The Economic Impact of Global Climate and Tropospheric Ozone on World Agricultural Production

by

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Submitted to the Engineering Systems Division and the Department of Civil and Environmental Engineering
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Abstract

The objective of my thesis is to analyze the economic impact on agriculture production from changes in climate and tropospheric ozone, and related policy interventions. The analysis makes use of the Emissions Prediction and Policy Analysis (EPPA) model, a computable general equilibrium model of the world economy and crop yield results from the Terrestrial Ecosystem Model (TEM), a biogeochemical model of terrestrial vegetation. I disaggregated the original EPPA model to capture the dynamic behaviors of crops, livestock and forestry within the agriculture sector. Further calibration was done to validate projections on future food shares according to Engel's Law. Results from AIDADS (An Implicit Direct Additive Demand System) were used to adjust the model, as the EPPA Agriculture Model was implemented using CES (Constant Elasticity of Substitution) consumption function that, other things equal, keeps the food share constant as income grows.

My research shows that the direct effects of environmental change on yields are substantially moderated in terms of production effects as a result of crop sector adaptations and reallocation of resources within the economy. However, costs (or benefits) resulting from reallocation of resources show up as losses (or gains) in aggregate economic consumption.

The findings also uncover additional benefits of policies that impose greenhouse gas emissions constraints as they mitigate damages from ozone pollutions. For example, in 2005 the consumption loss due to ozone damage is estimated to be 7.4 billions (5% of the value of crop production) for the United States, 16.5 billions (8.4%) for the European Union, and 17.8 billions (9.8%) for China. In a scenario where greenhouse gas emissions are controlled, the consumption loss is reduced by 28%, 33%, and 23% for the US, the EU and China by 2050, respectively. Therefore, ozone pollution policy and climate policy (because it reduces ozone precursor emissions) are both effective in reducing ozone damages considerably.

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Chapter 1: Introduction

Climate and agriculture are interconnected in a number of ways: climate directly affects agricultural yields through changes in temperature and precipitation, while agricultural activities contribute to emissions of greenhouse gases. The objective of my thesis is to analyze how global climate and tropospheric ozone impact agriculture in economic terms. However, before presenting the economic analysis, it is important to understand how climate and agriculture interact, as greenhouse gases are believed to be responsible for much of the global warming observed in the past century. In this section I review recent findings on various connections between climate and agriculture.

1.1 Climate and Agriculture

Global climate changes constantly, yet the global temperature increase in the past century has been unprecedented in the instrumental record. It is very likely that the 1990s was the warmest decade and 1998 the warmest year since 1861 (IPCC, 2001). This temperature increase has caused a reduction of snow packs in northern latitudes, the melting of mountain glaciers, and a shrinking of the polar ice caps. It also allows more moisture to stay in the atmosphere, causing more climate variability, more severe storms, and shifts in weather pattern

Agriculture is one of the economic sectors that remains heavily depend on climate. Any significant climate change will have profound impact on agriculture, in both positive and negative ways. Currently agriculture still accounts for a large share of human use of land. In 1999, pasture and crops alone took up 37 percent of the earth’s land area, while over two thirds of human water use is for agriculture (FAO 2003). Previous research suggests that as the temperature rises in high latitudes, the areas suitable for cropping will expand, the length of the growing period will increase, and the cost of overwintering livestock will fall, therefore improving the agricultural economies for countries in temperate latitudes (FAO, 2002).

On the other hand, climate variability in the past has caused major damages on agricultural production world wide, as reported by the Food and Agriculture Organization (2003). As the temperature increases in regions that are well watered—such as the tropics—evaporation will increase, leading to lower soil moisture levels. There has been evidence suggesting that the unusual warming conditions may have contributed to persistent droughts in North America, Europe, and Asia between 1998 and 2002 (Hoerling and Kumar, 2003). The cultivated areas in these regions have become unsuitable for cropping and some tropical grassland may become increasingly arid.

Furthermore, the climate may become more variable, which could bring greater fluctuations in crop yields and higher risks of landslides and erosion damage. The example of the El Niňo-Southern Oscillation (ENSO) phenomenon perfectly illustrates the consequences of climate variability. ENSO refers to the shift in surface air pressure at Darwin, Australia and the South pacific Island of Tahiti, with extreme phases of warming and cooling of the eastern tropical Pacific. Reilly *et al.* found that even with improved forecasts of ENSO if the frequency and intensity of these events increased, they would cause an annual average agricultural loss of $464 million due to agricultural impacts in the United States that could not be avoided even with adaptations (2003).

1.2 Interactions between Greenhouse Gases and Agriculture Sectors

The Intergovernmental Panel on Climate Change (IPCC) has concluded that anthropogenic emissions and accumulations of greenhouse gases are most likely responsible for much of the global temperature increase observed in the past 100 years (2001). The primary greenhouse gases include carbon dioxide, methane, nitrous oxide, ozone in the troposphere, and water vapor. These gases absorb the infrared radiation emitted by the Earth and emit certain amount of infrared radiation back to Earth, which causes the temperature on the Earth's surface to rise. According to a recent IPCC Report, *Climate Change 2001*, the levels of concentration of the greenhouse gases have increased substantially (2001a). Specifically:

- The atmospheric concentration of carbon dioxide (CO_2) has increased by 31% since 1750. The present carbon dioxide concentration has not been exceeded during the past 420,000 years and likely not during the past 20 million.
- The atmospheric concentration of methane (CH_4) has increased by 151% since 1750 and continues to increase. The present methane concentration has not been exceeded during the past 420,000 years.
- The atmospheric concentration of nitrous oxide (N_2O) has increased by 17% since 1750 and continues to increase. The present nitrous oxide concentration has not been exceeded during at least the past thousand years.
- The total amount of ozone (O_3) in the troposphere is estimate to have increased by 36% since 1750.

Although human activities – mainly deforestation and the combustion of fossil fuels are releasing large quantities of greenhouse gases (CBO, 2003), human activities are thought to not have a direct effect on water vapor that is important on the global scale. Changes in land cover and irrigation can have local to regional effects on climate. The bigger concern is that water vapor is indirectly increased as a result of the initial effects of greenhouse gases from human activities, creating a positive feedback and more warming than otherwise would be the case.

1.2.1 Agriculture as a Source of Greenhouse Gases

Agricultural activities and associated land use have contributed significantly to past changes in atmospheric composition (Table 1). In some cases, agricultural activities account for up to 50% of annual emissions for certain greenhouse gases. The three main sectors within agriculture – crops, livestock, and forestry –contribute to greenhouse gases accumulation differently, so they will be explained separately.

Table 1: Land use as sources of greenhouse gases (Ciesla, 1995)

Principal Greenhouse Gasses

Greenhouse Gasses	Importance to Climate Change	Land Use Related Sources of Greenhouse Gases
carbon dioxide	very high	mostly produced by deforestation and forest fires
methane	moderate	generated by livestock waste, ruminant digestion, decomposition of wetlands, Rice paddies, burning of biomass
nitrous oxide	moderate	caused by deforestation, burning of other biomass, and application of nitrogen fertilizer
carbon monoxide	moderate	comes from the incomplete burning of pasture and grasslands

Crops: Irrigated rice farming is one of the main agricultural sources of methane—accounting for almost a fifth of annual anthropogenic methane emissions. Methane is a relatively short-lived gas that is about 20 times more powerful than carbon dioxide in its warming action. Crops are also key sources of nitrous oxide. Nitrous oxide emissions result from volatilization of nitrogen in inorganic nitrogen fertilizers and in, crop residues and animal wastes. Ammonia, one form of nitrogen fertilizer, also produced from biomass burning, is responsible for 34% of annual global ammonia emission. Ammonia is a source nitrous oxide and contributes to acid rain as well (FAO, 2002).

