Effects of Climate on Agricultural Productivity in China

by

Katherine Kit-Yan Tso

Submitted to the Department of Electrical Engineering and Computer Science
in partial fulfillment of the requirements for the degrees of

Bachelor of Science in Electrical Engineering

and

Master of Engineering in Electrical Engineering and Computer Science

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

May 1996

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Abstract

Climate change has been a major concern in recent years. It would affect all nations and sectors of society. The purpose of this thesis is to study the potential effects of climate change on agricultural productivity in China. If China had a shortage of food, there would be worldwide effect. The five essential crops, *rice, wheat, maize, soybean* and *potato* were individually regressed against twelve explanatory variables. The coefficient of each independent variable is in fact the elasticity of a crop output with respect to the corresponding input variable. *Effective land, mechanization, fertilization, irrigation, labor force, mean temperature* and *total precipitation* were found to be positively significant at least at 5% confidence level. Among all the independent variables, the effective land has the highest elasticity for rice, maize and potato, whereas for wheat is irrigation and for soybean is fertilization.

A robust and flexible tool was developed for data extraction which enable users to extract data for other countries to be studied. The data extraction tool was written entirely in `C++`, with the use of stream manipulations. It was designed in such that subsequent extension of the tool would be straightforward. Macros and visual basics were also written for data organization.

Thesis Supervisor: Richard S. Eckaus
Title: Professor of Economics

Acknowledgments

May I extend my *deepest* gratitude towards Professor Eckaus, for his supportive and enthusiastic supervision, which made this project possible. I also appreciate the comments and suggestions from Xiang Ming Xiao, who supplied me the data needed for this research. I would like to thank Henry, for being an extraordinarily responsible librarian at Harvard Yenching Library.

I am also in debt to the following people, whose company has *immensely* enriched my life.

To my family: Grandpa, Dad, Mom, Marine and Calvin, for their love and support throughout my entire life.

To King, for his tender love and patience.

To Vivian, for being a good mentor and a caring and understanding friend for me.

To Phoebe and Jocelyn, for giving me a never-fading memory at 201.

To Elaine, for her caring and close companionship in these five years.

To Ada and Joyce, for being good listeners and sharing partners in our cell groups for two years.

And to countless others, who have walked with me in the Lord through prayer supports.

Lastly, to the Lord Jesus Christ, who has given me so many precious and wondeful gifts which enlightened my life.

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Chapter 1

Introduction

This thesis is part of the research on the economics of climate change by Professor Richard S. Eckaus in the Economics Department and Joint Program on the Science and Policy of Global Change at MIT. The primary goal of this thesis is to estimate the potential impacts of climate change on agricultural productivity in China. Data are collected and organized and used in multiple regression models to predict the impacts. Design and development of programs in organizing the data are principally written in `C++`. Programs in visual basics and macros are also written. Result of the regression is simulated by a `GAMS (General Algebraic Modeling System)` model for China. This introductory chapter describes the organization of this thesis.

Chapter 2 presents the motivation of this thesis.

Chapter 3 provides the basic knowledge and understands the effect of global warming.

Chapter 4 describes the `Terrestrial Ecosystem Model`, which is an integral part of a larger research on climate to study the impact of global warming and land-use in the terrestrial ecosystems.

Chapter 5 presents the detailed discussion of the multiple regression model and its parameters, i.e. dependent and independent variables. Data retrieval and organization are described.

Chapter 6 reviews the technical aspects in organization of the raw data in this project. Design, implementation and testing of the programs are described. Programs are written in `C++`, visual basic and macros for various usuages.

Chapter 7 shows the summary and analyzes on the result of the regression model.

Finally, Chapter 8 presents the final conclusions and suggestions of future work.

Chapter 2

Motivation

2.1 Climate Change

In recent decades, concern about the threat of global climate change has increased dramatically and become a major issue in our world. Various researches have shown that human activities are the sources of that threat. Fossil fuel and biomass combustion and increased intensity of land use have increased the concentration of carbon dioxide (CO_2) by approximately 50% comparing to the period 1976-1980 [37]. Human activities have also increased emissions of other radiative *greenhouse gases* such as *methane* (CH_4), *nitrous oxide* (N_2O), *chlorofluorocarbons* ($CFCs$), *tetrachloride* (CCl_4) and *ozone* (O_3). The increase in the concentration of these gases in the atmosphere can raise the global mean temperature. Moreover, the increases in the gas concentration also have significant impacts on the patterns of precipitation, the area of cloud coverage and frequency of weather extremes.

2.2 Agriculture

Agriculture is a sector that is highly sensitive to climate change as well as, itself, a contributor of greenhouse gases. Changes in climate certainly affects crop productions, both positively or negatively. The variables of concern include *carbon dioxide*, *methane*, *temperature*, *precipitation* and *cloud coverage*. The future food production and the global food security does significantly depend on the variability of the global climate change, especially since the present 5.5 billion population in the world will reach 8.5 billion by the year 2025 [26].

2.3 Agriculture in China

Agriculture is the foundation of the national economy in China which is one of the largest sources of agriculture production in the world. With only 7% of the world's cultivated land, China supports more than 20% of the world's population [26]. The topography in China is complicated and tremendously varied. Although China covers essentially the same land area as the United States, much of the country is desert and mountain. Only 10% of the land in China is cultivable.

Since 1949, China has made a great progress in food production (Figure 2-1).[1] However, from 1959 to 1961, China was suffered from a massive famine resulted from the *Great Leap Forward*.[2] During those years, the harvest production dropped from 193.4545 million tons in 1958, the highest record ever since 1949, to 155.31 million tons in 1962.

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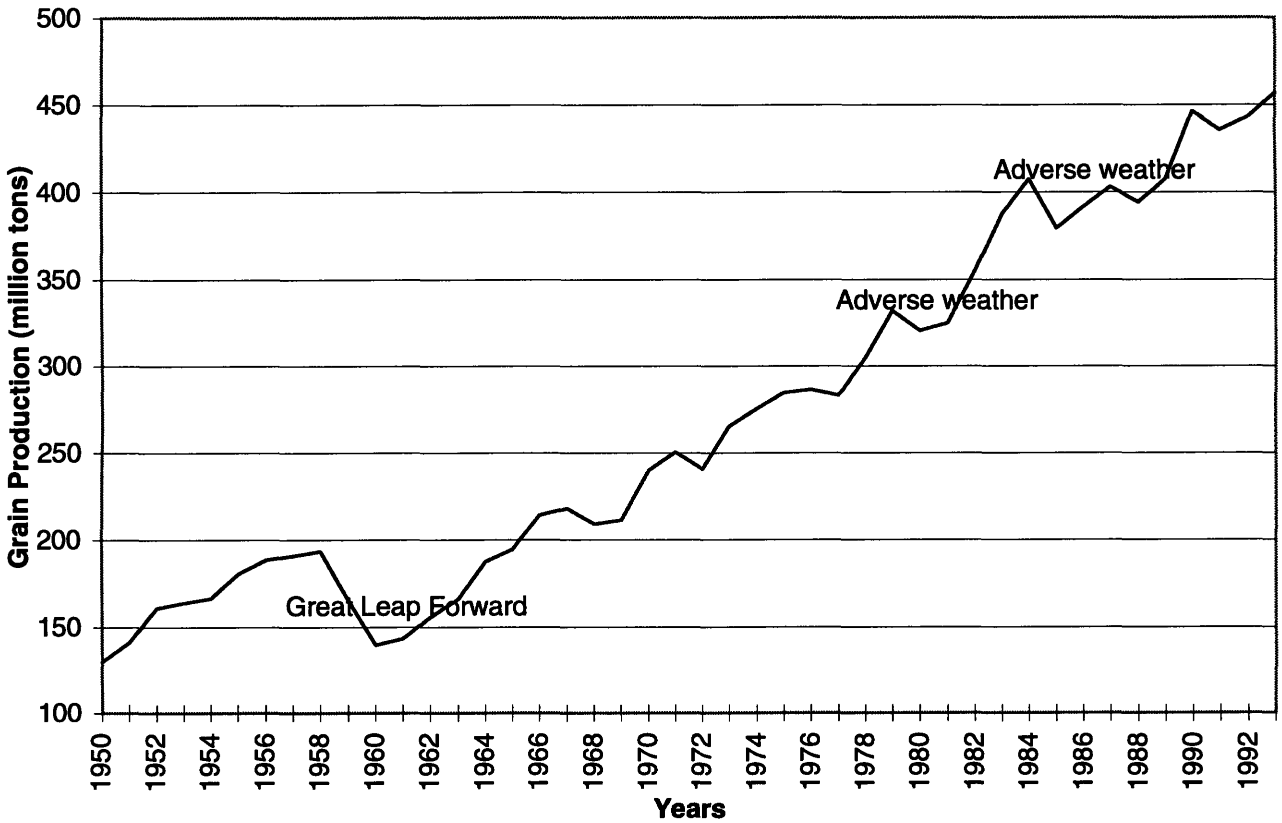
[1] *1950-1990:[4]; 1990-1993:[23]*

[2] *The Great Leap Forward is outcome of economic and political developments that took place in 1957 - mid 1960. In the economic development, Chen Yun, China's top economic official in the 1950s, discouraged heavy-industries. In reponse to that, the heavy-industry officials offered programs that aided agriculture, self-reliance and medium-sized or small industries. Mao Zedong, who was responsible for the political developments, encouraged intellectuals to criticize the Communist Party in the Hundred Flowers Movement. However, instead of creating a more open political system, Mao responded to these remarks angrily and charged these intellectuals. In October 1957, Mao merged with the programs and launched mass campaigns that were the Communists Party's response to the criticisms. "More, faster, better, and more economical" and "Politics in command" were the slogans that emerged at that time. Problems and doubts about the Leap were everywhere. Mao believed that to make the Leap proceed smoothly, it was necessary to attach those opponents. In 1959, the bad weather coupled with the poor leadership in the communes and lack of incentives caused the agricultural production to collapse. Untold millions died of starvation and diseases. The years 1960 - 1962 were then known as the "Three Hard Years" [24].*

Figure 2-1: **Total grain production in China (1950 - 1993)**



In 1980, China's foodgrain production experienced its second decline since 1949, when the production dropped from 332.115 million tons in 1979 to 320.56 million tons. The main factor responsible in this decline was the influence of the extreme weather: floods in the south, droughts in the north and severe cold. An extensive area of farmlands suffered severe drought and flooding. Many rivers and reservoirs in the north dried up. Large areas of rice seedlings were affected. In the south, the areas were affected by cold, persistent rain and lack of sunlight from spring to summer. The heavy rain in the summer caused severe floods whose magnitude was second only to the 1954 and 1931 floods [29].

However, the food harvest in China had grown from 304.77 million tons in 1978 to 407.31 million tons in 1984. This was the result of economic reforms and the institution of the contract system based on the household in China's rural areas. Subsequently, the production stagnated, then went down to 379.108 million tons in 1985, 391.512 million tons in 1986 and grew to 402.977 million tons in 1987. One of the reasons in the downward trend in food harvest was attributable to adverse weather conditions in 1988. Extensive areas of cropland were plagued by droughts, waterlogging, typhoons, frost or earthquakes.

An enormous population and not much land are major factors hampering the growth of China's national economy. At the inception of People's Republic in 1949, there were 109.959 million hectares of grain area in China. The acreage increased annually and reached 136.339 million hectares in 1956, after which it began to dwindle every year (Figure 2-2) [4]. One major factor responsible for the shrinkage was the conversion of large tracts of cropland into woodlands, orchards, pastures and fish ponds. Moreover, the diversion of irrigation water to nonfarm uses also causes water scarcity. Thus, China has major problems in increasing its food production.

Figure 2-2: **Total grain area in China (1949 - 1993)**

The increasing concentration of the greenhouse gases in the atmosphere and global warming would further affect China's grain production. Global warming would raise average temperatures and increase rainfall variability. This could in turn increase the frequency of droughts or floods. However, there are direct effects of increased CO_2 concentration on grain production including increment in photosynthesis and water efficiency. Climate change would also influence snow pack, groundwater recharge, stream flow and other factors involved with water supply. That will also affect available water supply. A rise in global mean temperature would increase some of the grain growing seasons. The combined effects of the increase in temperature, changes in rainfall patterns and other climate changes would alter grain production. Being the largest rice production country in the world, China has a significant role as a food importer or exporter. If China had a shortage of food, there would be worldwide effects. Thus, the effects of climate change on China's agriculture would have significant impacts in the world.

The motivation of this thesis is to estimate and analyze the potential impacts of climate change on agricultural production in China. The agronomic data and weather and climate information collected from various resources[3] provide quantitative information for the multiple regression models. The empirical analysis of this model suggests the degree of the effects of climate change, which, in turn can suggest the degree of urgency associated with implementing CO_2 control and industrializtion policies. It is important for the Chinese authorities to recognize that the climate change might reduce agricultural growth, which, in turn, could spawn problems such as inflation, stability and national development for China. It is important for the

[3] *The two main sources of agricultural data are taken from provincial statistical yearbooks published by China Statistics Bureau: Provincial Statistical Yearbooks in 1991 and Brief Statistics of Rural Economy by Counties (1990) [23]. Since these statistical yearbooks are annually published by the China Statistics Bureau, the data generated are considered very reliable. Weather and climate information are principally from the Ecosystem Center of Marine Biological Laboratories in Woods Hole, Mass.*

world to recognize that the slowing in agricultural growth in China could possibly lead to shortage of food supplies worldwide.

Chapter 3

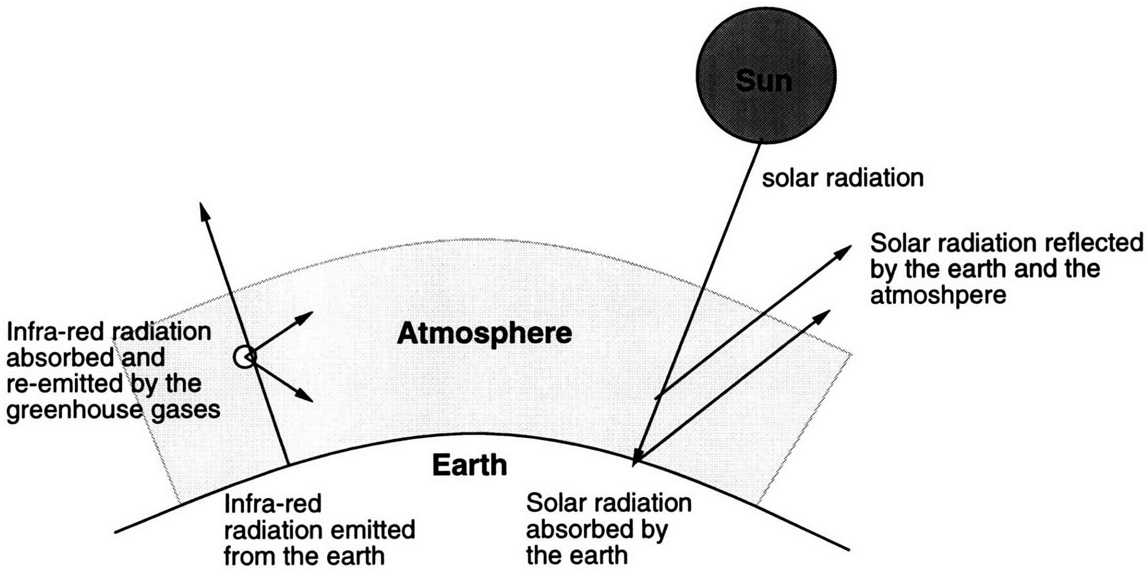
Global Warming

Climate change is not a recent problem. Research has been done dated back to 1895 [27]. Scientific activity has continued to focus on the problem of climate change and significant progress has been made in this decade.

3.1 The Climate System

In our climate system, some of the solar radiation emitted by the Sun is absorbed by the surface of the Earth. The rest of this infra-red energy is then reflected by the earth's surface. In the atmosphere, the radiatively-active gases called *greenhouse gases* absorb this reflected thermal energy. These greenhouse gases include *water vapor*, *carbon dioxide* (CO_2), *methane* (CH_4), *nitrous oxide* (N_2O), *chlorofluorocarbons (CFCs)*, *tetrachloride* (CCl_4) and *ozone* (O_3) [37]. The absorbed energy is then partially transmitted outward and partially reflected back to earth. The result of this phenomenon is called the *greenhouse effect* (Figure 3-1) in which the surface of the earth becomes warmer due to lower heat loss in space, which is the result of the increment of the greenhouse gases. This entire process increases the temperature of the Earth [37].

Figure 3-1: **The greenhouse effects**



3.2 The Factors

The factors that affect the climate include the factors alter the redistribution of energy within the atmosphere, land and ocean. Sources such as *aerosols*, small particles from volcanoes and *sulphates* emitted from industry can absorb and emit radiation which can disturb the radiative balance of the Earth [37]. According to the research done by the `Intergovernmental Panel on Climate Change (IPCC)` [37], the energy output of the Sun changes slightly over an 11-year cycle and larger variations over a long period of time may occur. These changes in radiation will tend to alter the temperatures and the associated circulation and thus the weather patterns. However, besides from man-made changes, climate also alters naturally.

