08.004.
Wolf, Christopher a., Glynn T. Tonsor, and Nicole J. Olynk. 2011. “Understanding U . S . Consumer Demand for Milk Production Attributes.” *Journal of Agricultural and Resource Economics* 36 (2): 326–42.
Woodpecker Food Safety Center. n.d. “About Woodpecker Food Safety Center.” http://www.food120.org/list.php?cid=17.
Wu, Linhai, Shuxian Wang, Dian Zhu, Wuyang Hu, and Hongsha Wang. 2015. “Chinese Consumers’ Preferences and Willingness to Pay for Traceable Food Quality and Safety Attributes: The Case of Pork.” *China Economic Review* 35: 121–36. doi:10.1016/j.chieco.2015.07.001.
Xiao, Guoan. 2014. *Education Yearbook of Hunan*. Haikou: South Press.
Xu, Lingling, and Linhai Wu. 2010. “Food Safety and Consumer Willingness to Pay for Certified Traceable Food in China.” *Journal of the Science of Food and Agriculture* 90 (8): 1368–73. doi:10.1002/jsfa.3985.
Yahaya, Iddrisu, Fred A. Yamoah, and Faizal Adams. 2015. “Consumer Motivation and Willingness to Pay for ‘safer’ Vegetables in Ghana.” *British Food Journal* 117 (3): 1043–65. doi:10.1108/BFJ-10-2013-0296.
Yang, Yang. 2014. “Study of the Role of NGO in Strengthening the Food Safety and Construction of the Relevant Law.” *Open Journal of Political Science* 4 (3): 137–42. doi:10.4236/ojps.2014.43015.
Yates, Andrew J. 2012. “On a Fundamental Advantage of Permits Over Taxes for the Control of Pollution.” *Environmental and Resource Economics* 51 (4): 583–98. doi:10.1007/s10640-011-9513-7.
Yau, Arthur. 2012. “Aflatoxins in Milk.” *Food Safety Focus*, no. 67. http://www.cfs.gov.hk/sc_chi/multimedia/multimedia_pub/files/FSF67_2012-02-15.pdf.
Young, Oran R. 2011. “The Effectiveness of International Environmental Regimes: Existing Knowledge, Cutting-Edge Themes, and Research Strategies.” *Proceedings of the National Academy of Sciences of the United States of America* 108 (50): 19853–60.
Zetterberg, Lars, Markus Wråke, Thomas Sterner, Carolyn Fischer, and Dallas Burtraw. 2012. “Short-Run Allocation of Emissions Allowances and Long-Term Goals for Climate Policy.” *Ambio* 41: 23–32. doi:10.1007/s13280-011-0238-1.
Zhang, Chunxiang, Chunxin Liu, and Jiayu He. 2014. “Hunan Food Safety Promotion Week Started is ‘Convoyed’ by 11 Departments.” *Sxdsb.voc.com.cn*, June 10.

http://sxdsb.voc.com.cn/article/201406/201406111014588951.html.

Zhang, Jing. 2011. "'Leather Milk' Is Only Behaviors of Unethical Small Companies." *Life Times*. http://paper.people.com.cn/smsb/html/2011-02/22/content_751306.htm.

Zhang, Peiwen, Shanshan Zhang, and Feng Tian. 2008. "Police's General Opinion on Public Security." In *Society of China Analysis and Forecast (2009),* edited by Xin Ru, Xueyi Lu, and Peilin Li, 100–111. Beijing: Social Sciences Academic Press.