Livestock: Livestock activities such as enteric fermentation and manure handling practices account for roughly a quarter of annual methane emission (USDA, 2004). Livestock also accounts for 40% of annual global ammonia emission (FAO, 2003).

Forestry: Net deforestation accounts for a quarter of the global anthropogenic emissions of carbon dioxide to the atmosphere during the past 20 years making it the human activity that emits second highest amount of carbon dioxide after fossil fueling burning (IPCC, 2001).

1.2.2 Agriculture as a Sink for Greenhouse Gases

The major natural terrestrial sink for greenhouse gases is forestry. As trees and other vegetations grow, they absorb carbon dioxide from the air. A forest continues absorbing carbon dioxide until trees reach full maturity; the forestry then becomes a carbon reservoir, as long as they are not disturbed by human activities (land clearing) or natural processes (forest fires). Climate change and other environmental changes are, themselves, disturbances to which the forest will gradually adapt. These disturbances may increase or decrease carbon stocks. For example, with rising CO_2 it is likely that different tree species, better suited to higher carbon dioxide levels, will come to predominate (USDA, 2004).

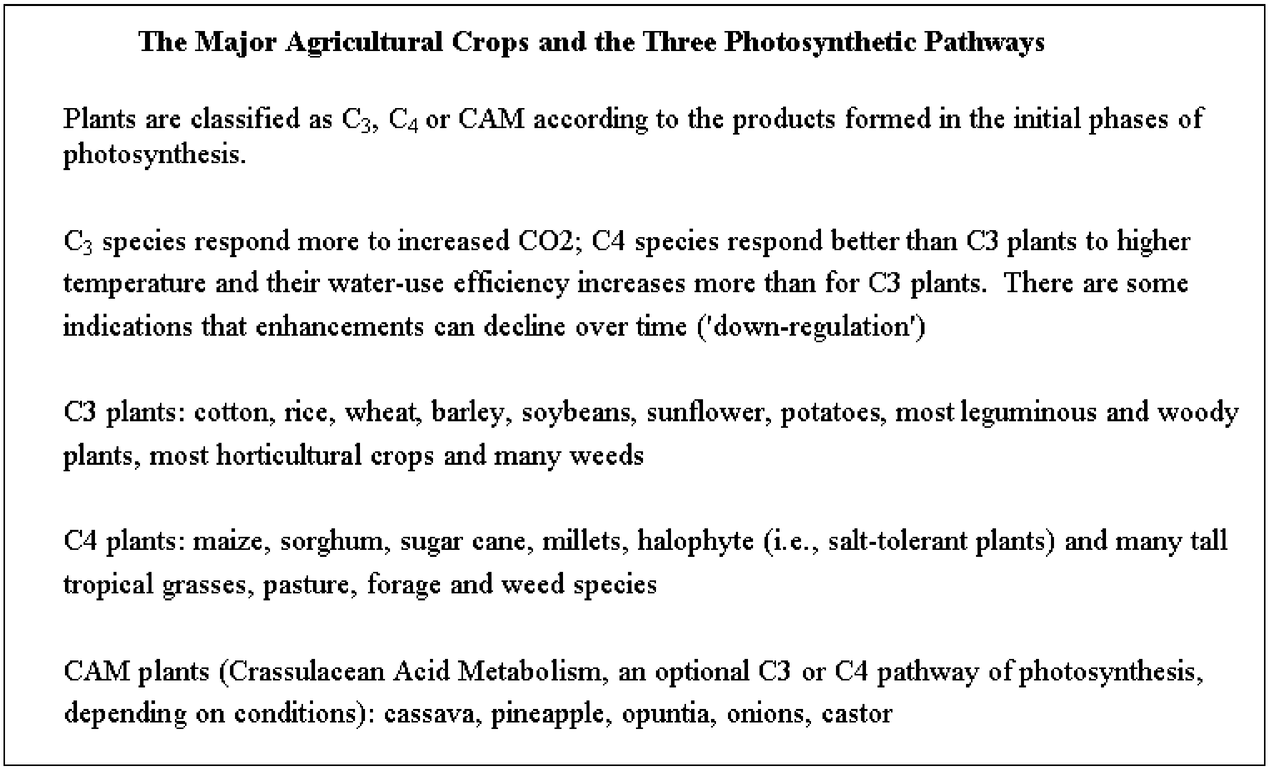
In addition to forestry, crops also function as carbon sinks by capturing atmospheric carbon as function of photosynthesis. However, because of the annual nature of the crops carbon is quickly returned to the atmosphere through the decomposition of vegetation or the burning of residues.

Cropping can create a more permanent sink for carbon, though the storage capacity is inherently limited. This occurs when residues are retained on the land, and carbon levels (soil organic matter) in soils are rebuilt. Once decomposition comes into balance with annual additions of carbon in vegetation, the land is fully saturated with carbon. This places some limits on the amount of carbon that can be stored in crop fields, as well as the rate of sequestration (FAO, 2003).

1.2.3 Impact of Greenhouse Gases on Agriculture

The relationship between agriculture and greenhouse gases is closely coupled. Greenhouse gases have a mixed impact on agriculture productivity—which complicates the issue of appropriate climate policy. Table 2 lists the effects of carbon dioxide on various types of crops from previous research (FAO, 1996). In general, higher concentration of atmospheric carbon dioxide due to increased use of fossil fuels, deforestation, and biomass burning may have a positive influence on the photosynthesis process of crops, strengthening the fertilization effect. Wolf and Erickson conclude that increased atmospheric carbon dioxide concentration also improves the efficiency in plants to consume water because of reduced transpiration (1993). This is induced by a contraction of plant stomata with the overabundance of carbon dioxide. The number of stomata per unit leaf area could also decrease, which is combined to restrict the escape of water vapor.

Table 2: Effects of carbon dioxide on crops



The Major Agricultural Crops and the Three Photosynthetic Pathways

Plants are classified as C_3, C_4 or CAM according to the products formed in the initial phases of photosynthesis.

C_3 species respond more to increased CO2; C4 species respond better than C3 plants to higher temperature and their water-use efficiency increases more than for C3 plants. There are some indications that enhancements can decline over time ('down-regulation')

C3 plants: cotton, rice, wheat, barley, soybeans, sunflower, potatoes, most leguminous and woody plants, most horticultural crops and many weeds

C4 plants: maize, sorghum, sugar cane, millets, halophyte (i.e., salt-tolerant plants) and many tall tropical grasses, pasture, forage and weed species

CAM plants (Crassulacean Acid Metabolism, an optional C3 or C4 pathway of photosynthesis, depending on conditions): cassava, pineapple, opuntia, onions, castor

On the other hand, tropospheric ozone has a negative impact on the growth of crops. Approximately half of tropospheric ozone originates from photochemical reactions involving nitrogen oxides, methane, carbon monoxide, and other substances. These gases are emitted through anthropogenic sources, mainly from combustion of fossil fuels but also, as discussed above, from some agricultural sources. The other half of the tropospheric ozone is produced from the downward movement of stratospheric ozone. High tropospheric ozone concentration has toxic effects on both plant and animal life. Exposure to tropospheric ozone leads to respiratory disorders for humans and animals, as well as the inhibition of crop growth (Mauzerall and Wang, 2001).

1.3 Policy Motivations

1.3.1 Food Policy

Climate affects agriculture, the major source of food consumed by human beings and animals. Climate shifts could cause land degradation, salinization, the over extraction of water and the reduction of genetic diversity in crops and livestock (FAO, 2002). The magnitude and geographical distribution of climate-induced changes may affect human's ability to expand food production in order to feed the growing population.