The increase in greenhouse gases reduces the efficiency of cooling the surface of the Earth and thus increases the average temperature over time. The elements that involve in these changes are the concentration of the greenhouse gases present in the atmosphere as well as the local effect such as the height of the greenhouse gas. The recent climate observations are included in appendix A.

3.3 The Global Problems

Although forecasting climate change is an uncertain and imprecise science, the economic issues that climate change would bring can be studied and estimated. Climate change has a great deal of economic significance which affects human welfare in different sectors. For instances, the melting of polar ice caps, alterations of hydrological balances and changes in ecosystems [1]. Numerous studies have shown that climate change has a major impact on agriculture and related resource linkages, such as length of growing season, water supply and soil quality. Other effects impact the fish and wildlife population. The buildup of atmoshperic CO_2 alarms the international policy makers and creates incentives to consider the abatement of the rapid increasing rate. Control policies such as reduction in fossil-fuel combustion or change of land-use can lessen the amount of the greenhouse gases, especially CO_2. The problems the climate change arouses much interest and concern from the world.

Chapter 4

The Terrestrial Ecosystem Model

4.1 Description

The `Terrestrial Ecosystem Model (TEM)`[1] is a monthly-time-stepped, *process-based model*[2] which is used to predict major carbon and nitrogen fluxes and pool sizes in terrestrial ecosystems from continental to global. The model has six state variables and eleven carbon and nitrogen fluxes.

State variables:

1. carbon in the vegtation (C_v)
2. structural nitrogen in the vegetation (N_{vs})
3. labile nitrogen in the vegtation (N_{vl})
4. organic carbon in soils and detritus (C_s)
5. organic nitrogen in soils and detritus (N_s)
6. available inorganic soil N (N_{av})

[1] *The information about the model are from two main sources: [3] and [30].*

[2] *Carbon cycle is simulated by equations that describe the transfer of carbon between different pools in an ecosystem.*

Carbon and nitrogen fluxes (arrows):

1. gross primary productivity (GPP)
2. autotrophic respiration (R_A)
3. heterotrophic respiration (R_H)
4. litterfall C (L_C)
5. litterfall N (L_N)
6. N uptake into the structural N pool of the vegtation ($NUPTAKE_S$)
7. N uptake into the labile N pool of the vegtation ($NUPTAKE_L$)
8. N resorption from dying tissue into the labile N pool of the vegtation (NMOBIL)
9. net N mineralization of soil organic N (NETNMIN)
10. N inputs from outside the ecosystem (NINPUT)
11. N losses from the ecosystem (NLOST)

Information from intensive research on monthly climate (*precipitation, mean temperature* and *mean cloudiness*), soil texture (*sand, clay* and *silt proportion*), elevation, vegetation and water availability is used in each cell with a grid size of 0.5^0 latitude and 0.5^0 longitude. This spatial resoultion has 62483 land grid cells, in which 3059 cells are ice and 1525 wetland [3]. However, TEM does not now take into effect of human land use since it applies only to natural vegtation and undisturbed ecosystem.

4.2 Purpose

A fundamental task of the TEM is to sucessfully predict the net primary productivity (NPP) (Equation 4.1), the rate at which the vegetation in an ecosystem fixes carbon from the atmosphere (gross primary productivity) (Equation 4.2) minus the rate at which it returns carbon to the atmosphere (plant respiration).

$$NPP_t = \frac{d}{dt}GPP_t - \frac{d}{dt}R_{At} \tag{4.1}$$

where t = the month and units are grams of carbon per square meter per month.

GPP = gross primary productivity.

R_A = plant respiration.

$$GPP_t = C_{max} \times f(PAR) \times f(LEAF) \times f(T) \times f(CO_2, H_2O) \times f(NA) \tag{4.2}$$

where C_{max} = the maximum rate of C assimilation.

PAR = photosynthetically active radiation.

$LEAF$ = leaf phenology, leaf area relative to maximum annual leaf area.

T = temperature.

NA = N availablilty.

`TEM` is an integral part of a larger research to study the impact of global warming and land-use in the terrestrial ecosystems. Directly linked to a `water-balance model (WBM)` [3], `TEM` can explicitly treat interactions between temperature and moisture availability.

Chapter 5

The Economic Model

5.1 Data Description

5.1.1 Sample Distribution

In China, there are 30 provinces and each province is broken into regions. Each region is then separated into counties. There are approximately 3000 counties in China. To reduce the magnitude of the data problems in this thesis, the samples are based on *provincial regions.*

Maps for each province were duplicated from the Harvard map research library[1] and the Harvard Asian library[2] to permit classification of data in each region. Some of the weather data was available in at a resolution of 0.5^0 longitude and 0.5^0 latitude while some other was given only at specific meteorological stations. Therefore, location for each data entry was identified and all the data within each region was averaged.

The initial sample consisted of regions in every province in China. However, some

[1] *Harvard Map Collection in Pusey Library.*
[2] *Fairbank Center for East Asian Research in Coolidge Hall Libraires.*

Table 5.1: **Number of regions from each province**

Number	*Province*	*Number of Regions*
1	Beijing	1
2	Tianjin	1
3	Heilongjiang	14
4	Anhui	16
5	Jianxi	11
6	Shandong	16
7	Henan	17
8	Hubei	16
9	Guangdong	19
10	Hainan	4
11	Yunnan	17
12	Xizang	7
13	Shaanxi	10
14	Qinghai	8
15	Ningxia	4
16	Xinjiang	14

Total : 175 regions

of the information was not provided in the data. For instance, crop data or sown area was not provided regionally for some of the provinces. In order to employ a sample that could allow maximum amount of useful data, the year 1990 was studied since that year contained the most regional data. Thus the samples were narrowed down to 16 provinces, i.e. 175 regions as shown in Table 5.1. Referring to the underlined provinces in Figure 5-1, the geographic locations of these choices of provinces were widespread over China.

Figure 5-1: **Sample of Data**

Table 5.2: **Available data for production of each crop**

Province	*Wheat*	*Rice*	*Maize*	*Potato*	*Soybean*
Beijing	√	√	√	√	√
Tianjin	√	√	√	√	√
Heilongjiang	√	√	√	√	√
Anhui	√	√		√	
Jianxi	√	√		√	√
Shandong	√	√	√		√
Henan	√	√	√	√	√
Hubei	√	√	√	√	√
Guangdong		√			√
Hainan	√	√	√	√	√
Yunnan	√	√	√	√	√
Xizang	√	√		√	√
Shaanxi	√	√	√		
Qinghai	√				
Ningxia	√	√	√	√	√
Xinjiang	√	√	√		√

5.2 Dependent Variables

The dependent variable is the output of the essential crops in China, i.e. *rice, wheat, maize, soybean* and *potato.*[3] The data available for production for each crop in each province is shown in Table 5.2. Next section is the description of each crop including the input requirements, growing seasons and locations of the plants. These information were retreived from *China Encyclopedia* [8].

5.2.1 Rice

Rice, a major crop in the south, requires a mean temperature of about 20^0C and rainfall of more than 1,000 *mm.* The growing season for rice ranges from 4 to 6 months. The Tsing Ling Range and the Huai River mark the northern boundary

[3] ***Barley is not studied due to insufficient data.***

of the principal rice producing area of China. Two crops of rice can be harvested annually south of the Nan Ling Range. The spring crop starts from March to August and the fall from September to February. Production in area north of the Tsing Ling Range and the Huai River is small, since the rainfall and temperature are low. China has long been the world's largest rice producer.

5.2.2 Wheat

The principal wheat-growing regions are south of the Great Wall and north of the Tsing Ling Range and the Huai River. There are a number of varieties of wheats:

- **Spring Wheat**

  The plants grow as summer annuals (February/March through August/September), the seed being planted in the spring and the harvest gathered in the fall of the same year. It is grown to the north of the Great Wall and Lung Shan.

- **Winter wheat**

  The plants grow as winter (November/December through May/June) annuals, the seed being planted in the fall and growing for awhile until stopped by cold weather, developing during that time an abundant root system which insures rapid growth in the spring of the following year. The mature crop is ready for harvest in early summer. Winter wheat is mainly grown in the south.

Compared with other grains, wheat requires a slightly longer growing season and a bit more heat. For acceptable yields, 3-month period during which the average temperature is 10^0C (50^0F) or higher is required. Optimal growth occurs at a temperature of about 25^0C (77^0F). Minimum occurs at 3.3^0 to 3.9^0C $(38^0$ to $39^0C)$. Cold-hardened winter wheat survives temperatures as low as -40^0C (-40^0F) when protected by snow; and as low as -31^0C (-25^0F) when unprotected.

5.2.3 Maize

Maize is mainly the production of a belt starting from the bank of the Amur River in the northeast and extending southwestward to the border of Yunnan province. China is second to the United States as a producer of maize. Maize is a warm-weather plant that requires relatively warm day and night temperatures during its growing season and a frost-free season of more than 140 days. Annual precipitation where a large percentage of the crop is grown ranges between 25 and 50 *inches* (63 and 127 *cm*). Thus, the low temperature and the short growing season in the northwest causes the small maize production. The temperature in central China is the most favorable. The maize seed germinates best at a temperature of about 30^0C (86^0C). Germination occurs, at progressively slower rates, until a minimum temperature of about 4.4^0C (40^0C) is encountered. Photosynthesis in maize is highest at a temperature from 25^0 to 30^0C (77^0 to 86^0F). The growing season in China is approximately from March to September.

5.2.4 Soybeans

Originating in northern provinces of China, soybean does not require particular kind of soil, but plenty of sunshine, high temperature and ample rainfall. It generally takes 4 months from planting to maturity. There are more than 6000 different kinds of soybean in China. The Sungari-Liao Plain and the Huang Huai Plain are the two most important producing regions. Heilongjiang has the highest production of soybean in China. Soybeans are nutritional, yet cheap in price and can be made to variety of products.

Table 5.3: **Growing seasons for each crop**

Number	*Crop*	*Growing Season*
1	Rice	Single Crop : March - September Double Crop : March - August, September - February
2	Wheat	Spring wheat : February - August Winter wheat : November - June
3	Maize	March - September
4	Potato	June - October
5	Soybean	May - August

5.2.5 Potatoes

Potatoes are mainly the products from the hilly land of the eastern plain south of the Great Wall. Warm weather and ample rainfall at the beginning of the growing season are required for production. It can be easily cultivated and used as a supplementary food.

The growing seasons for the crops are summarized in Table 5.3.

5.3 Independent Variables

The independent variables in the regression models are: *effective land,*[4] *mechanization, fertilization, irrigation, labor force* and *weather(average temperature, average minimum temperature, total precipiation, average pan evaportransportation,*[5] *minimum relative humitity, total growing degree days*[6]*).*[7]

[4] *effective land = net primary productivity × actual actual sown area.*

[5] *The transfer of moisture from the earth to the atmosphere by evaporation of water and transpiration from plants.*

[6] *Total growing degree days =* $\sum T_{T>0}$ *where* T *= temperature.*

[7] *Average hours of sunshine is not considered in the weather set due to lack of data available.*

5.3.1 Effective Land

The effective land use is the product of *Net Primary Productivity* (NPP) and the *sown area* as shown in Equation 5.1. The effective land thus takes into the account the climate effect in the terrestrial ecosystem through the NPP index.

$$Land_{i,r}^{effective} = NPP_r \times SownArea_{i,r}^{actual} \tag{5.1}$$

where $i's$ are the essential crops and $r's$ are the region numbers.

1. NPP

The effects of the contemporary climate, soil, sunshine, and water availability conditions, are based on NPP, the net assimilation of CO_2 into organic matter by plants [3]. NPP is used as index of the relative productivity of the land. It is the rate at which the vegetation ecosystem fixes carbon from the atmosphere minus the rate the plants return carbon to the atmopshere. It is sensitive to the effects of climate change in the terrestrial ecosystem, such as rises in temperature and CO_2 concentration, changes in precipitation and other factors [30]. According to the study from D.M. Gates, a doubling of CO_2 increases NPP from 25% to 50% [31]. An estimated 40% of the world's NPP has been co-opted by humans or lost due to land-use [31]. NPP data for China is retrieved from the TEM[8] at a spatial resolution of 0.5^o latitude and 0.5^0 by longitude.[9] The NPP at each location is identified on maps and is assigned to the corresponding region. Macros were written to average all the NPP in each region within a province.[10]

There are three sets of the NPP variables, each based on different constraints on inputs to TEM:

[8] *Thanks for the help from Xiang Ming Xiao from the Marine Biological Laboratory of the Ecosystem Center.*

[9] *See Chapter 4 for description of TEM*

[10] *See Chapter 6 for description of macro.*

1. limitation on water and nitrogen.
2. limitation on water only.
3. limitation on nitrogen only.

In addition to the above constraints, the output of TEM used in this thesis is based on the contemporary climate, 355 *ppmv* CO_2 and the assumption of natural grassland in all the pixels of China to simulate the NPP values. The three different sets of NPP were individually analysed by the regression model.

2. Actual Sown Area

The actual sown area is the sown area for each essential crop production. The data was originally in Chinese units (*mu*). A simple conversion was done for all the data to British unit (100 mu = 6.666 ha).

5.3.2 Mechanization

Mechanization is the power of all agricultural machinery and machinery used in producing and processnig farm products. It includes *different sizes of tractors, different usage of motors, combines, harvesters, threshers, ginning mills* and *grinders.* The components of the total power of agricultural machinery are shown in Table 5.4. Since this variable was not available for the separate crops within regions within provinces, the provincial total was allocated among crops proportionality to the sown area of the crops in each region. The variable for mechanization is shown in Equation 5.2.

$$MECH_{i,r} = Mechanization_r \times \frac{SownArea_{i,r}}{TotalSownArea_r} \tag{5.2}$$

where $i's$ are the essential crops and $r's$ are the region numbers.

Table 5.4: **Components of Mechanization**

Number	*Compontents of total Power of Agricultural Machinery*
1	Large and Medium Agricultural Tractors
2	Small Tractors and Walking Tractors
3	Large and Medium Tractor : Towed Farm Machines Ploughs Barrows Sowing Machines
4	Small and Walking Tractor : Towed Farm Machines
5	Boat Tractors
6	Motor : Driven Rice Transplanters
7	Motors for Agricultural Drainage and Irrigation Diesel Engines Electric Motors
8	Pumps for Agricultural Use
9	Sprinkler Machines
10	Combine Harvesters
11	Motor : Driven Harvesters
12	Motor : Driven Threshers
13	Seed : Selecting Machines
14	Grain : Drying Machines
15	Rice Mills and Wheat Mills
16	Cotton : Ginning Mills
17	Oil Presses
18	Trucks for Agricultural Use
19	Motor : Driven Sprayers
20	Fodder Grinders
21	Forage Grass Harvesters
22	Motorized Fishing Boats

5.3.3 Fertilization

Fertilization is also a factor affecting a crop production. The CO_2 *fertilizer effect* increases the concentration of CO_2 on photosynthesis and water use efficiency. The four major types of chemical fertilizers that are applied in agriculture include:

1. Nitrogeneous Fertilizer

2. Phosphate Fertilizer

3. Potash Fertilizer

4. Complex Fertilizer[11]

Fertilizer statistics in China are measured in three different production units: *actual, standard,* and *weight.* Actual weight is the gross weight of the product. Standard weight is weight converted into weight of standard fertilizers. Effective weight, which is used in regression models, measures the actual nutrient content. These fertilizers are essential to all the crops. Different soil types and crops, however, have different requirements for the four fertilizers. Due to lack of data for each fertilizer in some of the provinces (Table 5.5), the sum of the effective component of the four fertilizers is used in the regression models. The variable for fertilization for each crop in each region was allocated in proportion to sown area as shown in Equation 5.3.

$$FERT_{i,r} = AmountFertilizerUsed_r \times \frac{SownArea_{i,r}}{TotalSownArea_r} \tag{5.3}$$

where $i's$ are the essential crops and $r's$ are the region numbers.

5.3.4 Irrigation

One of the most important factors in crop production, especially rice production, is an adequate supply of water. The variable for irrigation for each crop in each region

[11] *Complex fertilizer is the combination of nitrogen, phosphate and potash.*

Table 5.5: **Data of Fertilization**

Number	*Province*	*Fertilizers given as 4 components*
1	Beijing	χ
2	Tianjin	$\surd$
3	Heilongjiang	χ
4	Anhui	$\surd$
5	Jianxi	$\surd$
6	Shandong	$\surd$
7	Henan	$\surd$
8	Hubei	$\surd$
9	Guangdong	χ
10	Hainan	$\surd$
11	Yunnan	$\surd$
12	Xizang	$\surd$
13	Shaanxi	χ
14	Qinghai	$\surd$
15	Ningxia	χ
16	Xinjiang	$\surd$

was also allocated in proportion to sown area as shown in Equation 5.4.[12]

$$IRRIGATE_{i,r} = EffectivelyIrrigatedArea_r \times \frac{SownArea_{i,r}}{TotalSownArea_r} \tag{5.4}$$

where $i's$ are the essential crops and $r's$ are the region numbers.