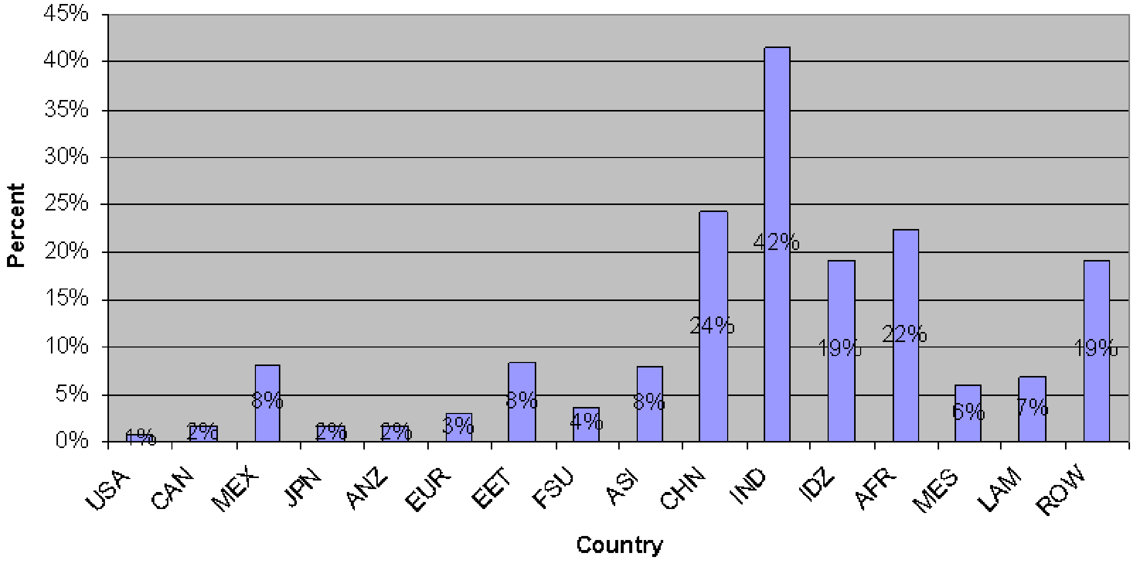
In addition to food production, consumption behavior might also shift in the future with unexpected consequences. Even though food demand has grown rapidly due to fast population growth, production of major food crops has kept up with that growth, and even exceeded it. The period known as the "Green Revolution" is responsible. This refers to the development of new varieties of crops in the 1950's and 1960's, particularly rice, that had higher yields and were able to make use of high levels of fertilizer applications. Yields have continued to increase in the 1980's and through to the present, as these varieties spread around the world and were further improved. More food became available and eased the fear of endemic famine in Asia (Rosegrant *et al*., 2001). At the same time, the consumption of meat in developed countries grew by the same proportion as consumption of cereals, whereas the consumption of meat in developing countries only grew by one fifth of the increased consumption of cereals. If the consumption patterns in developed countries are indicative of where developing countries are headed, future growth in cereal consumption is likely to be much smaller than that in meat, as the income level rises in developing countries. This may result in a “livestock revolution” (Delgado, 1999). Hence, there could be a significant switch in the importance of the crop sector and the livestock sector in the future.

1.3.2 Economic Policy

In many developing countries, the agricultural economies still contribute substantially to the final GDP (Gross Domestic Product) (Figure 1). However, greenhouse gases have aforementioned mixed effects on agricultural production. For example, countries that suffer from tropospheric ozone damage on crops may still benefit from elevated carbon dioxide level. Climate variability could induce an increase in agricultural production in high-latitude regions, but a decrease in tropical regions. This is a production pattern that could worsen the current imbalance of food production and welfare distribution, as many developing countries are located in the tropical and subtropical regions. In these developing countries, crop productivities may diminish due to climate or air pollution, which would in turn increase the dependency of developing countries on imports.

Furthermore, countries that benefit from climate change, or those that can adapt to the climate due to more advanced agricultural technologies could escalate the competition in the commodities market with increased agricultural production. The competition may lead to further declining prices in the market for several commodities. For example, the price of an agricultural commodity, robustra coffee, fell to US $0.5 per kg by January 2002, one fifth of what it was in the mid-1990s, when new countries such as Vietnam entered the market (FAO, 2002). Increases in the number and extent of extreme events (e.g., widespread drought in some years) could cause commodity prices to fluctuate widely.

Figure 1: Agricultural economies in final GDP



As a result, climate change will have far-reaching effects on patterns of trade among nations, influencing the economic welfare of producers and consumers. The economic impact of climate change and greenhouse gases on agricultural production becomes crucial to comprehend, not only because it is the backbone of the economy for many developing countries, but also because the dynamics could play an important role in addressing issues related to international trade.

1.3.3 Climate Policy

Forestry as a major natural sink for greenhouse gases is explicitly mentioned in the Kyoto Protocol. Under Article 2, section 1 (a) (ii) of the Kyoto Protocol, "each party included in Annex I[1], in achieving its quantified emission limitation and reduction commitments should implement and/or further elaborate policies and measures in accordance with its national circumstances, i.e. promotion of sustainable forest management practices, afforestation and reforestation." Therefore, any significant impact on the forestry will be closely monitored by the international community.

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[1] According to the United Nations Framework Convention on Climate Change, Annex I countries include developed countries and economies in transition.

In addition to the stated importance of forestry for developed countries that have ratified the Kyoto Protocol, developing countries are more interested in impacts of climate on agriculture, as they still heavily depend on the agricultural economy. This means that agriculture is central to these countries on any discussion about the need for climate policy. As summarized previously, major anthropogenic greenhouse emissions are almost always associated with agricultural activities. Developing countries such as India and China have ratified the Kyoto Protocol but have not agreed themselves to specific limits on their emissions. Yet emissions of greenhouse gases from agricultural activities in these countries are substantial. More sophisticated modeling for the emissions from these countries would be instrumental for future climate policies that might require the participation of major developing countries.

1.4 Structure of Thesis

This thesis consists of four sections, in addition to the introduction section. The first section outlines the framework of the EPPA Agriculture Model, which was developed based on the MIT Joint Program's Emissions Prediction and Policy Analysis (EPPA) Model version 4.0, with the original agriculture sector disaggregated into three sub-sectors: crops, livestock, and forestry, as well as an addition of a food processing sector separated from other industry. The disaggregation of the agriculture sector was motivated by the aforementioned vigorous interactions of the three sub-sectors with climate and greenhouse gases. Understanding the behavior of each sub-sector will provide more options for policy makers to create policies that target specific areas of interest within the agriculture sector.

The first section also describes further calibration of the EPPA Agriculture Model to better simulate Engel's Law, which states that the share of expenditure spent on food decreases as consumer's income increases. The economic derivation incorporates the recent development of An Implicit Direct Additive Demand System (AIDADS) that offers greater flexibility in modeling Engel's Law, which EPPA fails to capture as it is implemented using Constant Elasticity of Substitution production and consumption functions. The section is also supplemented with a comparison of results from other important agriculture models, i.e. the IMPACT model from International Food Policy Research Institute and the World Food Model

(WFM) from Food and Agriculture Organization (FAO) of United Nations. Because the EPPA Agriculture Model remains highly aggregated, it is useful to compare its behavior with other approaches and models.

The next section of the thesis analyzes the economic impact of the combined effects of climate, CO_2, and tropospheric ozone damage on agricultural production in the US, European Union and China, using the newly developed EPPA Agriculture Model. The analysis integrates results from the Terrestrial Ecosystem Model (TEM) developed by Marine Biology Lab on crops' net primary productivity in response to temperature, precipitation, ozone, carbon dioxide and other climatic conditions. The significant negative impact of tropospheric ozone on crop yields highlights the importance of pollution-control policies and the economic loss incurred from tropospheric ozone.

The third section investigates potential improvements on various policies related to agriculture, based on my findings. The scope of policy analysis includes implications on climate policies, stringency of air quality measurements, and the significance of adaptation technologies. Lastly, the conclusion section provides suggestions on what additional research should be done to further improve the model.

Chapter 2: Modeling Agriculture

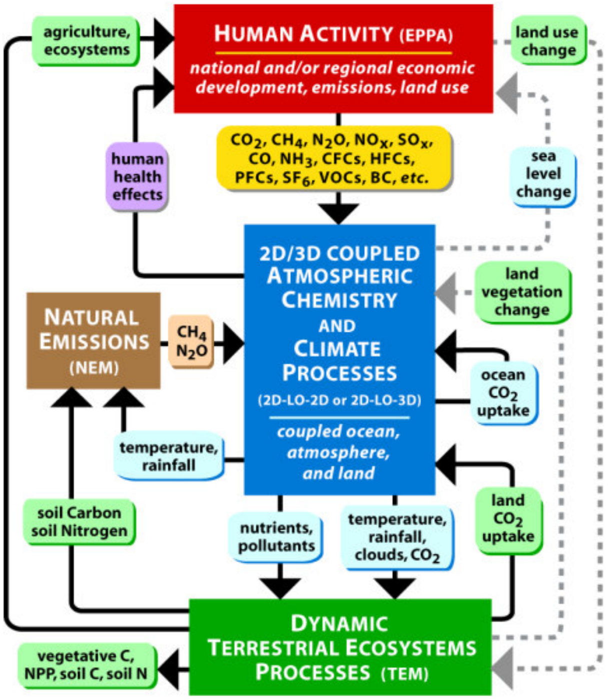
The basis of this thesis are results produced by the Emissions Predictions and Policy Analysis (EPPA) model constructed by the MIT Joint Program on the Science and Policy of Global Change, as part of MIT Integrated Global Systems Model (IGSM) (Prinn *et al.*, 1999). As noted previously, I have further disaggregated the agriculture (AGRI) sector in the most recent version of EPPA to model the dynamics of livestock, crops and forestry. Specifically, I have disaggregated the AGRI sector into livestock (LIVE), crops (CROP), forestry (FROS), and separated out a food-processing (FOOD) sector from the other industries products (OTHR) sector. Furthermore, I have incorporated data from the TEM Model for the impacts on crops productivity due to climate and ozone changes into my economic analysis. Because simulations of the MIT IGSM drives the TEM model, I thus begin with a brief overview of the entire MIT IGSM and the TEM model, then a description of the EPPA model, and finally adjustments made to the EPPA model.

2.1 MIT Integrated Global System Model

The MIT Integrated Global System Model (IGSM) (Prinn *et al.*, 1999) includes an economic systems component: the Emissions Prediction and Policy Analysis (EPPA) model, designed to project emissions of greenhouse gases (Babiker *et al.*, 2001) and economic impacts associated with climate policies. MIT IGSM also includes an earth systems component, a chemistry and climate model that comprises of a two-dimensional (2D) land-ocean resolving climate model (Sokolov & Stone, 1998), coupled to a 2D model of atmospheric chemistry (Wang *et al.*, 1998; Wang & Prinn, 1999; Mayer *et al.*, 2000), and a 2D or three-dimensional (3D) model of ocean circulations (Kamenkovich *et al.*, 2002).

The atmosphere-ocean- chemistry model further drives the TEM model of the Marine Biological Laboratory (Melillo *et al.*, 1993; Tian *et al.*, 1999; Xiao *et al.*, 1997, 1998), which simulates carbon and nitrogen dynamics of terrestrial ecosystems. TEM is a process-based model that uses spatially referenced information on climate, elevation, soils, vegetation and water availability as well as soil- and vegetation-specific parameters to describe carbon and nitrogen dynamics of plants and soils for terrestrial ecosystems of the globe, as described in Felzer *et al*. (2004). The integration of TEM into the MIT IGSM provides an important tool for directly analyzing the effect of climate and air pollution on agriculture (Figure 2).

Figure 2: MIT Integrated Global Systems Model

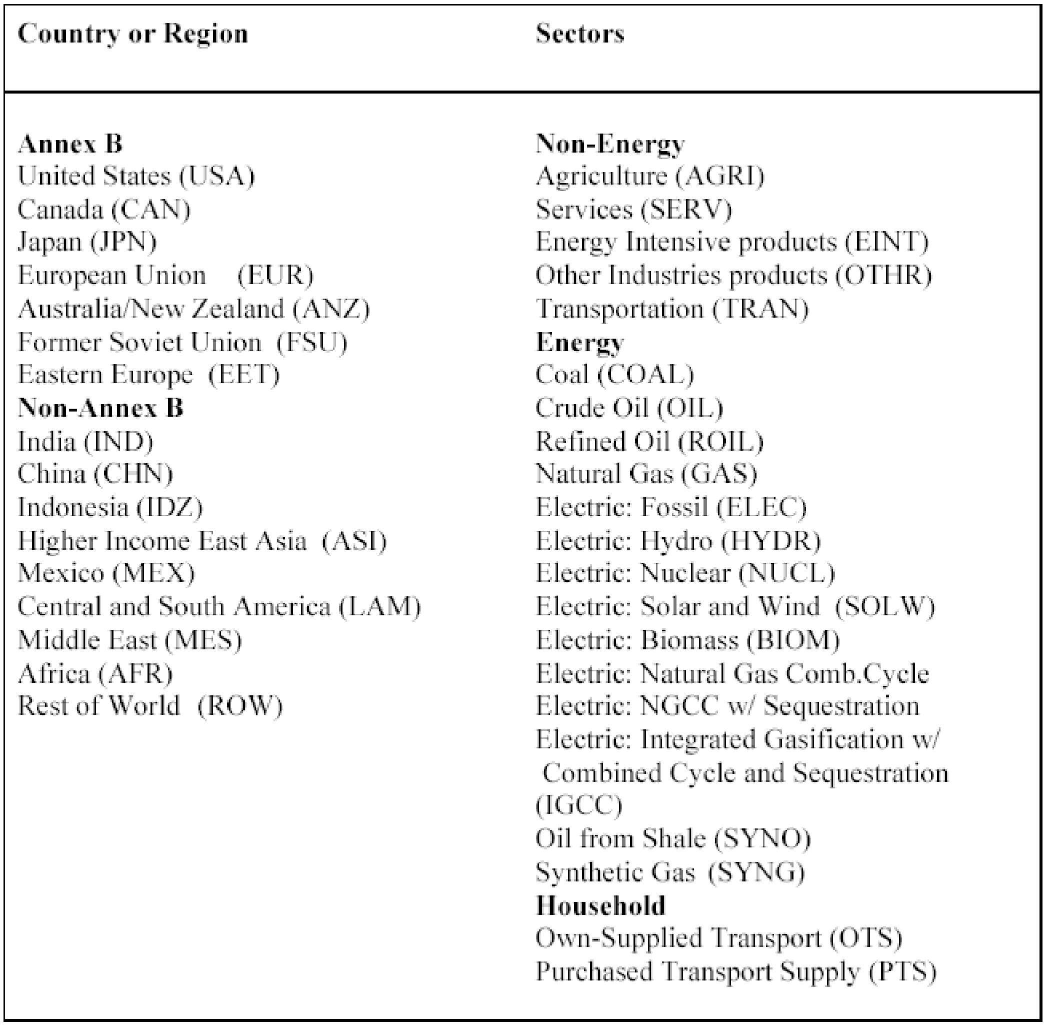


2.2 EPPA Model

The MIT Emissions Predictions and Policy Analysis (EPPA) model is a recursive-dynamic multi-regional computable general equilibrium (CGE) model of the world economy (Babiker *et al*., 2001), which is built on the economic and energy data from the GTAP dataset (Dimaranan & McDougall, 2002) and additional data for greenhouse gas and urban gas emissions. The model is used extensively to analyze economic growth and international trade, climate interactions (Reilly *et al*., 1999; Felzer *et al*., 2003b), and uncertainty issues involved in emissions and climate projections for climate models (Webster *et al*., 2002, 2003). The EPPA model is especially useful for understanding the effects of GHG emission restrictions on different markets and economies.