5.3.5 Labor Force

Labor force is the total number of people contributing to agriculture. The available data only have the rural labor force as a sum of the four sectors: *agriculture, forestry, animal husbandry* and *fishery.* The amount of the labor force for each crop is determined by Equation 5.5, using sown area to allocate the labor among crops.

$$LABOR_{i,r} = LaborForce_r \times \frac{SownArea_{i,r}}{TotalSownArea_r} \tag{5.5}$$

where $i's$ are the essential crops and $r's$ are the region numbers.

5.3.6 Weather

1. Selection of Weather Variable

The weather data collected from `National Center for Atmospheric Research (NCAR)`[13] contains weather information starting from 1987 to 1993 in monthly scale at each meteorological station for the five continents. The reason for the use of weather data is that annual weather may change dramatically from year-to-year and thus will result in very different agricultural yields. For instance, a dramatic increase in

[12] *Adjustment has been made due to errors in data. $IRRIGATE$ shoud be < 1 since the numerator is bounded by the denominator, i.e. total sown area is the limit for the effectively irrigated area for agriculture. A few of the regions have $IRRIGATE > 1$ due to some error in raw data and thus $IRRIGATE$ for these regions are set to 1.*

[13] *NCAR is located at Boulder, Colorado. It collects all the weather data from individual countries, that collects data from each meteorological station on a monthly basis. The weather data is also retrieved from Xiang Ming Xiao.*

Table 5.6: **Weather variables**

Numbers	*Variables*	*Descriptions*
1	*TMEAN*	Average daily mean temperature computed from all paired daily maximum and minimum temperatures.
2	*TMIN*	Average daily minimum temperature.
3	*EPCP*	Total precipitation including estimates for any periods that reported amounts were not available.
4	*APET*	Average pan evaportransporation.
5	*AMINRH*	Average minimum relative humitity.
6	*IGDD*	Total growing degree days.

precipitation in a year may change the productivity of a land. A robust tool was designed and implemented to retrieve the 1990 weather data from the tape at all the meteorological stations in China.[14] There are 49 variables in each record and 6 variables are chosen to be studied (See Table 5.6).

2. Organization of Weather Data

Each meteorological station was identified to its province and region on maps according to its given latitudes and longitudes. After identifying each meteorological station, an average of all the stations within a region was calculated to estimate the weather data for that region. If no meteorological station was available in a region, the average of a few of the closest stations was taken. Some of the meteorological stations were not in representative locations, such as the station on the top of a mountain. These data were dropped due to its unrepresentive weather. The weather data were applied to individual crop based on its growing season as shown in Table 5.3.

[14] *See Chapter 6 for more detail.*

3. Deviation of TEM Inputs and Actual Weather Data

The TEM inputs, such as *mean temperature* and *total precipiation*, are in fact climate variables since they represent the long run weather phenomenon. Referring to Equation 5.6 and Equation 5.7, deviations of the TEM climate data from the actual NCAR weather data were calculated for *mean temperature* and *total precipitation*, which were the data used for TMEAN and EPCP in the yield equation.[15]

$$TMEAN_r = TMEAN_r^{NCAR} - TMEAN_r^{TEMinput} \tag{5.6}$$

where $r's$ are the region numbers.

$$EPCP_r = EPCP_r^{NCAR} - EPCP_r^{TEMinput} \tag{5.7}$$

where $r's$ are the region numbers.

5.4 Model Specification

According to the discussion in previous section, 12 independent variables were proposed for the regression model. These variables are shown in Table 5.7 and were regressed by the multiple regression model described in next section.

5.4.1 Yield Equation

The yield equations are specified to be functions of two major categories: (1). *weather and climate characteristics,* (2). *farming and crop characteristics* as shown in Equation 5.8.

[15] *Deviations of other climate variables from weather variables were not calculated due to lack of* TEM *data.*

Table 5.7: **Independent Variables of Multiple Regression Model**

Number	*Independent Variable*	*Item*
1	$LAND^{eff}$	Net primary productivity × Sown area
2	$MECH$	Mechanization
3	$FERT$	Fertilization
4	$IRRIGATE$	Irrigation
5	$LABOR$	Labor Force
6	$TMEAN$	Average daily mean temperature in growing seasons
7	$TMIN$	Average daily minimum temperature in growing seasons
8	$EPCP$	Total precipitation in growing seasons
9	$EPCPN$	Total precipitation in non-growing seasons
10	$APET$	Average pan evaportransporation
11	$AMINRH$	Average minimum relative humitity
12	$IGDD$	Total growing degree days

Yield Equation:

$$\begin{aligned} ln\, YIELD_{i,r} \;=\; & ln\, a_0 + ln\, a_1\, LAND^{eff}_{i,r} + ln\, a_2\, MECH_{i,r} + ln\, a_3\, FERT_{i,r} + \\ & ln\, a_4\, IRRIGATE_{i,r} + ln\, a_5\, LABOR_{i,r} + ln\, a_6\, TMEAN_{i,r} + \\ & ln\, a_7\, TMIN_{i,r} + ln\, a_8\, EPCP_{i,r} + ln\, a_9\, EPCPN_{i,r} + \\ & ln\, a_{10}\, APET_{i,r} + ln\, a_{11}\, AMINRH_{i,r} + ln\, a_{12}\, IGDD_{i,r} + \\ & ln\, e_{i,r} \end{aligned} \tag{5.8}$$

where $i's$ are the essential crops and $r's$ are the region numbers.

Variable List:

1. $LAND^{eff}_{i,r}$, $MECH_{i,r}$, $FERT_{i,r}$, $IRRIGATE_{i,r}$, $LABOR_{i,r}$, $TMEAN_r$, $TMIN_r$, $EPCP_r$, $EPCPN_r$, $APET_r$, $AMINRH_r$ and $IGDD_r$ are the values for the independent variable of the i^{th} essential crop in the r^{th} region.

2. $YIELD_{i,r}$ corresponds to the dependent variable to the i^{th} setting of independent variables.

3. $a_0, a_1, a_2, a_3, a_4, a_5, a_6, a_7, a_8, a_9, a_{10}, a_{11}$ *and* a_{12} are the coefficients in the non-linear relationship. For instance, a change of one unit in the independent variable $LAND_{i,r}^{eff}$ *does not* translate into a change of one unit in the dependent variable.

4. The random variable $e_{i,r}$ is error that create the scatter around the non-linear relationship. These errors are assumed to be mutually independent and normally distributed with zero and variance.

5.4.2 Elasticities

Elasticity, a measure of the percentage change in one variable resulting from the 1% increase in the other variable, can be found in this regression model. The differential of the logarithmic function in Equation 5.8 with respect to one of the independent variables, such as $FERT$, can be shown as Equation 5.9.

$$\frac{1}{YIELD} dYIELD = a_1 \frac{1}{FERT} dFERT \tag{5.9}$$

$$\frac{\frac{dYIELD}{YIELD}}{\frac{dFERT}{FERT}} = a_1 \tag{5.10}$$

or a_1 is the elasticity of $YIELD$ with respect to $FERT$.

Hence according to Equation 5.10, the coefficients, $a_0, a_1, a_2, a_3, a_4, a_5, a_6, a_7, a_8, a_9, a_{10}, a_{11}$ *and* a_{12} are the elasticities of $YIELD$ with respect to their corresponding independent variables. Therefore, percentage change of the dependent variable with respect to the percentage change of an independent variable can be studied, which in turn can show the importance of the independent variable contributing to the dependent variable.

Chapter 6

Technical Background

6.1 Program Organization

The NPP and climatic data have posed the most difficult issues since the data had to be extracted from a massive set of information. Moreover, the data were not available by regions. Thus, it was necessary to estimate the weather and NPP data by regions. Programs were written to perform these tasks, which can be categoried into two major sections (Figure 6-1): *data retrieval* and *data organization.*

1. **Data Retrieval**

   A robust and flexible tool was developed for users to retrieve weather data for any countries from the global weather data given by NCAR. The data extraction tool was written in C++, with use of *stream manipulations.*[1] It was designed in such a way that subsequent extension of the tool would be straightforward. Therefore, data retrieval for other countries for the regression models can be done for future regression research. Details will be further described in Section 6.2.

[1] *Streams are objects created for input and output operations in C++, taken from the iostream library. Refer to chapter 10 of The C++ Programing Language [35] for a general description of the library.*

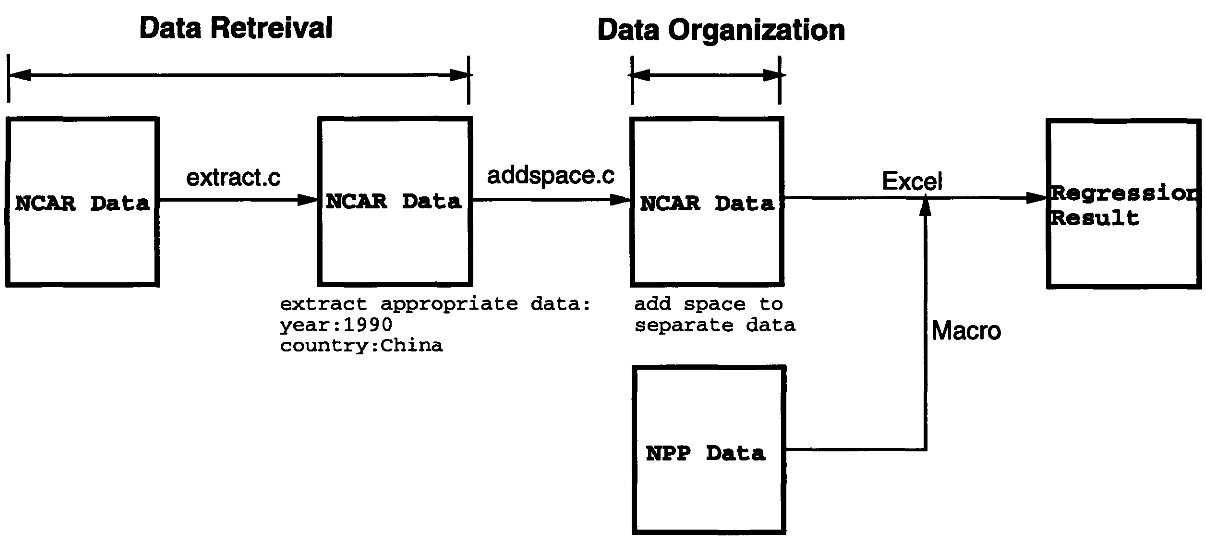
2. **Data Organization**

   Organization of data is performed after data retrieval. There are two major purposes:

   - **Set Structure for Spreadsheet:** Program in `C++` were written to organize the data in a specific structure for spreadsheet. This will be discussed in Section 6.3.1

   - **Perform Calculation of Data:** The `NPP` data are all classified into each region for each province. Macros were developed to average the `NPP`'*s* for each region. The results were put in a specific format for the regression model. Details will be described in Section 6.3.2.

Figure 6-1: **Building block diagram for overall program organization**



From the building block diagram in Figure 6-1, there are the two main cores of the utility: **`extract.c`** and **`addspace.c`**, which are attached at the end of this chapter. **`extract.c`**, extracts the relevant lines of text from the input weather data file, in order to import into Excel for processing. `addspace.c`, formats the data such that the information can be used readily for the regression model.

6.1.1 Format of Weather Data

The weather data from `NCAR` comes in the form of a single large file in ASCII format, with each line representing the weather data at a particular year and month in a particular meteorological station. An example is shown below:

```
19900150691 5 -4 ....
```

In this example, `1990` is the year that this line of weather data pertains to, `01` is the month (`01` is January, `02` is February, and so on), `50691` is the number representing the geographical region, and the remaining of the line (`5 -4 ...`) is a sequence of numbers representing various measurements of the weather at that time and place. For instance, `5` in the above line is the mean temperature, and `-4` is the minimum temperature. China has region numbers ranging from `50136` to `60005`. These are the only regions we are interested in for the regression model.

6.2 Data Retreival

6.2.1 Function of extract.c

`extract` takes in an optional parameter, a year number. If specified, the program extracts all lines of weather data which matches this year number. If not specified, the program extracts all lines of weather data, regardless of the year number. `extract` scans through the input file. It puts into the output file all lines which matches the desired year, and with location number lying within the range we are interested in.

Notes about optimizations used

Since the input file is extremely large, performance does matter in this extraction process. Some heuristics and optimizations were used. For each line of input, `extract` first looks at the 7^{th} character to see if it is either `5` or `6` since we are only interested in region numbers from `50136` to `60005`, which start with either `5` or `6`. This first check quickly eliminates a lot of unmatched lines for consideration. If the 7^{th} character passes, it then proceeds to check the entire region number. If this matches it proceeds to check the year number.

6.3 Data Organization

6.3.1 Function of addspace.c

In the sequence of numbers on each input line in the weather data file, there are places where spaces are missing between two numbers. Without the space, the data cannot be imported into Excel as separate cells. This is where addspace comes into use. It is a utility which looks for such instances in the weather data file, and adds spaces as necessary. As an example, consider the following input line in the weather data file:

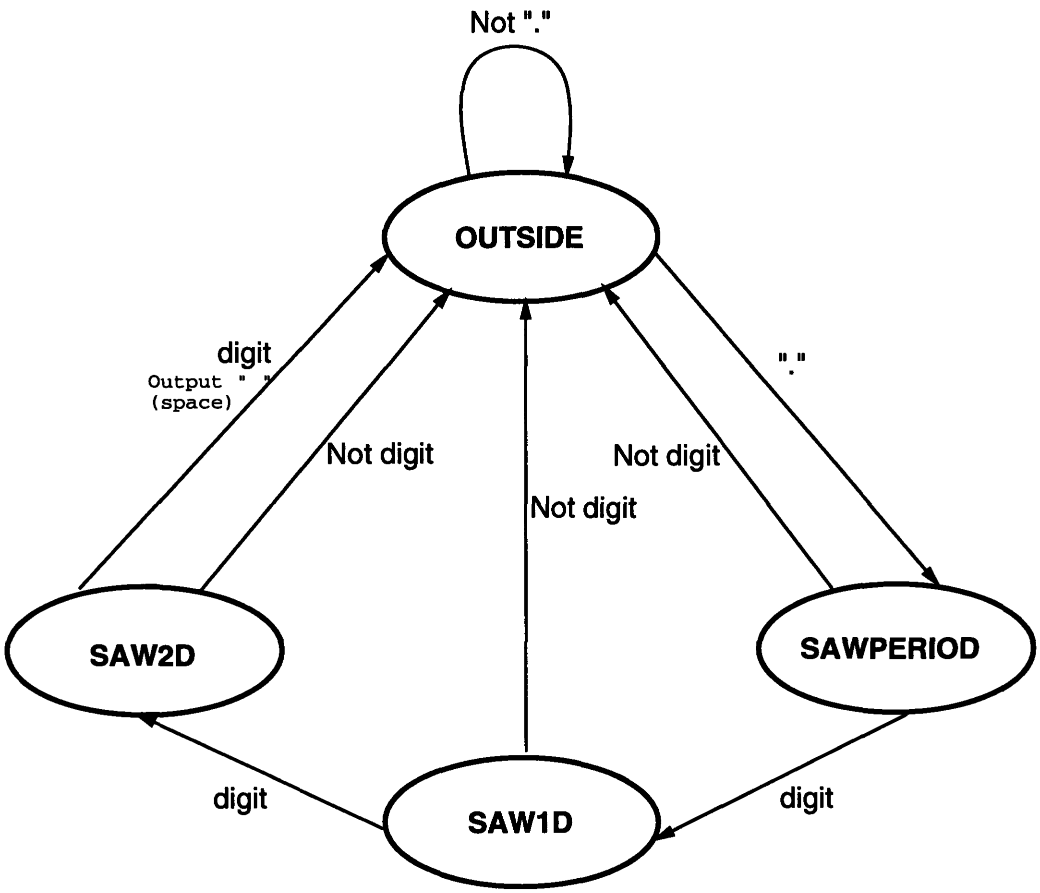
```
19900150691 5 2 4.239 2
```

In this line, `4.23` is one measurement, and the adjoining `9` is a separate measurement. A space is needed to separate them.

Algorithm used

It has been determined that such missing spaces always happen after a number with two decimal places. This knowledge has been used in implementing addspace. It scans through each input line, and adds a space every time it has seen a decimal point (a period) and two numeric characters immediately following. This has been

Figure 6-2: **Algorithm for addspace.c – Finite State Machine**



done using a *finite state machine* approach as shown in Figure 6-2, having addspace remembering where it is (whether it has just seen a period, the following digit, etc).

6.3.2 Function of Macro

Macros are written to average the NPP'*s* assigned in each region of each province. Since the NPP data from NCAR are in a spatial resolution of 0.5^0 by 0.5^0, region numbers of each province are assigned to the NPP'*s*. The sample data for a NPP is shown in Table 6.1.