The most current version, EPPA 4, which incorporates sixteen regions and multiple sectors, includes additional disaggregated technologies and sectors and updated evaluation of economic growth and resource availability (Hyman *et al.*, 2003; McFarland *et al.*, 2004; Reilly *et al.*, 2003) with new GTAP 5 economic data (Table 3). The simulated time span for the model is 1997-2100. It solves for equilibrium levels of all inputs and outputs in each economic sector in all regions, the amount of inter-regional trade, and product and factor prices, and GHG emissions. The model also computes emissions of a number of other substances that are important for the atmospheric chemistry of the greenhouse gases, tropospheric ozone, and production of aerosols, i.e. carbon monoxide, nitrogen oxide, ammonia, non-methane volatile organic compounds, and black carbon.

Table 3: Countries, regions, and sectors in the EPPA model



Country or Region	Sectors
Annex B	**Non-Energy**
United States (USA)	Agriculture (AGRI)
Canada (CAN)	Services (SERV)
Japan (JPN)	Energy Intensive products (EINT)
European Union (EUR)	Other Industries products (OTHR)
Australia/New Zealand (ANZ)	Transportation (TRAN)
Former Soviet Union (FSU)	**Energy**
Eastern Europe (EET)	Coal (COAL)
Non-Annex B	Crude Oil (OIL)
India (IND)	Refined Oil (ROIL)
China (CHN)	Natural Gas (GAS)
Indonesia (IDZ)	Electric: Fossil (ELEC)
Higher Income East Asia (ASI)	Electric: Hydro (HYDR)
Mexico (MEX)	Electric: Nuclear (NUCL)
Central and South America (LAM)	Electric: Solar and Wind (SOLW)
Middle East (MES)	Electric: Biomass (BIOM)
Africa (AFR)	Electric: Natural Gas Comb.Cycle
Rest of World (ROW)	Electric: NGCC w/ Sequestration
	Electric: Integrated Gasification w/ Combined Cycle and Sequestration (IGCC)
	Oil from Shale (SYNO)
	Synthetic Gas (SYNG)
	Household
	Own-Supplied Transport (OTS)
	Purchased Transport Supply (PTS)

2.3 EPPA Agriculture Model

As noted above, in order to capture the dynamics within the agriculture I have disaggregated the agriculture sector to create three additional sectors: crops, livestock, and forestry, as well as a food-processing sector disaggregated from other industries products. Associated consumption and production structures are explained below.

2.3.1 Updating GHG Inventories

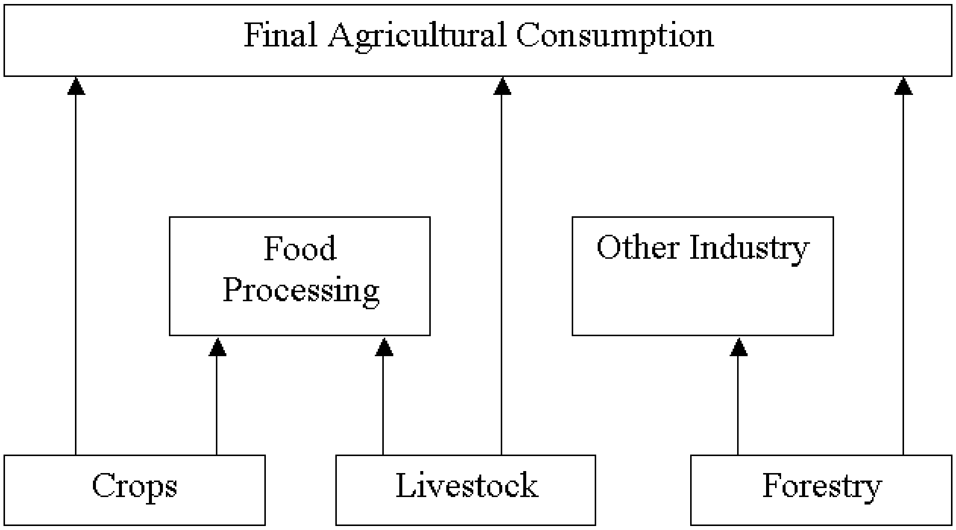
Since the agriculture sector is an aggregated sector in EPPA 4, disaggregation also entails readjustment of GHG inventories for inputs of the new EPPA Agriculture Model. This means that the current dataset used for emission prediction has to be updated to specify the appropriate sectors that the emission sources belong to. For example, the data we have obtained from EPA (Environmental Protection Agency) on methane emission contains emissions from enteric fermentation, livestock manure management, other agriculture sources, rice, and biomass combustion. These emission sources were grouped together originally for the agricultural sector in EPPA 4, but now are grouped in two different sectors, livestock and crops in the EPPA Agriculture Model.

By separating previously aggregated physical data in EPPA, we are able to simulate the characteristics of each sector more accurately. I can also examine the impacts of policies or regulations that only address a certain part of agriculture, therefore introducing more functionality into the model.

2.3.2 Agricultural Consumption Structure

The structure of final consumption changes because of the new sectors we have introduced. The new consumption structure is shown in Figure 3. Forestry continues to go into OTHR industry and directly into final consumption, while most of crops and livestock go into food processing first before consumption. In fact, especially for more developed countries, most crops, livestock and forestry products only get to final consumption after being processed. The food-processing sector is explicitly modeled in the EPPA Agriculture Model. At the same time, crops, livestock, and forestry products are sometimes purchased by the household sector directly. For instance, people living in developing countries would consume rice produced from their own farms.