Table 6.1: **Sample NCAR data**

Province	Region	Longitude	Latitude	NPP
AH	2	78.5	69.5	450

The interpretation of the line in Table 6.1 is: NPP at 78.5^0 by 69.5^0, which belongs to region 2 of Ahui, is 450. In order to find the NPP for that region, all the NPP$'s$ belonging to that region are averaged. Each NPP that is read is added to a cell belonging to the same region of the same province. A counter for each region is used to keep track of the number of NPP$'s$ that have been read. Finally, the sum of NPP$'s$ of each region in each province is divided by the corresponding counter. The result is organized and recorded.

1. Addspace

```
/*
 * addspace.C
 * Addspace
 * Katherine Kit-Yan Tso, CEEPR
 */


#include <ctype.h>
#include <iostream.h>
#include <fstream.h>

#define OUTSIDE   0
#define SAWPERIOD 1
#define SAW1D     2
#define SAW2D     3

main(int argc, char* argv[])
{
  ifstream inFile(argv[1]);
  ofstream outFile(argv[2]);
  int state = OUTSIDE;
  char c;

  while (inFile) {
    inFile.get(c);
    switch(state) {
    case OUTSIDE:
      if (c == '.') state = SAWPERIOD;
      break;
    case SAWPERIOD:
      if (isdigit(c)) state = SAW1D;
      else state = OUTSIDE;
      break;
    case SAW1D:
      if (isdigit(c)) state = SAW2D;
      else state = OUTSIDE;
      break;
    case SAW2D:
      if (isdigit(c)) {          outFile << ' '; state = OUTSIDE; }
      else state = OUTSIDE;
      break;
    }

    outFile << c;
  }
}
```

2. Extract

```
/*
 * extract.C
 * Extract
 * Katherine Kit-Yan Tso, CEEPR
 */


#include <math.h>
#include <string.h>
#include <iostream.h>
#include <fstream.h>

#define LB      50136
#define UB      60005


main(int argc, char* argv[])
{
 char  line[500], callnoStr[6], yearStr[5];
 long  callno, year, yearThis;

 if (argc < 3) {
  cout << "Usage:  ext <input filename> <output filename> [-y<year>]" << endl;
  exit(1); }

 ifstream inFile(argv[1]);
 ofstream outFile(argv[2]);

 cout << "Extracting data\n  Input file:  " << argv[1] << '\t'
  << "Output file:  " << argv[2] << endl
   << "  for region numbers from " << LB << " to " << UB << endl;

 if (argc > 3)
  for (int i = 3; i < argc; i++)
   if (strncmp(argv[i], "-y", 2) == 0) {
       strncpy(yearStr, argv[i]+2, 4);
       year = atoi(yearStr);
       cout << "  for year " << year << endl; }

 while (inFile) {
  inFile.getline(line, 500);

  if (line[7] == '5' || line[7] == '6') {
   strncpy(callnoStr, &line[7], 5);
   callno = atoi(callnoStr);

   /* test call no. range: */
   if (callno >= LB && callno <= UB) {
```

```
      if (year) {   /* if year is nonzero, then test year */
        strncpy(yearStr, &line[1], 4);
        yearThis = atoi(yearStr);
        if (yearThis == year)
          outFile << line << endl; }

      else
        outFile << line << endl; }}
  }

  cout << "Done!" << endl;
}
```

3. NPP Averages

```
=ECHO(FALSE)
=ACTIVATE("NPP.XLS")
=WORKBOOK.SELECT("NPP Avg", "NPP Avg")
=SET.NAME("NPP_orig", !A1)
=SET.NAME("counts_orig", OFFSET(NPP_orig, 22, 0))
=FOR.CELL("CurrCell", OFFSET(NPP_orig, 1, 1):OFFSET(NPP_orig, 20, 16), TRUE)
=FORMULA(0, CurrCell)
=NEXT()
=FOR.CELL("CurrCell", OFFSET(counts_orig, 1, 1):OFFSET(counts_orig, 20, 16), TRUE)
=FORMULA(0, CurrCell)
=NEXT()

=WORKBOOK.SELECT("NPP", "NPP")
=FOR.CELL("CurrCell",!A2:A4030, TRUE)

=IF(CurrCell="AH")
=SET.NAME("province", 1)
=ELSE.IF(CurrCell="BJ")
=SET.NAME("province", 2)
=ELSE.IF(CurrCell="GD")
=SET.NAME("province", 3)
=ELSE.IF(CurrCell="HA")
=SET.NAME("province", 4)
=ELSE.IF(CurrCell="HE")
=SET.NAME("province", 5)
=ELSE.IF(CurrCell="HL")
=SET.NAME("province", 6)
=ELSE.IF(CurrCell="HB")
=SET.NAME("province", 7)
=ELSE.IF(CurrCell="JX")
=SET.NAME("province", 8)
=ELSE.IF(CurrCell="NX")
=SET.NAME("province", 9)
=ELSE.IF(CurrCell="QH")
=SET.NAME("province", 10)
=ELSE.IF(CurrCell="SD")
=SET.NAME("province", 11)
=ELSE.IF(CurrCell="SX")
=SET.NAME("province", 12)
=ELSE.IF(CurrCell="TC")
=SET.NAME("province", 13)
=ELSE.IF(CurrCell="XJ")
=SET.NAME("province", 14)
=ELSE.IF(CurrCell="XZ")
=SET.NAME("province", 15)
=ELSE.IF(CurrCell="YN")
=SET.NAME("province", 16)
=END.IF()
```

```
=SET.NAME("npp", OFFSET(CurrCell, 0, 4))
=IF(npp<>-999.9)
=SET.NAME("region", OFFSET(CurrCell, 0, 1))
=WORKBOOK.SELECT("NPP Avg", "NPP Avg")
=SET.NAME("answerCell", OFFSET(NPP_orig, region, province))
=FORMULA(answerCell+npp, answerCell)
=SET.NAME("count", OFFSET(counts_orig, region, province))
=FORMULA(count+1, count)
=WORKBOOK.SELECT("NPP", "NPP")
=END.IF()
=NEXT()

=WORKBOOK.SELECT("NPP Avg", "NPP Avg")
=FOR.CELL("CurrCell", OFFSET(NPP_orig, 1, 1):OFFSET(NPP_orig, 20, 16), TRUE)
=FORMULA(CurrCell/OFFSET(CurrCell, 22, 0), CurrCell)
=NEXT()
=RETURN()
```

Chapter 7

Result and Analysis

7.1 Regression Results

The yield equation as shown in Equation 5.8 in Chapter 5 was estimated for each essential crop. The results were separated into three scenarios depending on the choices of `NPP's` and can be found in appendix B. The general character of the results for each independent variable was consistent across the three scenarios. Thus, the following discussion will be based on the results in scenario 1 (Table 7.1), with the `NPP` calculated with limitations on water and nitrogen inputs. As decribed in section 5.4.1, the equations were specified to be functions of two major categories: (1). *farming characteristics* and (2). *weather characteristics.* The following analysis will focus on these two categories for each crop. The elasticities of $YIELD$ with respect to the independent variables will also be analysed.

- **Farming Characteristics:** $LAND^{eff}$, $MECH$, $FERT$, $IRRIGATE$ and $LABOR$. In general, the sign coefficients on the farming characteristics conformed to expectations and the relative magnitude of the coefficients were reasonable. The strong positive t-statistics for the slope coefficients for the farming variables would reject the null hypothesis that the corresponding farming variable is unrelated to the output yield and support the alternative hypothesis

Table 7.1: **Result of scenario 1**

Variable	*Rice*	*Wheat*	*Maize*	*Soybean*	*Potato*
$LAND^{eff}$	0.564529 (8.825978)	-0.02527 (-0.26233)	0.402138 (5.045209)	0.115514 (1.483835)	0.625078 (5.317396)
$MECH$	0.080713 (2.789429)	0.219136 (4.680584)	0.089095 (1.91306)	0.079825 (1.139737)	0.254027 (3.68827)
$FERT$	0.055724 (1.124423)	0.340879 (3.373358)	0.299842 (4.038715)	0.543665 (6.540776)	0.173777 (1.583325)
$IRRIGATE$	0.109885 (2.791699)	0.337912 (5.265259)	0.181471 (3.300737)	0.1198 (2.210793)	0.264409 (2.715065)
$LABOR$	0.118957 (2.261974)	0.199642 (2.332834)	-0.00658 (-0.09362)	0.009734 (0.138279)	-0.19588 (-1.988)
$TMEAN$	0.034263 (1.461115)	0.110545 (2.420911)	0.086741 (2.118658)	0.281293 (1.702225)	0.194038 (1.908746)
$TMIN$	N/A N/A	N/A N/A	-0.34664 (-1.41069)	-0.31881 (-0.56473)	0.092902 (0.207873)
$EPCP$	0.074963 (3.458012)	0.0335 (1.416567)	0.079457 (2.75077)	0.061132 (1.865474)	0.03703 (1.655287)
$EPCPN$	N/A N/A	N/A N/A	-0.01132 (-0.16908)	-0.19882 (-0.86688)	0.027197 (0.598179)
$APET$	-0.05861 (-0.81047)	-0.18552 (-1.43503)	0.076298 (0.897009)	-0.29778 (-1.15359)	0.059175 (0.233519)
$AMINRH$	-1.0085 (-5.95126)	-0.05597 (-0.35825)	-0.78101 (-2.90304)	0.08128 (0.171601)	-0.08041 (-0.18893)
$IGDD$	-0.06509 (-2.08717)	-0.50577 (-3.84331)	-0.1488 (-1.04059)	-0.7049 (-2.02809)	-0.23809 (-0.75364)

that the variable is positively related to crop yield. $LAND^{eff}$, which is actual sown area scaled by its corresponding `NPP` index, measures not only the amount of land used, but also the productivity of the land itself, as captured by `NPP` index. The highly positive t-statistics of $LAND^{eff}$ for rice, maize and potato have the highest elasticities of $YIELD$ with respect to $LAND^{eff}$. Thus, a rise in the effective land can significantly increase the output for these three crops. The highest elasticity for wheat is $IRRIGATE$ whereas for soybean is $FERT$.

- **Weather Characteristics:** $TMEAN$, $TMIN$, $EPCP$, $EPCPN$, $APET$, $AMINRH$ and $IGDD$. The coefficients obtained for the weather characteristics, however, were quite mysterious, except for the mean temperature, average minimum temperature and total precipitation. The mean temperature and total precipitation, which were actually the measure of the deviations of the `TEM` inputs from the actual data, were positively significant for most of the crops. The average minimum temperature, constrastly, had negative and nearly significant t-statistics. This means that the higher the average minimum temperature, i.e, the more positive the temperature, the lower is the crop yield. The logic behind this relationship is subtle. Higher minimum temperature can have two different effects: (1). longer growing season, which raises `NPP` and thus increases the crop yield. (2). If precipitation is constant, the higher the minimum temperature, the higher the evapotranspiration, the lower the soil moisture is, which enhances water stress of a plant. This in turn, lowers the `NPP` and thus lowers the crop production. Since the latter effect dominates the entire process, the minimum temperature is expected to be negatively correlated to the output yield.

7.1.1 Rice

Farming Characteristics

Rice has strong positive and significant elasticities for $LAND^{eff}$, $MECH$, $IRRIGATE$ and $LABOR$, though $FERT$ is positive and nearly significant as shown in Table 7.2. Among the significant independent variables for rice, $LAND^{eff}$ has the highest elasticity with a t-statistic of 8.825978, which is within the 1% confidence level using a two-tailed test. Rice is a relatively labor intensive crop, which can be reflected by $LABOR$'s highly positive t-statistic of 2.261974. As it is expected, the higher the labor force, the higher the rice yield would be.

Water supply is very critical in determining the rice yield since rice requires relatively larger amount of water. The result does show that irrigation certainly plays a significant role in the rice production. Fertilization, compared to other farming characteristics, is less significant, with a t-statistic of only 1.124423. The reason is possibly that other inputs, such as $LAND^{eff}$, $IRRIGATE$, $LABOR$ and $MECH$ are far more dominant in affecting the rice yield. It is also possible that fertilizer use is not sufficiently intensive to have a significance impact on output.

Table 7.2: **Regression result for rice**

Crop	$LAND^{eff}$	$MECH$	$FERT$	$IRRIGATE$	$LABOR$
Rice	0.564529	0.080713	0.055724	0.109885	0.118957
	(8.825978)	(2.789429)	(1.124423)	(2.791699)	(2.261974)
	$TMEAN$	$EPCP$	$APET$	$AMINRH$	$IGDD$
	0.034263	0.074936	-0.05861	-1.0085	-0.06509
	(1.461115)	(3.458012)	(-0.81047)	(-5.95126)	(-2.08717)

Weather Characteristics

Rice is a major crop in southern China, where the weather is featured by its high temperature and heavy rainfall. The regression result in fact does show this dependency: precipitation strongly and positively correlates with the rice yield though the mean temperature is a bit less than the 95% significant test. ($TMEAN$ has a t−statistic of 1.461115 and $EPCP$ has 3.458012.) Nevertheless, the significant negativities of humidity and total growing degree days are far from expectations as one would expect them to be positive.

7.1.2 Wheat

Farming Characteristics

The result in Table 7.3 shows that $MECH$, $FERT$, $IRRIGATE$, and $LABOR$ are positively and highly significant at the 1% confidence level, except $LABOR$, which is statistically significant at the 5% confidence level. These variables are all the basic inputs for wheat production, thus the results are undoubtedly expected to be positive and significant. Note that $IRRIGATE$ has the highest elasticity with a strong t-statistic of 5.265259. The high sensitivity of the change of output to the change of amount of irrigation is possibly due to the lower dependency of precipitation as shown in Table 7.3, where $EPCP$ is a little less than significant.

Table 7.3: **Regression result for wheat**

Crop	$LAND^{eff}$	$MECH$	$FERT$	$IRRIGATE$	$LABOR$
Wheat	-0.02527	0.219136	0.34089	0.337912	0.199642
	(-0.26233)	(4.680584)	(3.373358)	(5.265259)	(2.332834)
	$TMEAN$	$EPCP$	$APET$	$AMINRH$	$IGDD$
	0.110545	0.0335	-0.18552	-0.05597	-0.50577
	(2.420911)	(1.416567)	(-1.43503)	(-0.35825)	(-3.84331)

However, the puzzle lies on the variable $LAND^{eff}$, which is negative and insignificant. When alternative NPP's were used, $LAND^{eff}$ has the t-statistics of 0.746026435 for scenario 2 and 0.272544546 for scenario 3, which shows that $LAND^{eff}$'s are positive but insignificant. This raises the question of whether the NPP is the correct index of relative productivity of the land for wheat. The reason that the TEM NPP might not be a good approximation for the productivity of land is that the NPP is calculated for natural grassland only. A test regression using the actual sown area showed that the sown area itself has very strong correlation with the yield and thus the negativity of $LAND^{eff}$ comes mostly from its interaction with NPP. Therefore, $LAND^{eff}$ is probably a better approximation for some crops, such as rice described in previous section, in some regions than other crops in the same or other regions. This points out one of the possible sources of errors.

Weather Characteristics

Generally, wheat requires high temperature for growth though it can survive in freezing temperatures as discussed in Section 5.2.2 in Chapter 5. The result in Table 7.3 shows that $TMEAN$ has the highest elasticity among the weather variables and is significant with a t-statistic of 2.420911. Precipitation perhaps is less significant, with its elasticity of 0.0335 and t-statistic of 1.416567. Again, the negative elasticity of the total growing degree days and evaportransporation poses the problems with the data.

7.1.3 Maize

Farming Characteristics

For maize, $LAND^{eff}$, $FERT$ and $IRRIGATE$ are statistically significant at the 1% level as shown in Table 7.4. As it was discussed for rice before, the higher the productivity of the land, the higher the output yield would be. Effective land also has the highest elasticity among the farming variables. Adequate irrigation and fertiliza-

Table 7.4: **Regression result for maize**

Crop	$LAND^{eff}$	*MECH*	*FERT*	*IRRIGATE*	*LABOR*		
Maize	0.402138	0.089095	0.299842	0.181471	-0.00658		
	(5.045209)	(1.91306)	(4.038715)	(3.300737)	(-0.09362)		
	TMEAN	*TMIN*	*EPCP*	*EPCPN*	*APET*	*AMINRH*	*IGDD*
	0.086714	-0.34664	0.079475	-0.01132	0.076298	-0.78101	-0.1488
	(2.118658)	(-1.41069)	(2.75077)	(-0.16908)	(0.897009)	(-2.90304)	-1.04059

tion are essential to most of the crop and both input has relatively high elasticity as well. Mechanization is also significant in affecting the maize yield though it is approximately 0.05 less then the 1.96 t-statistic requirement for the significant level of 5% in a two-tailed test.

However, the negative and insignificant coefficient of labor force suggests there is a surplus labor force on the land. One possibility contributing to the negative relationship is that there is a negative marginal return on labor. However, it is hard to believe that labor is used to the point that it has a negative return. More likely the regression reflects that the labor inputs were not measured accurately.

Weather Characteristics

Maize is a warm-weather plant which also requires ample rainfall. Table 7.4 reasonably shows that $TMEAN$ and $EPCP$ are positive and significant with 5% confidence level of t-statistics of 2.118658 and 2.75077 respectively. The average minimum temperature has a negative and nearly significant t-statistic. The result of precipitation in non-growing season, $EPCPN$, suggests there is little correlation with the maize output yield.

7.1.4 Soybeans

Farming Characteristics

The regression result in Table 7.5 shows that the highly significant t-statistic of fertilization rejects the null the hypothesis that fertilization is not related to the soybean yield. Irrigation also plays a significant role contributing to soybean output, with its t-statistic of 2.210793. Other inputs, such as $LAND^{eff}$ and $MECH$, are positively and nearly significant. They both are important to the yield, but less crucial when comparing to fertilization, which has the highest elasticity among all other input variables. Labor force has an insignificant t-statistic of 0.138279. This can suggest that soybean growth doesn't require that much labor force or that there is so much labor that it is not a critical factor.

Weather Characteristics

Soybeans require relatively high temperature, adequate rainfall and a great deal of sunshine. The regression result in Table 7.5 shows that $TMEAN$ and $EPCP$ are nearly significant at the 5% confidence level. $TMIN$ has the correct sign, negatively related to the soybean yield, but is insignificant.

Table 7.5: **Regression result for soybeans**

Crop	$LAND^{eff}$	$MECH$	$FERT$	$IRRIGATE$	$LABOR$		
Soybean	0.115514	0.079825	0.543665	0.1198	0.009734		
	(1.483835)	(1.139739)	(6.540776)	(2.210793)	(0.138279)		
	$TMEAN$	$TMIN$	$EPCP$	$EPCPN$	$APET$	$AMINRH$	$IGDD$
	0.281293	-0.31881	0.061132	-0.10882	-0.29778	0.08128	-0.7049
	(1.702225)	(-0.56473)	(1.865474)	(-0.86688)	(-1.15359)	(0.171601)	(-2.02809)

7.1.5 Potatoes

Farming Characteristics

From the regression result in Table 7.6, $LAND^{eff}$, $MECH$ and $IRRIGATE$ are the crucial inputs with their highly positive t-statistics in at least 95% confidence level test. Among all other independent variables, $LAND^{eff}$ has the highest elastcitiy and the t-statistic of 5.317396. On the other hand, the result shows that fertilization, which has the lowest elasticity, is relatively less important compared to other inputs. Irrigation is principally important for most of the crops and is statistically significant. The negatively significant in the labor input again is possibly a result of the excess labor force on the land in China for potato production. Potato production certainly requires much less labor force than the labor intensive crop, such as rice, except during the harvest time, when more laborers are needed.

Weather Characteristics

Potatoes require a relatively warm weather. The result showed that the mean temperature is positively significant with only approximately 0.05 away from the 1.96 significance testing requirement. Total precipitation, as it is one of the most important inputs for most of the crops, is nearly significant with the elasticity of 0.03703 and the t-statistic of 1.655287.

Table 7.6: **Regression result for potatoes**

Crop	$LAND^{eff}$	$MECH$	$FERT$	$IRRIGATE$	$LABOR$		
Potato	0.625078	0.254027	0.173777	0.264409	-0.19588		
	(5.317396)	(3.68827)	(1.583325)	(2.715065)	(-1.988)		
	$TMEAN$	$TMIN$	$EPCP$	$EPCP$	$APET$	$AMINRH$	$IGDD$
	0.194038	0.092902	0.03703	0.027197	0.059175	-0.08041	-0.23809
	(1.908746)	(0.207873)	(1.655287)	(0.598179)	(0.233519)	(-0.18893)	(-0.75364)

7.2 The Three Scenarios

The three scenarios were distinguished by the choices of NPP, which differ according to the constraints of the inputs to TEM:

1. limitation on water and nitrogen.

2. limitaiton on water only.

3. limitation on nitrogen only.

Table 7.7 shows the result for $LAND^{eff}$ across the three scenarios. Ignoring the negative values, $LAND^{eff}$ in scenario 3 generally has higher elasticities than in scenario 1, which in turn has higher elasticities than in scenario 2, but the latter two have closer elasticities across all the crops. The reason for this relationship is possibly that the NPP$'s$ vary depending on the input constraints. One would expect that $NPP_2's$ and $NPP_3's$ are actually higher than $NPP_1's$ due to the less input constraint conditions compared to scenario 1. The TEM actually have $NPP_3's$ much higher than the NPP$'s$ in the prior two conditions and $NPP_2's$ are only slightly higher than $NPP_1's$. The TEM results show that limitation on water has more negative effect on the NPP$'s$ due to the limitation on nitrogen. This effect certainly affects the effectiveness of land, which in turn affects the yield output. This anaylsis again shows that the availability of water greatly affects the output yield.

Table 7.7: **Coefficients and *t*-statistics of $LAND^{eff}$ across the three scenarios**

	Rice	*Wheat*	*Maize*	*Soybean*	*Potato*
1	0.564529 (8.825978)	-0.02527 (-0.26233)	0.402138 (5.045209)	0.115514 (1.483835)	0.625078 (5.317396)
2	-0.19592 (-1.82738)	0.072154 (0.746026)	0.374985 (4.964672)	0.151062 (2.032067)	0.64585 (5.217437)
3	0.590522 (8.801468)	0.028093 (0.272545)	0.458981 (5.310742)	0.170207 (2.173412)	0.676142 (5.426261)

7.3 Regression Diagnostics

7.3.1 Coefficient Determination Checks

The coefficient determination, R^2, measures the proportion of the variance of the dependent variable, $YIELD_{i,r}$, explained by the regression. As shown in Table 7.8, the R^2's, the percentages of variances attribute to the crop productions, are at least 95%. This means that a substantial portion (> 95%) of the variances in the crop productions, $YIELD_{i,r}$, are explained by the dependent variables in the yield equation.

7.3.2 Residual Checks

The residual test is related to the R^2 test in the way that the bigger the residual, the worse the fit is, then the smaller the R^2 is. The residuals of mode built in Equation 5.8 were plotted against every one of the twelve independent variables and fitted value (see appendix C). No observable pattern was observed in any of these plots. This regression equations were fitted such that the sum of the squares of the residuals were minimized.

7.3.3 F-test Checks

The F-statistic test is used to access an analysis of variance of the entire equation. The purpose is to check whether the explanation provided by the equation as a whole is significant. Significantly large values of F indicate that the variability between the samples is significantly larger than the variability within the samples. Table 7.9 shows

Table 7.8: **The coefficient determinations for all the crops**

	Rice	*Wheat*	*Maize*	*Soybean*	*Potato*
R^2	99.5505%	98.2917%	98.9411%	95.7256%	98.4716%

Table 7.9: **Critical F values and F-statistics from the result**

	Rice	*Wheat*	*Maize*	*Soybean*	*Potato*
Critical F	1.6	1.6	1.55	1.55	1.55
F-statistics	1524.688	72.70407	360.138	105.8788	226.4218

the critical F values[1] associating to the degrees of freedom between and within the samples. From Table 7.9, the F-statistics are much higher than the critical F values and thus indicate significant degrees of explanation for each crop yield equation.

7.4 Process of Improving the Regression Model

This non-linear regression model estimated by Equation 5.8 as shown in Chapter 5 was actually a series of modifications from the original linear equations as shown in Equation 7.1:

Original Yield Equation:

$$\begin{aligned}\frac{Production_{i,r}}{SownArea_{i,r}} = \; & a_0 + a_1 NPP_r + a_2 MECH_{i,r} + a_3 FERT_{i,r} + a_4 IRRIGATE_{i,r} + \\ & a_5 LABOR_{i,r} + a_6 TMEAN_{i,r} + a_7 TMIN_{i,r} + a_8 EPCP_{i,r} + \\ & a_9 EPCPN_{i,r} + a_{10} APET_{i,r} + a_{11} AMINRH_{i,r} + \\ & a_{12} IGDD_{i,r} + e_{i,r} \end{aligned} \tag{7.1}$$

where $i's$ are the essential crops and $r's$ are the region numbers.

[1] *The critical F values are given by Kitchens in Statistics [28].*

When the regression model in Equation 7.1 was employed, the results were noisy and did not provide any insights. For example, the $\texttt{NPP}'s$ were negative and significant and most of the weather variables were of the wrong sign. Although there are sources of errors which we are not able to eliminate, modifications of the regression improved the results. These modifications are categorized into four general steps:

1. Estimation of farming characteristics for each crop.

2. Changing sown area as independent variable.

3. Creation of effective land variable.

4. Calculation of weather deviations.

7.4.1 Estimation of Farming Characteristics for Each Crop

The statistical books generally provide data on each farming characteristic, *mechanization, fertilization, irrigation* and *labor force*, as an aggregate for all the crops in each region. For instance, mechanziation data is regionally given as a sum of the power used for all the crop productions. In order to retrieve the data for each crop, ratios based on the sown areas were calculated as shown in Equation 7.2:

$$Ratio_{i,r} = \frac{SownArea_{i,r}}{TotalSownArea_r} \tag{7.2}$$

where $i's$ are the essential crops and $r's$ are the region numbers.

Each $Ratio_{i,r}$ was then used as a scaler for *mechanization, fertilization, irrigation* and *labor force*. The reason for this calculation is that some regions might be more productive on certain crops and most of the consumption of the farming characteristics might mainly belong to these crops. This ratio estimation greatly improved the regression results.

7.4.2 Changing Sown Area as Independent Variable

Equation 7.3 was first employed as an investigation of the relationships of the independent variables and the dependent variable. However, the sown area is one of the critical inputs to the crop production and its input coefficient should be estimated. Therefore, Equation 7.4 was used to include the sown area effect. Note that the NPP and the sown area was raised to the same power α. NPP was thus used as index for the sown area. This will be further explained in the next section.

$$\frac{X}{L} = a_0\, NPP \;+\; a_1\, M \;+\; a_2\, F \;+\; a_3\, I....... \tag{7.3}$$

$$X = (NPP \cdot L)^{\alpha}\, M^{\beta}\, F^{\omega}\, I^{\zeta}.... \tag{7.4}$$

7.4.3 Creation of Effective Land Variable

Since NPP captured the productivity of land, it was reasonable to scale the sown area by NPP index as shown in Equation 7.5 so that the actual productivity of land could be estimated.

$$LAND^{eff} = NPP \times SownArea \tag{7.5}$$

The regression with this modification showed that $LAND^{eff}$ was very positive and significant, which was expected.

7.4.4 Calculation of Weather Effects

Finally, the weather variables have posed the most problems since in most of the early results they had their wrong signs. To deal with this, weather variables were entered as the deviations of the TEM climate data from the actual NCAR weather data as shown in Equation 7.6.

$$WeatherVar = WeatherVar^{NCAR} - WeatherVar^{TEMinput} \tag{7.6}$$

The mean temperature and the total precipitation were adjusted using the above equation. Deviations of other climate variables from weather variables were not calculated due to lack of TEM data. The results then turned out to be reasonable as expected.

7.5 Possible Sources of Errors

From the discussion of regression results, there appear to be various possible sources of errors:

1. *Allocation of data within one region.*

   The data source books in general do not supply input data for each crop for inputs of machinery, fertilization, irrigation and labor force. Specific land inputs for the crops are provided, however. Ratios of the sown area for each specific crop relative to the total sown area were calculated. These ratios were in turn employed as scalers to the total machinery, total fertilization, total irrigation and total labor force to have a rough estimate of the amounts of each of these inputs in each region r for each crop i.

2. *Approximation of* NPP.

   NPP is used as indices of relative productivity of the land for each region in this model. However, the NPP is the approximation for the natural grassland. Thus, the calculated effective land does not necessarily reflect the true relationship for some crops, while it works for others, such as for maize.

3. *Approximation of weather information.*

   The weather data was based on meterological stations while they were not located evenly across regions. Thus, it was necessary to identify the locations on the map for each station and then calculated the average within one region. This can also lead to errors. Other errors could happen when identifying the stations on the maps.

Chapter 8

Conclusions and Implications

8.1 Conclusions

The results discussed in last chapter suggest that the statistics from China Statistics Bureau were, on the whole, reliable and not much random error exists, though some obviously impossible data points were excluded from the sample. The coefficients of the independent variables are in fact the elasticities of $YIELD$ with respect to the corresponding independent variable. The independent variables for farming characteristics, *effective land, mechanization, fertilization, irrigation* and *labor force*, were, as expected, positively significant for most of the crops in relation to the crop output yields. However, the negative labor variable for maize and potato suggested that there was possibly a surplus of labor force on land for these two crops, whereas, for the labor intensive crop, rice, there was a strong positive relation of labor with the rice yield. In general, the labor requirement for potato is crucial only in harvesting season. Thus, it is possible that there is other source of error in the labor observation in China.

The effective land variables, individual crop sown area scaled by the corresponding `NPP` index, have the highest elasticities among all other input variables and are significant for most of the crops, except for soybean and wheat, which their value was positively significant and negatively insignificant respectively. The negativity in the effective land coefficient raised the question of whether the TEM NPP is the correct index of relative productivity of the land for the different crops. It is possible that NPP was a better approximation of productivity for some crops in some regions, such as for rice, potato and maize, than other crops in the same regions. Nevertheless, the results showed that NPP in general was good index although TEM used the natural vegetation to generate the NPP's. Moreover, NPP worked as a good approximation for effect of global warming since it is sensitive to the effects of climate change in the terrestrial ecosystem.

The results for weather variables are generally noisy, except for the *mean temperature, average minimum temperature* and *total precipitation.* The observations used for mean tempeature and total precipitation were actually the deviations of the TEM climate data from the actual NCAR weather data. As it was expected, the t-statistics of the mean temperature and the total precipitation were positive and statistically significant for most of the crops, especially for rice since it required relatively high temperature and heavy rainfall. Wheat, which was less water demanding, was less significant compared to rice production. Other crops, which required only ample rainfall, had reasonably significant precipitation value. The average minimum temperature is expected to have negative correlation to the output. This means the higher the average minimum temperature, the lower the output would be. The decrease in output yield is due to the lower NPP if precipitation is constant. However, there were many sources of errors that account for the inconsistent results for evaportransporation, humidity and total growing degree days. These results can be improved in further research in data searching and organization.

Finally, a point that is worthy to give attention is that a typical cross-sectional regression to estimate agricultural output employs zero-one dummy variables to distinguish special land characteristics. In this research, a dummy variable could not be used to capture the differences of soil quality in each region. Instead, an explicit parameter, NPP, was used to identify the special characteristics of each region. This explicit parameter provides a specific explanation of regional fertility differences as compared to the dummy variables.

8.2 Suggestions for Future Work

These are some suggestions for furture extension of the project:

1. *Examine the effects of certain changes based on partial derivatives.*

   For instance: take $\frac{\partial WeatherVar}{\partial NPP}$, e.g. $\frac{\partial FERT}{\partial YIELD}$, to examine the effects of partial change in inputs to outputs.

2. *Examine the effect of doubling of CO_2.*

   This can be examined using TEM to generate a new set of NPP indices by doubling the CO_2 level from the orginal 355 *ppmv*. The effects of doubling in CO_2 on agricultural production can be pursued based on the new NPP indices.

3. *Data acquistion on weather variable.*

   Collect better set of weather data to eliminate the puzzles on the weather results.

Appendix A

The Climate Observations

The information in this appendix is a summary from `IPCC 1992` [37] and `IPCC 1994` [25].

A.1 Observations of Greenhouse Gases Change

The concentrations of the major greenhouse gases have been increased due to immense human activities over the past century. The growth rates of most of these gases have been increased except for that of methane (CH_4), having a decling rate from approximately 20 $ppbv/yr$[1] in the late 1970s to as low as 10 $ppbv/yr$ in 1989.

A.1.1 Ozone

Over the most recent decades, one of the most effective greenhouse gases, ozone (O_3), in both stratosphere and troposhpere have been decreasing, predominantly in the lower stratosphere (below 25 km). The decreasing rate was as high as 10% per decade. Moreover, the research indicates that ozone in the troposhpere have increased up to 10% per decade over the past two decades. The substantial cause of depletion is the industrial halocarbons.

[1] *ppbv = parts per billion* (10^9) *by volume*

A.1.2 Carbon Dioxide

Significant sources of emission of carbon dioxide (CO_2) are from combustion of fossil fuels and change of land-use. According to IPCC 1992 study, the aggregate amount of combustion of fossil fuels in 1989 and 1990 was 6.0 ± 0.5 GtC[2] which has increased from 5.7 ± 0.5 GtC in 1987. Since the pre-industrial era, concentration of CO_2 has increased from 280 to 356 *ppmv*,[3] being the largest contribution of greehouse gas radiative forcing (1.56 WM^{-2}) [25]. The increase of atmoshperic CO_2 due to land conversion correlates to the area and the rate of reforestation and afforestation,[4] the density of the carbon concentration of the original land and replacement forests and the fate of soil carbon [37]. According to Rosenzweig's general circulation models (GCMs), doubling of atomospheric (CO_2) increases the global surface temperature from 1.5 to 4.5^0C[5] and alters amounts and frequency of precipitation [32].