Figure 3: New agricultural consumption pattern in the EPPA Agricultural Model



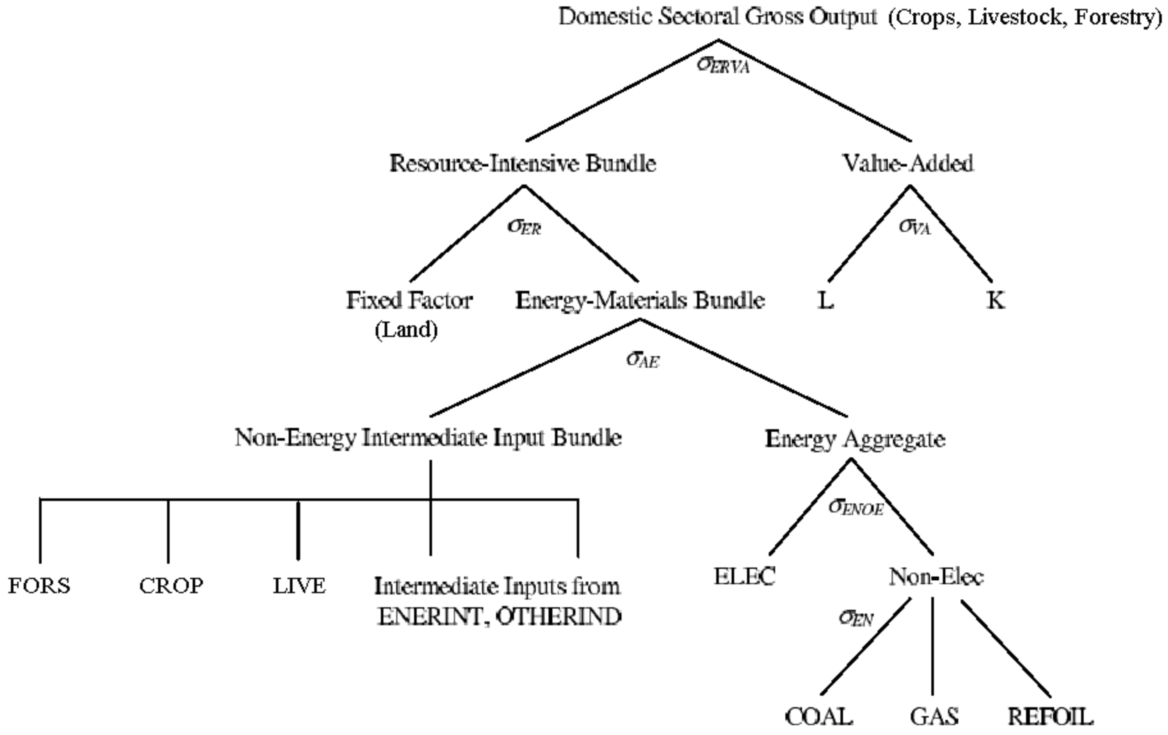
2.3.3 Agriculture Production Structure

Production technologies in EPPA are modeled using nested constant elasticity of substitution (CES) functions, which exhibit constant returns to scale. The nesting structure aggregates all Armington goods into a single consumption good, which is then aggregated together with savings to determine the level of consumer utility. Armington goods are defined such that domestically produced goods are treated as different commodities from imported goods in the same industry.

The production structure for all the sectors share the feature of substitution between energy and value added of primary factors (with elasticity σ_{EVA}), capital-labor substitution (with elasticity σ_{VA}), and substitution between electric and non-electric energy (σ_{ENOE}). The energy-related substitution elasticities are important because they exert the most direct influence on the cost of carbon control policies (Babiker *et al.*, 2001). In diagrams below, vertical and horizontal lines represent a Leontief production function, which has an elasticity of substitution of zero. Other elasticity of substitution values can be found in Appendix A.

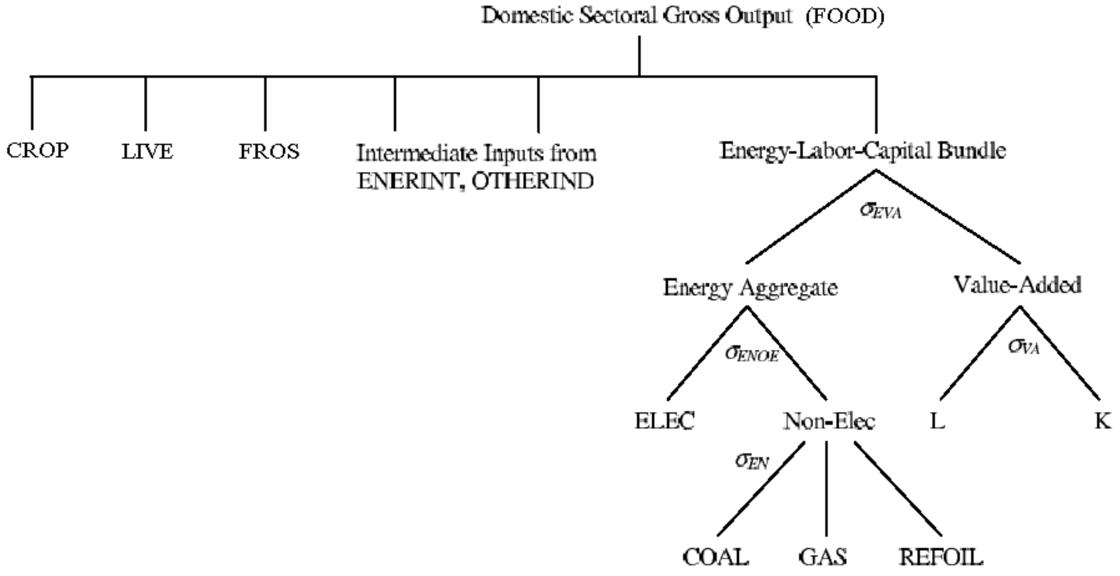
For crops, livestock and forestry I follow the same nested structure as for the aggregate agriculture sector in EPPA 4 (Figure 4) to reflect the role of natural resources in the production of output. At the top level of the nesting structure there is a resource-intensive bundle made up of a fixed factor that represents land and an Energy-Materials bundles. The value–added composite of Labor and Capital substitute for the Resource-Intensive bundle.

Figure 4: Production structure for crops, livestock and forestry



The structure of the food-processing sector follows that of other industries in EPPA, using intermediate inputs of non-energy Armington goods (crops, livestock) and a labor-capital-energy bundle (Figure 5). The energy-labor-capital bundle is composed of an aggregate of Armington energy inputs and a combination of labor and capital.

Figure 5: Production structure for food-processing sector



2.4 Adjusting the EPPA Agriculture Model

One of the main advantages of using CES functions to implement consumer demand is homogeneity. It greatly simplifies the solution of the model. However, CES presents a major drawback in modeling agriculture—it does not accurately represent Engel's Law, which states that as people become wealthier, the share of total expenditure on food declines. This is an empirical regularity in the study of demand patterns across expenditure levels (Banks *et al.*, 1997; Rimmer and Powell, 1992). A recent improvement in modeling consumption that better treats the variation in food demand across countries with widely varying incomes is called AIDADS, An Implicitly Directly Additive Demand System (Rimmer and Powell, 1992). While I retain the CES consumption function in the EPPA Agriculture Model, I calibrate its baseline projections to broadly match projections of AIDADS based on EPPA income growth to reflect a less than one, and declining income elasticity of food that is consistent with Engel's law.

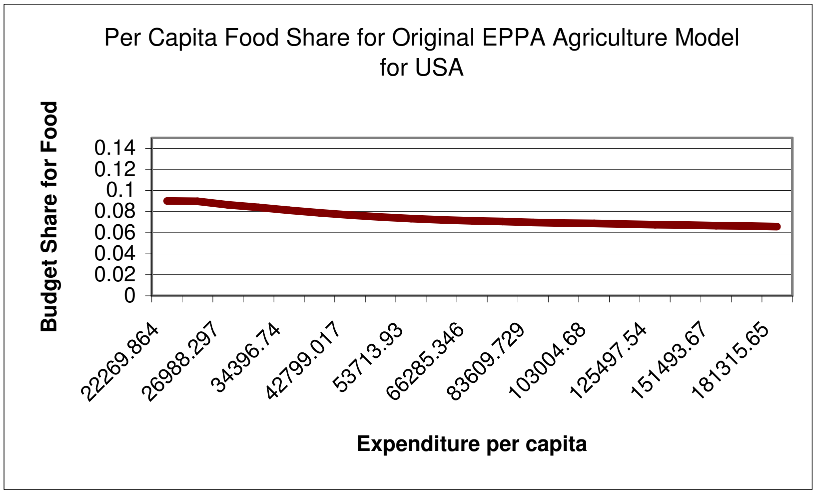
2.4.1 Constant Elasticity of Substitution

Utilizing relatively simple functional forms for demand systems with limited Engel flexibility is very common for world food prediction models (Yu *et al.*, 2002). Many partial equilibrium models use a simple log-log specification in which income elasticities are held constant. Examples here include: the International Food Policy Research institute's global model of food products (Agcaoili and Rosegrant, 1995) and the FAO's World Agricultural Model (Alexandratos, 1995).

Consumption functions used in EPPA are homogenous of degree one. These are even more restrictive, implying that, other things equal, the share of each good in total consumption remains unchanged as total income rises (Babiker *et al.*, 2001). In other words, the utility function underlying the demand system is homothetic, so if total consumption doubles, then the consumption of all goods including food doubles, and the share of food will remain unchanged. This eliminates the possibility that consumers adjust their purchasing behavior as their income changes. A brief economic derivation of constant elasticity of substitution for CES utility function is included in Appendix B.