A.1.3 Methane

Studies from IPCC 1992 shows that 20% (100 Tg)[6] of methane (CH_4) emission comes from fossil, i.e. coal, oil and natural gas while some percentage comes from soil characteristics on growing condition, such as rice agriculture, mainly in Japan, India, Australia, Thailand and China. Since the pre-industrial era, CH_4 has increased from 0.7 to 1.7 *ppmv*, contributing to 0.5 Wm^{-2} radiative forcing. However, study from IPCC 1994 records that there is a sharp decline in CH_4 growth rate over the last decade [25].

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[2] *GtC = gigatons of carbon = one billion (10^9) tons of carbon = 3.7 Gt CO_2*

[3] *ppmv = parts per million (10^6) by volume*

[4] *Greenhouse gases can be released or taken up by soil and vegtation when lands convert from one use to another. Burning of forests or amendment of soils have significant effects of emission of CO_2.*

[5] *0^0C = 273 K*

[6] *Tg = teragram*

A.1.4 Nitrous Oxide

Major contributions of N_2O come from adipic acid (nylon) production, nitric acid production and automobiles. The increase in N_2O since pre-industrial era is from 275 to 310 $ppbv$ which have a 0.1 Wm^{-2} contribution in radiative forcing.

A.1.5 Aerosols

Sources of aerosols are principally from *inductral activity, volcanic eruptions* and *biomass burning.*

A.2 Observations of Climate Change

Despites there are unstantial uncertainties in the understanding of the climate change, the major climate observations of the IPCC scientific assessment are the following:

- The global mean surface temperature has been increased by 0.3 to 0.6^0C over last century and is expected to increase in the rate of 0.3^0C per decade.
- The stratospheric ozone depletion reduces the radiative forcing which is approximately the amount of contribution of radiative forcing from $CFCs$ over qrecent decades. Thus, the will be a small net decreasing rate in global warming over the next few decades due to the reduction in stratospheric ozone layer.
- The lower troposphere has warmed over the last decade.
- The average warming has largely increased in minimum (night-time) as opposed to maximum (day-time).
- The short-lived sulphate aerosols have cooling effect which is comparable to the greenhouse effect.
- The sulphate aerosols causes acid rain and other environment effects.

Appendix B

The Regression Summary

Next fifteen pages are the summary results of the regression models of the three scenarios:

1. limitation on nitrogen and water.
2. limitation on water only.
3. limitation on nitrogen only.

Each summary result include:

- Multiple R, R Square, Adjusted R Square
- Standard Error
- Degrees of Freedom, *df*
- Sum of Squares, SS; Mean Squares, MS
- F Statistics
- Coefficients, t-statisctics, standard error and P-value of each independent variable.

B.1 Scenario 1

Figure B-1: **Regression Summary: rice – scenario 1**

SUMMARY

Regression Statistics	
Multiple R	0.995504975
R Square	0.991030155
Adjusted R Sq	0.990380167
Standard Error	0.247314652
Observations	149

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	10	932.5684574	93.25684574	1524.688168	5.8014E-136
Residual	138	8.440706097	0.061164537		
Total	148	941.0091635			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	2.829180313	0.580660311	4.872350077	2.98329E-06	1.681037691	3.977322935	1.681037691	3.977322935
EFFLAND	0.564529341	0.063962245	8.825977552	4.32275E-15	0.438056464	0.691002217	0.438056464	0.691002217
MECH	0.080713462	0.028935476	2.789429228	0.006026976	0.023499197	0.137927727	0.023499197	0.137927727
FERT	0.055723943	0.049557826	1.124422655	0.262785796	-0.042267002	0.153714888	-0.042267002	0.153714888
IRRIGATE	0.109885098	0.039361366	2.791699319	0.005987139	0.032055667	0.18771453	0.032055667	0.18771453
LABOR	0.11895744	0.052590089	2.261974494	0.025261876	0.014970786	0.222944095	0.014970786	0.222944095
TMEAN	0.034263273	0.023450084	1.461115163	0.146257029	-0.012104698	0.080631244	-0.012104698	0.080631244
EPCP	0.074962977	0.021678054	3.458012239	0.000723965	0.032098849	0.117827106	0.032098849	0.117827106
APET	-0.058607905	0.072313378	-0.810471127	0.419064914	-0.201593519	0.08437771	-0.201593519	0.08437771
AMINRH	-1.008495002	0.169458949	-5.951264337	2.08466E-08	-1.343567054	-0.673422949	-1.343567054	-0.673422949
IGDD	-0.065091678	0.031186641	-2.087165398	0.038712374	-0.126757183	-0.003426172	-0.126757183	-0.003426172

Figure B-2: **Regression Summary: wheat – scenario 1**

SUMMARY

Regression Statistics	
Multiple R	0.982917243
R Square	0.966126306
Adjusted R Sq	0.963617144
Standard Error	0.434537028
Observations	146

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	10	727.0406605	72.70406605	385.0393547	5.08987E-94
Residual	135	25.49102786	0.188822429		
Total	145	752.5316884			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	6.179932426	1.099060645	5.622922133	1.03674E-07	4.006329331	8.353535521	4.006329331	8.353535521
EFFLAND	-0.025274696	0.096346274	-0.262331845	0.793465494	-0.21581792	0.165268529	-0.21581792	0.165268529
MECH	0.219135539	0.046817988	4.680584309	6.8749E-06	0.126543994	0.311727085	0.126543994	0.311727085
FERT	0.340879034	0.101050346	3.373358398	0.000969368	0.141032605	0.540725463	0.141032605	0.540725463
IRRIGATE	0.337911795	0.06417762	5.265259036	5.37939E-07	0.210988249	0.464835341	0.210988249	0.464835341
LABOR	0.199641862	0.085579125	2.332833656	0.021135012	0.030392739	0.368890985	0.030392739	0.368890985
TMEAN	0.11054538	0.045662724	2.420910795	0.016810772	0.020238592	0.200852169	0.020238592	0.200852169
EPCP	0.033499646	0.023648469	1.41656723	0.158912882	-0.013269734	0.080269027	-0.013269734	0.080269027
APET	-0.185517152	0.129277196	-1.435033851	0.153590149	-0.441187586	0.070153282	-0.441187586	0.070153282
AMINRH	-0.055972301	0.156240224	-0.358245139	0.720719433	-0.364967293	0.253022691	-0.364967293	0.253022691
IGDD	-0.505770249	0.131597403	-3.843314832	0.000186136	-0.766029337	-0.245511161	-0.766029337	-0.245511161

Figure B-3: **Regression Summary: maize – scenario 1**

SUMMARY

Regression Statistics	
Multiple R	0.989410838
R Square	0.978933807
Adjusted R Sq	0.976215588
Standard Error	0.286836163
Observations	106

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	12	355.5641914	29.63034928	360.1380117	2.48005E-72
Residual	93	7.651573547	0.082274984		
Total	105	363.2157649			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.000%*	*Upper 95.000%*
Intercept	4.555408539	1.341571594	3.395576173	0.001008675	1.8913159	7.219501178	1.8913159	7.219501178
EFFLAND	0.402137979	0.079706908	5.045208636	2.23581E-06	0.243856016	0.560419943	0.243856016	0.560419943
MECH	0.08909472	0.046571838	1.913060007	0.058816809	-0.003387627	0.181577068	-0.003387627	0.181577068
FERT	0.299842073	0.074241943	4.038715304	0.000110441	0.152412435	0.447271712	0.152412435	0.447271712
IRRIGATE	0.181471164	0.054978989	3.300736675	0.001368472	0.072293898	0.29064843	0.072293898	0.29064843
LABOR	-0.006577863	0.070264701	-0.093615472	0.925616008	-0.146109495	0.132953768	-0.146109495	0.132953768
TMEAN	0.086741331	0.040941635	2.118658193	0.036784986	0.005439439	0.168043223	0.005439439	0.168043223
TMIN	-0.346640634	0.245723407	-1.410694399	0.161671001	-0.834598132	0.141316865	-0.834598132	0.141316865
EPCP	0.079475243	0.028891995	2.750770313	0.00714599	0.022101524	0.136848962	0.022101524	0.136848962
EPCPN	-0.011323018	0.066968636	-0.169079418	0.866101387	-0.144309323	0.121663287	-0.144309323	0.121663287
APET	0.076298328	0.085058633	0.897008633	0.372030515	-0.092611091	0.245207748	-0.092611091	0.245207748
AMINRH	-0.781007139	0.269031175	-2.903035825	0.00461506	-1.3152492	-0.246765078	-1.3152492	-0.246765078
IGDD	-0.148796587	0.142992537	-1.040589886	0.300763646	-0.432751142	0.135157967	-0.432751142	0.135157967

Figure B-4: **Regression Summary: soybean – scenario 1**

SUMMARY

Regression Statistics	
Multiple R	0.957255892
R Square	0.916338843
Adjusted R Sq	0.907684241
Standard Error	0.56834992
Observations	129

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	12	410.4136769	34.20113974	105.8787909	1.46864E-56
Residual	116	37.47050922	0.323021631		
Total	128	447.8841861			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	7.131260474	2.442919939	2.919154394	0.004217214	2.292752653	11.96976829	2.292752653	11.96976829
EFFLAND	0.115514105	0.077848357	1.483834839	0.140564858	-0.038674282	0.269702492	-0.038674282	0.269702492
MECH	0.079824824	0.070037958	1.139736591	0.256744013	-0.058894093	0.21854374	-0.058894093	0.21854374
FERT	0.543664594	0.083119278	6.540776152	1.72268E-09	0.37903649	0.708292699	0.37903649	0.708292699
IRRIGATE	0.11980048	0.054188921	2.210792863	0.02901167	0.012472559	0.227128402	0.012472559	0.227128402
LABOR	0.009733779	0.070392311	0.138279009	0.890259673	-0.129686978	0.149154536	-0.129686978	0.149154536
TMEAN	0.281292951	0.165250197	1.702224603	0.091391733	-0.046005688	0.60859159	-0.046005688	0.60859159
TMIN	-0.318806642	0.564529889	-0.564729429	0.573348269	-1.436928541	0.799315257	-1.436928541	0.799315257
EPCP	0.061131516	0.032769964	1.865473988	0.064641508	-0.003773488	0.12603652	-0.003773488	0.12603652
EPCPN	-0.108815338	0.125525833	-0.866876046	0.387799541	-0.357434916	0.13980424	-0.357434916	0.13980424
APET	-0.297779536	0.258132945	-1.153589813	0.251039725	-0.80904405	0.213484978	-0.80904405	0.213484978
AMINRH	0.081280499	0.473658832	0.171601359	0.864049938	-0.856859931	1.019420929	-0.856859931	1.019420929
IGDD	-0.704902137	0.347569454	-2.028090011	0.044841986	-1.393306818	-0.016497457	-1.393306818	-0.016497457

Figure B-5: **Regression Summary: potato – scenario 1**

SUMMARY

Regression Statistics	
Multiple R	0.984715795
R Square	0.969665197
Adjusted R Square	0.965382636
Standard Error	0.378819865
Observations	98

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	12	389.9105991	32.49254993	226.4218344	4.23642E-59
Residual	85	12.19788167	0.14350449		
Total	97	402.1084808			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.953271814	1.311518004	-0.726846152	0.469317265	-3.560922541	1.654378913	-3.560922541	1.654378913
EFFLAND	0.625077613	0.117553332	5.317395951	8.37651E-07	0.391349954	0.858805271	0.391349954	0.858805271
MECH	0.254026892	0.068874261	3.688270303	0.000397164	0.117086326	0.390967457	0.117086326	0.390967457
FERT	0.173777405	0.109754735	1.583324897	0.117061278	-0.044444544	0.391999354	-0.044444544	0.391999354
IRRIGATE	0.264408708	0.097385788	2.715064621	0.008023991	0.070779554	0.458037862	0.070779554	0.458037862
LABOR	-0.195877779	0.098530188	-1.987997626	0.05003045	-0.391782307	2.67489E-05	-0.391782307	2.67489E-05
TMEAN	0.194037969	0.101657285	1.908746333	0.059669591	-0.008084069	0.396160007	-0.008084069	0.396160007
TMIN	0.092902055	0.446917706	0.207872844	0.835825508	-0.795690613	0.981494722	-0.795690613	0.981494722
EPCP	0.037030484	0.022371031	1.655287351	0.101554046	-0.007449145	0.081510114	-0.007449145	0.081510114
EPCPN	0.027196552	0.045465561	0.598179168	0.551310977	-0.063201219	0.117594323	-0.063201219	0.117594323
APET	0.059174656	0.253403724	0.233519283	0.815919669	-0.444660139	0.563009451	-0.444660139	0.563009451
AMINRH	-0.080408734	0.42560917	-0.188926226	0.850601008	-0.926634298	0.765816829	-0.926634298	0.765816829
IGDD	-0.238088955	0.315919533	-0.753637967	0.453149198	-0.866222003	0.390044093	-0.866222003	0.390044093

B.2 Scenario 2

Figure B-6: **Regression Summary: rice – scenario 2**

SUMMARY

Regression Statistics	
Multiple R	0.9966967
R Square	0.993404313
Adjusted R Sq	0.992874732
Standard Error	0.21284658
Observations	149

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	11	934.8025612	84.98205102	1875.831632	1.6786E-143
Residual	137	6.206602337	0.045303667		
Total	148	941.0091635			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	3.067026145	0.567350893	5.405871714	2.78363E-07	1.945128064	4.188924225	1.945128064	4.188924225
EFFLAND	-0.195916567	0.107211959	-1.827376052	0.069819398	-0.407920977	0.016087843	-0.407920977	0.016087843
MECH	0.049981812	0.026433019	1.890885472	0.060751191	-0.002287699	0.102251322	-0.002287699	0.102251322
FERT	0.078561403	0.043479732	1.806851123	0.072980073	-0.007416832	0.164539637	-0.007416832	0.164539637
IRRIGATE	-0.013565516	0.037743963	-0.359408908	0.719842583	-0.088201654	0.061070621	-0.088201654	0.061070621
LABOR	0.11161038	0.04759406	2.345048525	0.020460493	0.01749634	0.205724419	0.01749634	0.205724419
TMEAN	0.036693581	0.020292394	1.808243095	0.072762042	-0.003433258	0.076820419	-0.003433258	0.076820419
EPCP	0.067098436	0.018703766	3.587429272	0.000463748	0.030113003	0.10408387	0.030113003	0.10408387
APET	-0.049141296	0.062251616	-0.789397927	0.431243537	-0.172239663	0.07395707	-0.172239663	0.07395707
AMINRH	-0.001880603	0.155229599	-0.012114977	0.990351508	-0.308836653	0.305075447	-0.308836653	0.305075447
IGDD	-0.022691501	0.027305245	-0.831030831	0.407402205	-0.07668578	0.031302778	-0.07668578	0.031302778
LAND	0.924057076	0.121702419	7.592758528	4.37838E-12	0.683398761	1.164715391	0.683398761	1.164715391

Figure B-7: **Regression Summary: wheat – scenario 2**

SUMMARY

Regression Statistics	
Multiple R	0.982979239
R Square	0.966248185
Adjusted R Sq	0.963748051
Standard Error	0.433754583
Observations	146

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	10	727.1323782	72.71323782	386.4784919	3.99261E-94
Residual	135	25.39931021	0.188143039		
Total	145	752.5316884			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	5.569514221	1.242129261	4.483844312	1.55155E-05	3.112965514	8.026062928	3.112965514	8.026062928
EFFLAND	0.072153754	0.096717422	0.746026435	0.45694853	-0.119123488	0.263430995	-0.119123488	0.263430995
MECH	0.204024696	0.047716076	4.27580627	3.57743E-05	0.10965701	0.298392383	0.10965701	0.298392383
FERT	0.322114633	0.098179993	3.280858183	0.001317111	0.127944878	0.516284387	0.127944878	0.516284387
IRRIGATE	0.340282396	0.0639677	5.319597193	4.20607E-07	0.213774008	0.466790784	0.213774008	0.466790784
LABOR	0.1409174	0.090994234	1.548640985	0.123809161	-0.03904114	0.32087594	-0.03904114	0.32087594
TMEAN	0.102461186	0.045754636	2.239361847	0.026768212	0.011972623	0.192949749	0.011972623	0.192949749
EPCP	0.035450693	0.023593484	1.502562898	0.135287388	-0.011209943	0.08211133	-0.011209943	0.08211133
APET	-0.172807112	0.128777309	-1.341906537	0.181878946	-0.427488925	0.0818747	-0.427488925	0.0818747
AMINRH	-0.111402765	0.151853345	-0.733620753	0.464452027	-0.411721863	0.188916332	-0.411721863	0.188916332
IGDD	-0.480680158	0.135540301	-3.54640026	0.000537458	-0.748737083	-0.212623233	-0.748737083	-0.212623233

Figure B-8: **Regression Summary: maize – scenario 2**

SUMMARY

Regression Statistics	
Multiple R	0.989337887
R Square	0.978789455
Adjusted R Sq	0.97605261
Standard Error	0.287817229
Observations	106

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	12	355.5117605	29.62598004	357.6342895	3.40452E-72
Residual	93	7.704004411	0.082838757		
Total	105	363.2157649			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	4.361322723	1.359206535	3.20872701	0.001829731	1.66221062	7.060434826	1.66221062	7.060434826
EFFNPP	0.374985349	0.075530735	4.964672314	3.10731E-06	0.224996428	0.524974269	0.224996428	0.524974269
MECH	0.088612297	0.04684951	1.891424203	0.061679843	-0.004421452	0.181646047	-0.004421452	0.181646047
FERT	0.363835576	0.074631435	4.875098247	4.46665E-06	0.215632486	0.512038666	0.215632486	0.512038666
IRRIGATE	0.16183628	0.055174635	2.93316448	0.0042246	0.052270499	0.271402062	0.052270499	0.271402062
LABOR	-0.027337871	0.074112315	-0.36887083	0.713062443	-0.174510092	0.11983435	-0.174510092	0.11983435
TMEAN	0.082845518	0.041239724	2.008876655	0.04744962	0.000951682	0.164739354	0.000951682	0.164739354
TMIN	-0.301669559	0.247712629	-1.217820663	0.226372942	-0.793577255	0.190238138	-0.793577255	0.190238138
EPCP	0.078194034	0.028988094	2.6974534	0.008296578	0.020629481	0.135758586	0.020629481	0.135758586
EPCPN	0.034448103	0.065955541	0.522292783	0.602708397	-0.096526399	0.165422605	-0.096526399	0.165422605
APET	0.073928608	0.085303383	0.866655051	0.388361539	-0.095466835	0.243324051	-0.095466835	0.243324051
AMINRH	-0.802739595	0.270400641	-2.968704482	0.003803245	-1.339701142	-0.265778049	-1.339701142	-0.265778049
IGDD	-0.138714766	0.143506494	-0.966609676	0.336246156	-0.423689937	0.146260405	-0.423689937	0.146260405

Figure B-9: **Regression Summary: soybean – scenario 2**

SUMMARY

Regression Statistics	
Multiple R	0.956561162
R Square	0.915009256
Adjusted R Sq	0.90621711
Standard Error	0.572848375
Observations	129

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	12	409.8181759	34.15151466	104.0712089	3.63909E-56
Residual	116	38.06601023	0.328155261		
Total	128	447.8841861			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	6.358853589	2.48904055	2.554740858	0.011921454	1.428998143	11.28870903	1.428998143	11.28870903
EFFLAND	0.151061952	0.074339071	2.032066711	0.044431247	0.003824144	0.298299761	0.003824144	0.298299761
MECH	-0.00106	0.071003948	-0.014928745	0.988114673	-0.141692181	0.139572181	-0.141692181	0.139572181
FERT	0.589463308	0.085530095	6.891881862	3.04409E-10	0.420060281	0.758866334	0.420060281	0.758866334
IRRIGATE	0.106486634	0.054874329	1.940554647	0.054738871	-0.002198823	0.215172091	-0.002198823	0.215172091
LABOR	0.012821483	0.070577257	0.181665936	0.856161963	-0.126965582	0.152608548	-0.126965582	0.152608548
TMEAN	0.375716806	0.166837192	2.251996698	0.026204365	0.045274925	0.706158686	0.045274925	0.706158686
TMIN	-0.505519954	0.572664451	-0.882750715	0.379196674	-1.639753368	0.628713461	-1.639753368	0.628713461
EPCP	0.057525371	0.033201239	1.732627248	0.085819662	-0.008233826	0.123284569	-0.008233826	0.123284569
EPCPN	-0.148087203	0.121844809	-1.215375564	0.226690726	-0.389416053	0.093241647	-0.389416053	0.093241647
APET	-0.296187227	0.260192981	-1.13833673	0.257325459	-0.811531899	0.219157444	-0.811531899	0.219157444
AMINRH	0.293314244	0.472001081	0.62142706	0.535537988	-0.641542803	1.228171291	-0.641542803	1.228171291
IGDD	-0.657539089	0.350881054	-1.873965782	0.063451203	-1.352502807	0.037424629	-1.352502807	0.037424629

Figure B-10: **Regression Summary: potato – scenario 2**

SUMMARY

Regression Statistics	
Multiple R	0.98457125
R Square	0.969380546
Adjusted R Sq	0.965057799
Standard Error	0.380593071
Observations	98

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	12	389.7961385	32.48301154	224.2510739	6.29169E-59
Residual	85	12.31234229	0.144851086		
Total	97	402.1084808			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-2.345432509	1.452057968	-1.61524716	0.109963238	-5.232514505	0.541649487	-5.232514505	0.541649487
EFFLAND	0.645849667	0.123786763	5.217437232	1.26232E-06	0.39972827	0.891971063	0.39972827	0.891971063
MECH	0.246638541	0.070005724	3.523119647	0.000689073	0.107448323	0.385828758	0.107448323	0.385828758
FERT	0.269383723	0.105427989	2.555144271	0.012394765	0.059764509	0.479002938	0.059764509	0.479002938
IRRIGATE	0.196448866	0.098404938	1.996331375	0.049098667	0.000793367	0.392104365	0.000793367	0.392104365
LABOR	-0.238165412	0.104135282	-2.287077031	0.024676198	-0.445214376	-0.031116448	-0.445214376	-0.031116448
TMEAN	0.228022666	0.101195298	2.253293096	0.026814972	0.026819182	0.42922615	0.026819182	0.42922615
TMIN	0.455226629	0.428842801	1.061523309	0.291458964	-0.397428263	1.307881522	-0.397428263	1.307881522
EPCP	0.026591421	0.022476202	1.183092304	0.240071079	-0.018097316	0.071280159	-0.018097316	0.071280159
EPCPN	0.045273465	0.045418482	0.996807095	0.32168742	-0.045030699	0.135577629	-0.045030699	0.135577629
APET	0.099970715	0.256345877	0.389983706	0.697524115	-0.409713873	0.609655303	-0.409713873	0.609655303
AMINRH	-0.156834932	0.434849304	-0.360665019	0.719244645	-1.021432368	0.707762503	-1.021432368	0.707762503
IGDD	-0.208429138	0.320320676	-0.650688994	0.517002341	-0.845312842	0.428454565	-0.845312842	0.428454565

B.3 Scenario 3

Figure B-11: **Regression Summary: rice – scenario 3**

SUMMARY

Regression Statistics	
Multiple R	0.995495941
R Square	0.991012169
Adjusted R Sq	0.990360877
Standard Error	0.247562479
Observations	149

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	10	932.5515325	93.25515325	1521.609443	6.6608E-136
Residual	138	8.457630969	0.061287181		
Total	148	941.0091635			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	2.200158785	0.587088114	3.747578482	0.000261643	1.039306435	3.361011135	1.039306435	3.361011135
EFFLAND	0.590522336	0.067093619	8.801467983	4.97199E-15	0.457857778	0.723186893	0.457857778	0.723186893
MECH	0.086038378	0.028658675	3.002175766	0.003182907	0.029371434	0.142705323	0.029371434	0.142705323
FERT	0.044236079	0.049669539	0.890607803	0.374689679	-0.053975756	0.142447915	-0.053975756	0.142447915
IRRIGATE	0.098092892	0.03967613	2.472340194	0.01463892	0.019641075	0.176544709	0.019641075	0.176544709
LABOR	0.114632535	0.05305281	2.160725022	0.032442966	0.00973094	0.21953413	0.00973094	0.21953413
TMEAN	0.033283406	0.02346849	1.418216772	0.158381751	-0.01312096	0.079687771	-0.01312096	0.079687771
EPCP	0.07747578	0.021640438	3.58013921	0.000474672	0.034686031	0.120265529	0.034686031	0.120265529
APET	-0.071059529	0.072329477	-0.982442175	0.327601332	-0.214076976	0.071957919	-0.214076976	0.071957919
AMINRH	-0.882022844	0.162423764	-5.430380509	2.46316E-07	-1.203184189	-0.560861499	-1.203184189	-0.560861499
IGDD	-0.080251734	0.031120751	-2.578721012	0.010963913	-0.141786955	-0.018716513	-0.141786955	-0.018716513

Figure B-12: **Regression Summary: wheat – scenario 3**

SUMMARY

Regression Statistics	
Multiple R	0.98291794
R Square	0.966127676
Adjusted R Sq	0.963618615
Standard Error	0.434528241
Observations	146

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	10	727.0416914	72.70416914	385.0554726	5.07603E-94
Residual	135	25.48999698	0.188814792		
Total	145	752.5316884			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.000%*	*Upper 95.000%*
Intercept	5.975961828	1.107948005	5.393720465	2.99962E-07	3.784782275	8.16714138	3.784782275	8.16714138
EFFLAND	0.028093241	0.103077612	0.272544546	0.785619775	-0.175762494	0.231948976	-0.175762494	0.231948976
MECH	0.211993519	0.047244661	4.487142363	1.53081E-05	0.118558146	0.305428892	0.118558146	0.305428892
FERT	0.325757968	0.101293729	3.215973705	0.001627092	0.125430203	0.526085733	0.125430203	0.526085733
IRRIGATE	0.338641912	0.064065806	5.285844841	4.90149E-07	0.2119395	0.465344324	0.2119395	0.465344324
LABOR	0.17161526	0.086258465	1.989546882	0.048661594	0.001022611	0.342207909	0.001022611	0.342207909
TMEAN	0.106622011	0.045682496	2.333979555	0.021072983	0.016276119	0.196967902	0.016276119	0.196967902
EPCP	0.034838197	0.023741979	1.467366979	0.144602104	-0.012116119	0.081792512	-0.012116119	0.081792512
APET	-0.178049375	0.129149611	-1.378628812	0.17028943	-0.433467487	0.077368737	-0.433467487	0.077368737
AMINRH	-0.088359732	0.154227486	-0.572918186	0.567653109	-0.393374149	0.216654685	-0.393374149	0.216654685
IGDD	-0.50706143	0.131702017	-3.850065806	0.000181576	-0.767527413	-0.246595448	-0.767527413	-0.246595448

Figure B-13: **Regression Summary: maize – scenario 3**

SUMMARY

Regression Statistics	
Multiple R	0.989652339
R Square	0.979411752
Adjusted R Sq	0.976755204
Standard Error	0.283563654
Observations	106

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	12	355.7377888	29.64481573	368.6783438	8.5516E-73
Residual	93	7.477976153	0.080408346		
Total	105	363.2157649			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	4.02407318	1.352852015	2.974510986	0.003738212	1.337579884	6.710566477	1.337579884	6.710566477
EFFLAND	0.458981194	0.086425057	5.310742157	7.41458E-07	0.28735833	0.630604057	0.28735833	0.630604057
MECH	0.083794043	0.046164873	1.815103945	0.072731219	-0.007880154	0.175468239	-0.007880154	0.175468239
FERT	0.298928044	0.073391608	4.073054827	9.74892E-05	0.153187001	0.444669087	0.153187001	0.444669087
IRRIGATE	0.154834139	0.054418349	2.84525612	0.005458206	0.046770192	0.262898086	0.046770192	0.262898086
LABOR	-0.027793117	0.070947622	-0.391741348	0.69614554	-0.168680894	0.113094659	-0.168680894	0.113094659
TMEAN	0.077060689	0.040768185	1.890216337	0.061843075	-0.003896765	0.158018144	-0.003896765	0.158018144
TMIN	-0.382665767	0.242238002	-1.57970989	0.117568685	-0.863701948	0.098370415	-0.863701948	0.098370415
EPCP	0.076427487	0.028559539	2.676075656	0.008803436	0.01971396	0.133141015	0.01971396	0.133141015
EPCPN	-0.009719123	0.066041267	-0.147167416	0.883318453	-0.140863859	0.121425614	-0.140863859	0.121425614
APET	0.07925992	0.084098976	0.942459987	0.348399015	-0.087743813	0.246263653	-0.087743813	0.246263653
AMINRH	-0.758603708	0.265562619	-2.856590694	0.005282421	-1.285957911	-0.231249504	-1.285957911	-0.231249504
IGDD	-0.133979394	0.141402166	-0.947505954	0.345836562	-0.414775792	0.146817003	-0.414775792	0.146817003

Figure B-14: **Regression Summary: soybean – scenario 3**

SUMMARY

Regression Statistics	
Multiple R	0.95677988
R Square	0.915427738
Adjusted R Sq	0.906678883
Standard Error	0.571436323
Observations	129

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	12	410.0056074	34.16713395	104.6340088	2.73926E-56
Residual	116	37.87857871	0.326539472		
Total	128	447.8841861			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	6.630719791	2.459076799	2.696426477	0.008052436	1.760211292	11.50122829	1.760211292	11.50122829
EFFLAND	0.170207472	0.078313474	2.173412345	0.031781798	0.015097862	0.325317081	0.015097862	0.325317081
MECH	-0.009728005	0.071719027	-0.135640505	0.892340584	-0.151776489	0.132320479	-0.151776489	0.132320479
FERT	0.579990672	0.08507704	6.817240814	4.41353E-10	0.411484976	0.748496369	0.411484976	0.748496369
IRRIGATE	0.10945737	0.054621945	2.003908315	0.047410084	0.001271791	0.21764295	0.001271791	0.21764295
LABOR	0.0080243	0.070431747	0.113930161	0.909490111	-0.131474565	0.147523165	-0.131474565	0.147523165
TMEAN	0.373982174	0.166397696	2.247520152	0.02649739	0.044410771	0.703553577	0.044410771	0.703553577
TMIN	-0.579423938	0.572726078	-1.0116947	0.313789666	-1.713779414	0.554931538	-1.713779414	0.554931538
EPCP	0.057774322	0.033093722	1.745778906	0.083497003	-0.007771925	0.123320569	-0.007771925	0.123320569
EPCPN	-0.16704572	0.123786889	-1.349462142	0.17981644	-0.412221102	0.078129662	-0.412221102	0.078129662
APET	-0.302274039	0.259511138	-1.164782527	0.246496827	-0.816268236	0.211720158	-0.816268236	0.211720158
AMINRH	0.358868061	0.474526865	0.756265004	0.45102346	-0.580991616	1.298727739	-0.580991616	1.298727739
IGDD	-0.693125368	0.349743178	-1.981812404	0.049865171	-1.38583538	-0.000415356	-1.38583538	-0.000415356

Figure B-15: **Regression Summary: potato – scenario 3**

SUMMARY

Regression Statistics	
Multiple R	0.984873197
R Square	0.969975214
Adjusted R Sq	0.965736421
Standard Error	0.376879151
Observations	98

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	12	390.0352598	32.50293831	228.8328652	2.74203E-59
Residual	85	12.07322102	0.142037894		
Total	97	402.1084808			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.000%*	*Upper 95.000%*
Intercept	-1.422237003	1.338861456	-1.062273468	0.291120351	-4.084253872	1.239779867	-4.084253872	1.239779867
EFFLAND	0.676142042	0.124605522	5.426260644	5.33832E-07	0.428392732	0.923891352	0.428392732	0.923891352
MECH	0.24626029	0.068951459	3.571502214	0.000587311	0.109166233	0.383354346	0.109166233	0.383354346
FERT	0.175098589	0.108913253	1.607688539	0.111611857	-0.041450268	0.391647446	-0.041450268	0.391647446
IRRIGATE	0.234499761	0.096918457	2.419557309	0.017671353	0.041799787	0.427199734	0.041799787	0.427199734
LABOR	-0.214115425	0.099449641	-2.153003494	0.034151751	-0.411848074	-0.016382776	-0.411848074	-0.016382776
TMEAN	0.2284398	0.100157691	2.280801379	0.025061735	0.029299357	0.427580242	0.029299357	0.427580242
TMIN	0.134960725	0.440965519	0.30605732	0.76030937	-0.741797393	1.011718843	-0.741797393	1.011718843
EPCP	0.0335762	0.022237311	1.509903805	0.134776516	-0.010637558	0.077789957	-0.010637558	0.077789957
EPCPN	0.035887021	0.045072882	0.796199829	0.428134011	-0.053729998	0.12550404	-0.053729998	0.12550404
APET	0.055935442	0.25185842	0.222090817	0.824775931	-0.444826873	0.556697758	-0.444826873	0.556697758
AMINRH	0.042307219	0.413836413	0.102231746	0.918813521	-0.780510936	0.865125374	-0.780510936	0.865125374
IGDD	-0.318089549	0.308340327	-1.031618383	0.305177345	-0.931153095	0.294973996	-0.931153095	0.294973996

Appendix C

The Residual Plots

C.1 Residual Plots

The following series of graphs are the residual plots for maize in scenario 1 for the purpose of resdiual checks.