Figure 6 plots the food share against total expenditure per capita in the US to illustrate the inaccuracy of CES function. The food share is projected to stay relatively constant by EPPA, yet previous research has shown that while food expenditure is projected to grow, its share of total expenditure is projected to fall (Cranfield *et al.*, 1998).

Figure 6: Food share projection from the EPPA Agriculture Model for USA



2.4.2 An Implicitly Directly Additive Demand System (AIDADS)

Rimmer and Powell (1992) proposed a new demand system that addressed the issue of limited Engel's flexibility in projecting global food demand. The model is called An Implicitly Directly Additive Demand System (AIDADS). According to Cranfield *et al.* (1998), although it requires estimations of several parameters, AIDADS has several features that make it an attractive alternative for food projection:

- AIDADS reflects the relationship between demands for different goods, so it could appropriately model the behavior of different goods, i.e. luxuries that have income elasticities that are greater than one and others goods such as food that have income elasticities of less than one.
- AIDADS satisfies adding-up, homogeneity of degree zero in prices and expenditure, and Slutsky symmetry. Since it is directly additive, the estimated model results in a net substitute relationship between competing goods, and rules out inferior goods.
- AIDADS does not constrain demand's response to an income change to be constant.
- AIDADS constrains the budget share to a theoretically admissible range, namely between zero and one. Other commonly used demand systems do not restrict the budget share in such a manner.

2.4.3 Economic Derivation of AIDADS

Hanoch (1975) defines implicit direct additivity by the utility function:

$$\sum_{i=1}^{n} Ui(x_i, u) = 1 \tag{1}$$

where {x_1, x_2, x_3…} is the consumption bundle, *u* is the utility level, U_i is a twice-differentiable monotonic function with the form:

$$Ui = \frac{[\alpha_i + \beta_i G(u)]}{[1 + G(u)]} \ln\left(\frac{x_i - \gamma_i}{Ae^u}\right) \tag{2}$$

where $G(u)$ is a positive, monotonic twice-differentiable function, and the simplest form of $G(u)$ is e^u. α_i, β_i, γ_i and A are parameters that can be estimated from historical data using econometric methods. γ_i is the subsistence level of consumption, and α_i, β_i have the restrictions that:

$$0 \le \alpha_i, \beta_i \le 1; \sum_{i=1}^{n} \alpha_i = 1; \sum_{i=1}^{n} \beta_i = 1 \qquad (3)$$

Solving for the first order cost minimization conditions, the budget share is calculated as:

$$W_i = \left(\phi_i + \frac{p_i \gamma_i}{M - p'\gamma} \right) \left(\frac{M - p'\gamma}{M} \right) \qquad (4)$$

where W_i is the ith good's budget, M is the expenditure. $p'\gamma$ represents the minimally sustainable per-capita expenditure in any country:

$$p'\gamma = \sum_{i=1}^{n} p_i \gamma_i \qquad (5)$$

From equation (4), Φ is defined as:

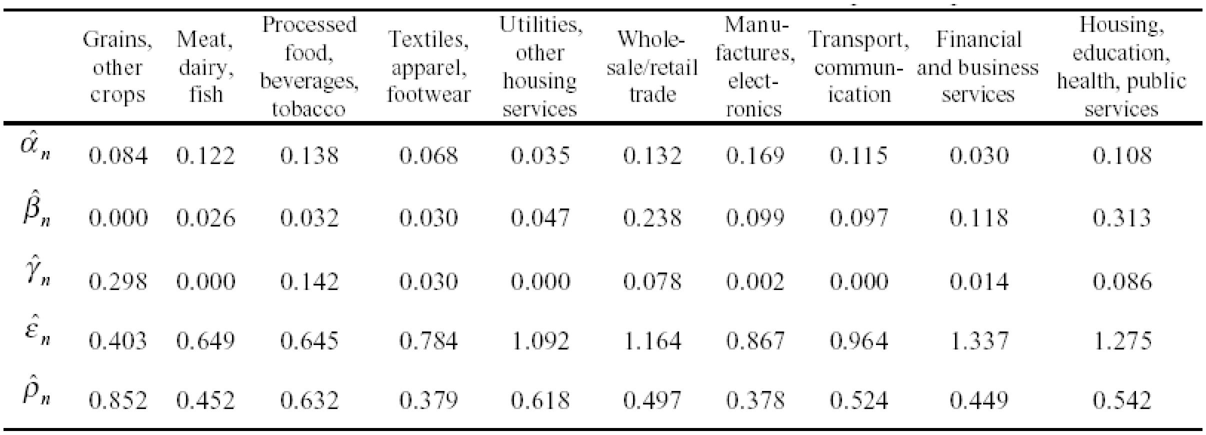
$$\phi_i = \frac{[\alpha_i + \beta_i G(u)]}{[1 + G(u)]} \qquad (6)$$

2.4.4 Projecting Food Share Using AIDADS

My goal is to recreate equation (4) with available data from EPPA to correctly approximate the food share using AIDADS. From equation (4), M as total expenditure, p_i as the price of food, u as utility level can all be obtained directly from EPPA. I only need to estimate $p'\ \gamma$, the total subsistence expenditure, in order to implement (4).

Table 4 presents AIDADS estimates from GTAP 5 data for the parameters needed for AIDADS calculation (Reimer and Hertel, 2004). AIDADS parameters α_n and β_n represent the bounds of the marginal budget share at low-income level and high-income level, respectively. Both parameters are normalized for all goods so they would satisfy equation (3). From (2), one can clearly understand that when the utility level is low, the utility function is adjusted by α_i. As an example from Table 4 given by Reimer and Hertel (2004), at low-income level, a consumer will need to spend 8.4% of an additional one dollar of expenditure, or 8.4 cents, on "Grains, other crops". On the other hand, at a high-income level, a consumer will spend 2.6% of every additional dollar of expenditure on “Meat, dairy, fish”, since β_n equals 0.026 for “Meat, dairy, fish. β_n estimate of zero for “Grain, other crops” means that at higher income level, “Grains, other crops” is no longer part of any increases in expenditure. Thus, the value α_n is vital to understand how consumption is allocated among commodities at subsistence-income levels.

Table 4: GTAP-based AIDADS estimates for household consumption expenditure



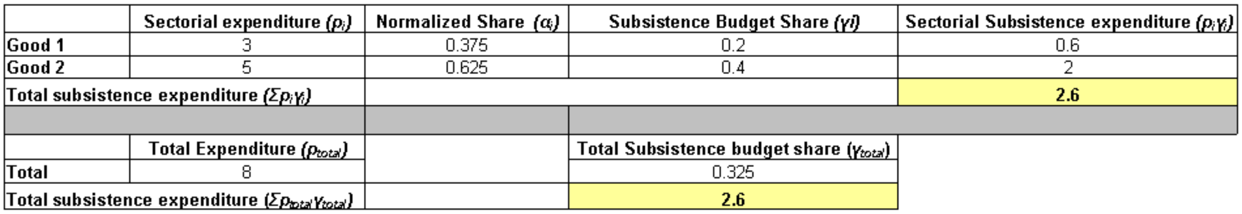
	Grains, other crops	Meat, dairy, fish	Processed food, beverages, tobacco	Textiles, apparel, footwear	Utilities, other housing services	Whole-sale/retail trade	Manu-factures, elect-ronics	Transport, commun-ication	Financial and business services	Housing, education, health, public services
$\hat{\alpha}_n$	0.084	0.122	0.138	0.068	0.035	0.132	0.169	0.115	0.030	0.108
$\hat{\beta}_n$	0.000	0.026	0.032	0.030	0.047	0.238	0.099	0.097	0.118	0.313
$\hat{\gamma}_n$	0.298	0.000	0.142	0.030	0.000	0.078	0.002	0.000	0.014	0.086
$\hat{\varepsilon}_n$	0.403	0.649	0.645	0.784	1.092	1.164	0.867	0.964	1.337	1.275
$\hat{\rho}_n$	0.852	0.452	0.632	0.379	0.618	0.497	0.378	0.524	0.449	0.542

The parameter γ_n estimates subsistence budget share for each commodity. Again using the example from the table above, 0.298 shares of “Grains, other crops” is needed for every unit of “Grains, other crops” in order to maintain survival. Therefore, if we multiply α_n and γ_n, we can obtain the subsistence level of expenditure on commodities required for each additional dollar of total expenditure. In the example, we would need to spend 2.5% of every dollar of expenditure on “Grains, other crops”, by multiplying 8.4% and 0.298. Because only the minimal survival level is needed for AIDADS calculation in equation (5), I assume that the subsistence budget share level will not change as income increases, so we only need to consider α_n as it is the parameter that estimates the budget share at low income level. The sum of products of α_n and γ_n, γ_{total}, is sufficient to estimate the subsistence level budget share for the total expenditure.