Figure C-1: **Effective Land vs. Residuals**

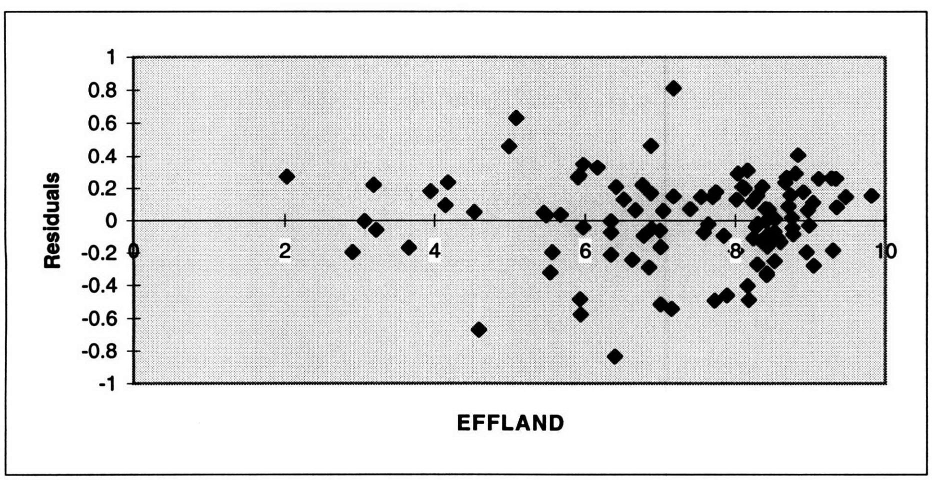


Figure C-2: **Mechanization vs. Residuals**

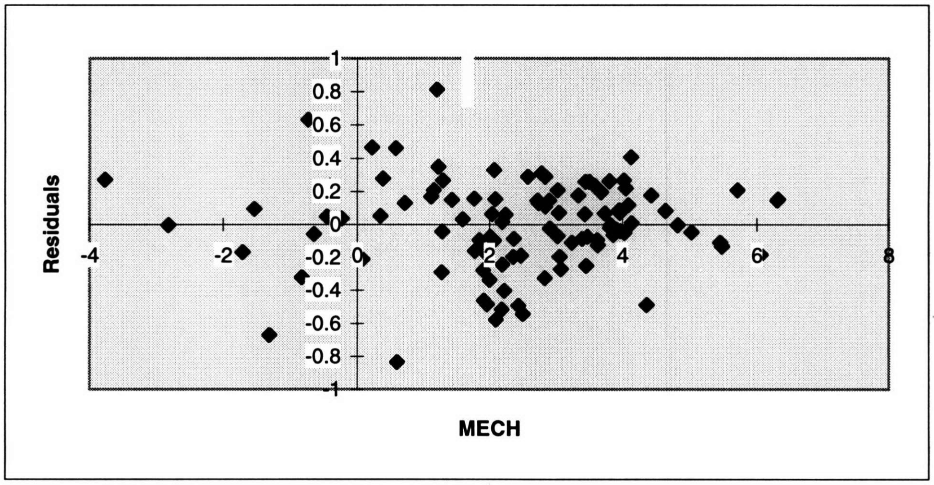


Figure C-3: **Fertilization vs. Residuals**

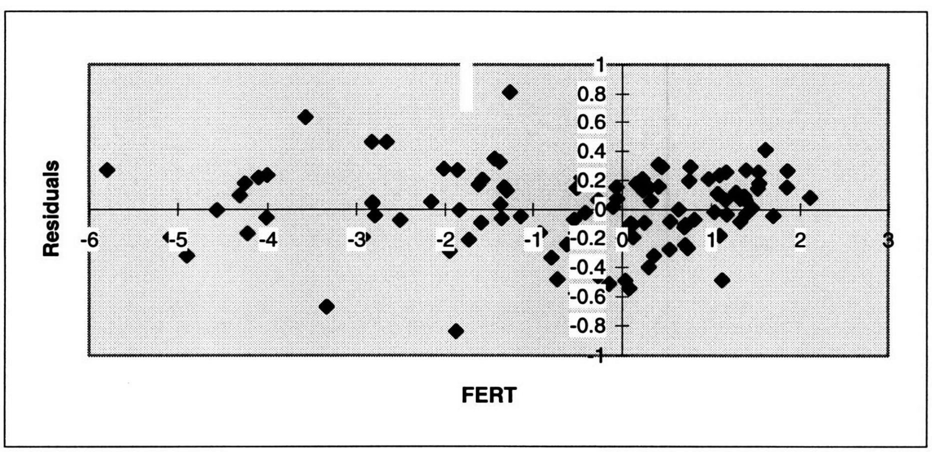


Figure C-4: **Irrigation vs. Residuals**

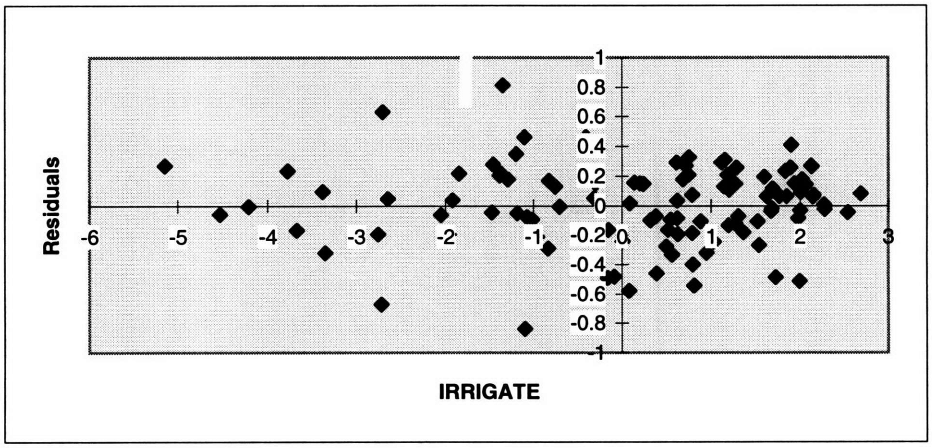


Figure C-5: **Labor Force vs. Residuals**

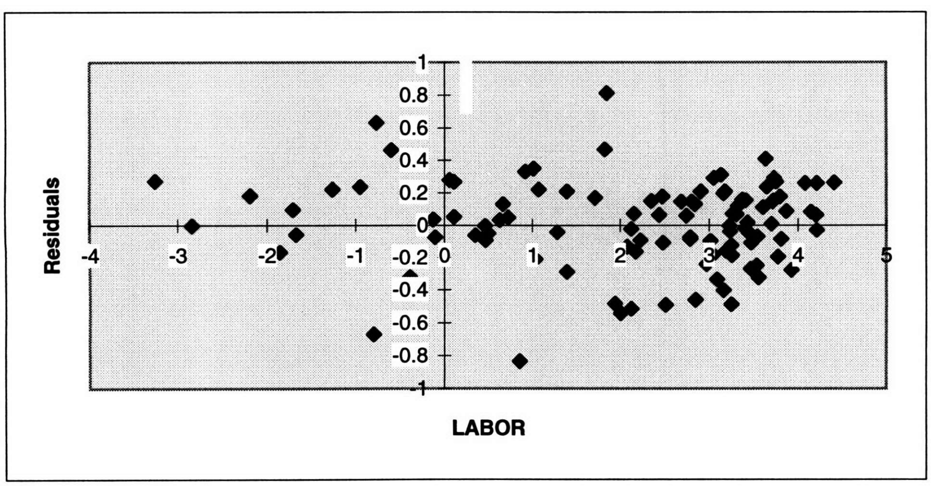


Figure C-6: **Mean Temperature vs. Residuals**

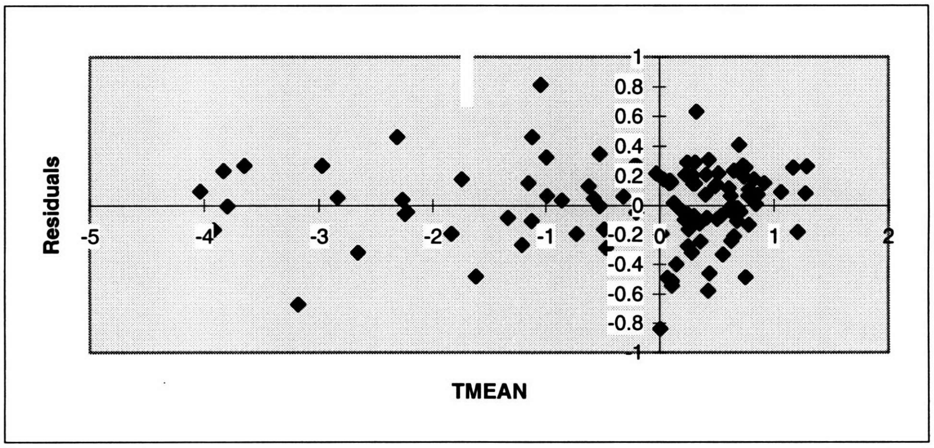


Figure C-7: **Average Minimum Temperature vs. Residuals**

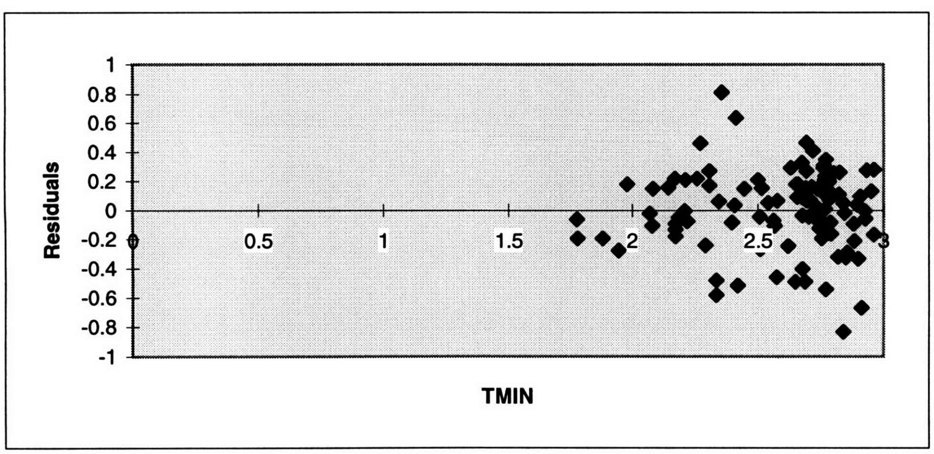


Figure C-8: **Total Precipitation in Growing Season vs. Residuals**

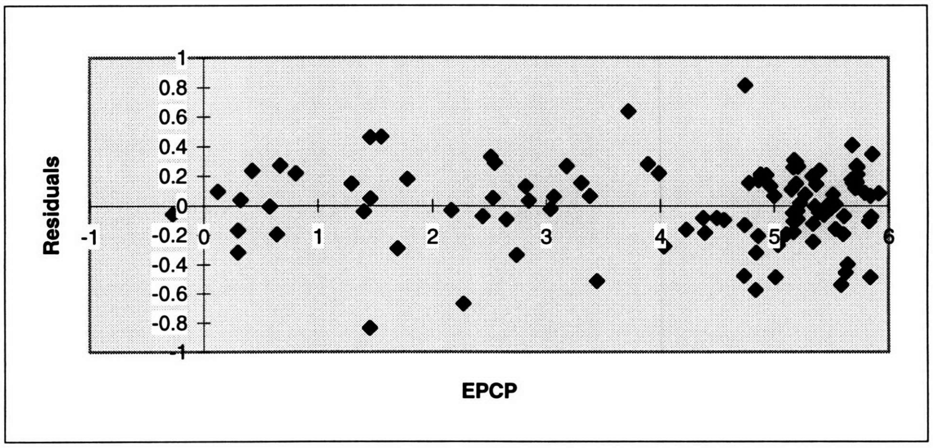


Figure C-9: **Total Precipitation in Non-growing Season vs. Residuals**

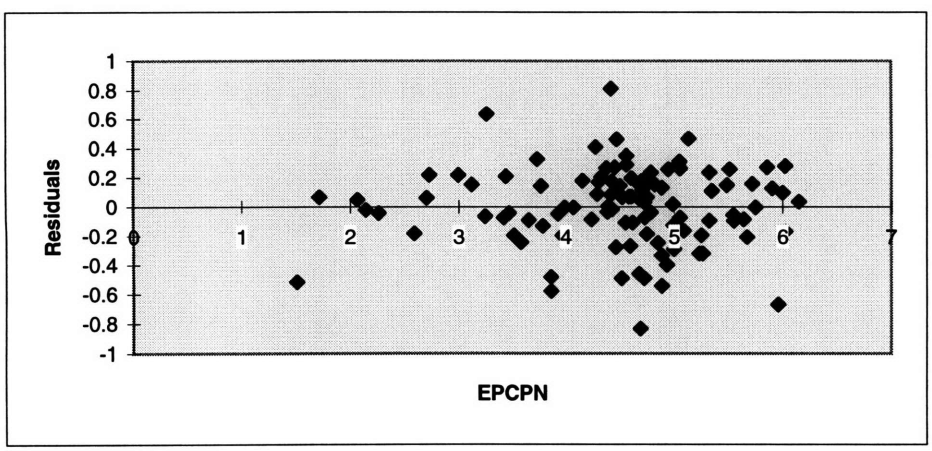


Figure C-10: **Evaportransportation vs. Residuals**

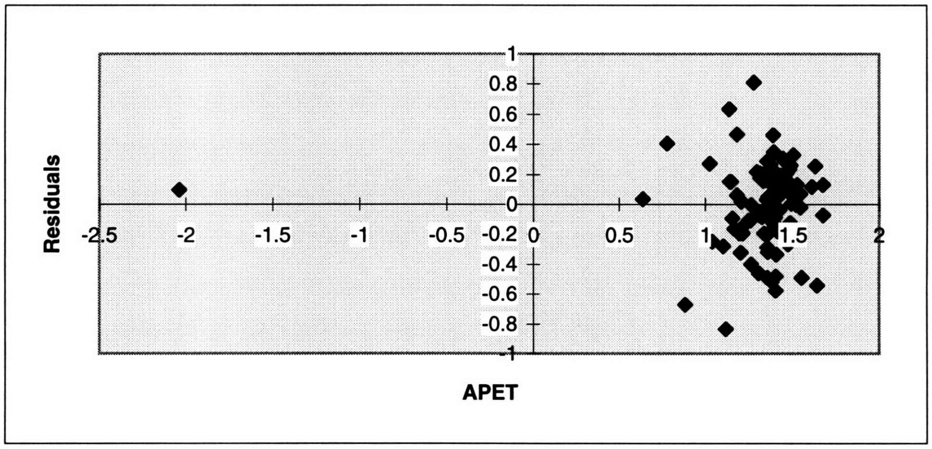


Figure C-11: **Humidity vs. Residuals**

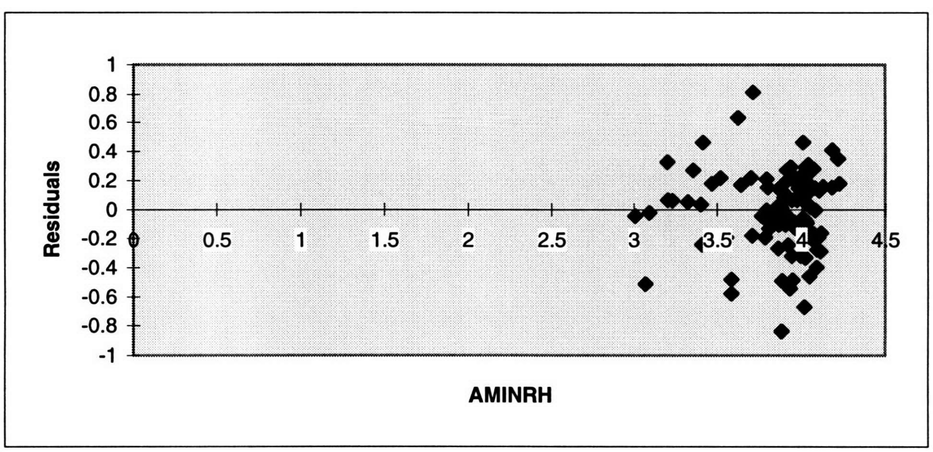
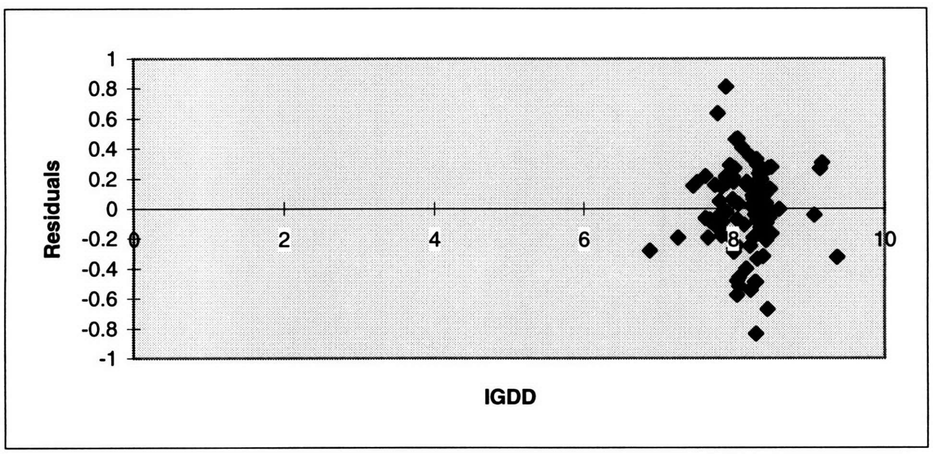


Figure C-12: **Total Growing Degree Days vs. Residuals**



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