After calculating γ_{total}, or the subsistence level budget share, we can easily estimate $p'\gamma = \sum_{i=1}^{n} p_i \gamma_i$, the subsistence level expenditure, by multiplying total expenditure p_{total} and γ_{total}.

Ultimately we want to calculate total subsistence level budget share without having to aggregate subsistence budget shares from each commodity. We are able to do so because sectorial budget share α_n is normalized to add up to one, reflecting inclusion of the entire economy. A simple example in Table 5 demonstrates this property.

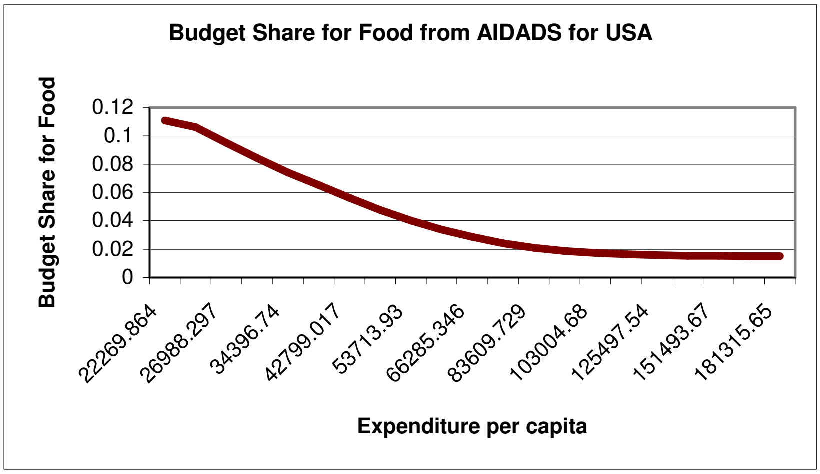
Table 5: A simple example estimate total subsistence level expenditure



	Sectorial expenditure (p_i)	Normalized Share (α_i)	Subsistence Budget Share (γ_i)	Sectorial Subsistence expenditure ($p_i\gamma_i$)
Good 1	3	0.375	0.2	0.6
Good 2	5	0.625	0.4	2
Total subsistence expenditure ($\Sigma p_i\gamma_i$)				**2.6**
	Total Expenditure (p_{total})		Total Subsistence budget share (γ_{total})	
Total	8		0.325	
Total subsistence expenditure ($\Sigma p_{total}\gamma_{total}$)			**2.6**	

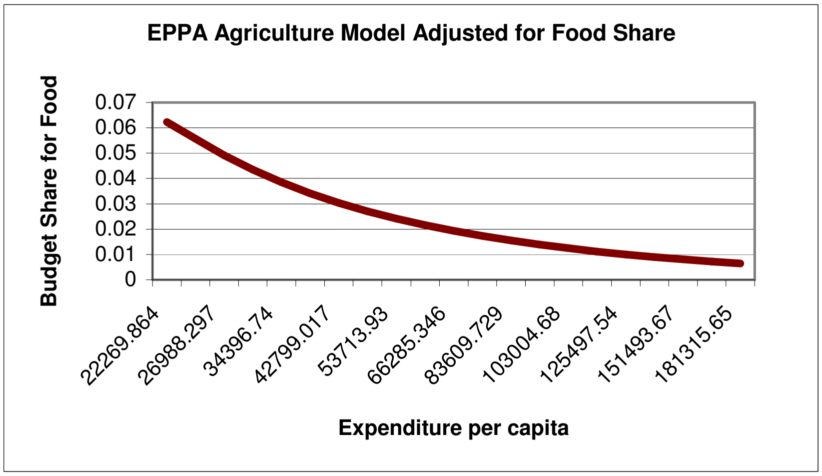
Figure 7 plots the food share projected by AIDADS for USA based on EPPA projections of utility level, total expenditure, and price of food. The downward sloping curve affirms Engel's law, which the budget share for food decreases as expenditure per capita increases.

Figure 7: Per capita food budget share estimated using AIDADS for EPPA



I then calibrate the EPPA Agriculture Model to incorporate Engel's Law into the model based on the above projections. I have modified the food share in the EPPA model for US, EU and China by shifting a portion of food processing to other industries in those countries when solving for equilibrium in each period. The adjusted EPPA Agriculture Model produces the budget share shown in FIGURE 8 for the US, and it resembles the projection based on the AIDADS estimate. Estimates for EU and China can be found in Appendix C.

Figure 8: Food share estimates from calibrated EPPA Agriculture Model



2.5 Model Comparison

In addition to the EPPA Agriculture Model, there are other food prediction models that are widely cited in the field. Two of the most commonly mentioned models are the IMPACT model from International Food Policy Research Institute (IFPRI), and the World Food Model (WFM) from Food and Agriculture Organization (FAO) of United Nations. The projections for the business as usual case from the EPPA Agriculture model is similar to those projected by IFPRI and FAO, which provides a valuable reference for interpreting results from EPPA.

IFPRI's IMPACT model is global and covers crops and livestock that enter competitive agricultural markets. The model uses a system of supply and demand elasticities, incorporated into a series of linear and nonlinear equations, to approximate production and demand functions. Demand is a function of prices, income, and population growth. Growth in crop production in each country is determined by crop prices and the rate of productivity growth. Unlike TEM that simulates carbon and nitrogen dynamics in the ecosystem to produce land productivities, IMPACT model's core components for sources of productivity growth come from crop management research, conventional plant breeding, wide-crossing and other types of breeding (Rosegrant *et al.*, 2001).

The model is solved on an annual basis with 16 commodities for 36 countries and regions. Similar to EPPA, the market-clearing condition solves for the set of world prices that clears international commodity markets, so the global total imports of each commodity equals total exports. When a shock is introduced in the model, such as an increase in crop yields from higher investment in crop research, the world price adjusts. Changes in domestic prices subsequently affect the supply and demand of commodities to readjust for a new level of equilibrium (Delgado *et al.*, 1999).

WFM is a non-spatial, recursive-dynamic, synthetic, multi-regional, multi-product partial-equilibrium world trade model for basic food products. It provides a framework to forecast supply, demand and net trade for approximately 150 countries. WFM is a multi-commodity, partial equilibrium model with individual country coverage and agricultural commodity details. Similar to EPPA, the income elasticity estimates used in WFM are obtained from previous literatures, or estimates using simple econometric models.

Both the IMPACT model and WFM solve for various commodities in agriculture, so they are able to describe future projections for specific types of crops or livestock in greater detail than EPPA. Although results from the EPPA Agriculture Model are still highly aggregated, they are comparable to projections from IMPACT and WFM. Table 6 presents growth trends predicted by IFPRI, FAO and EPPA from 2000 – 2030 (FAO, 2003a[2]; Delgado *et al.*, 1999[3]).

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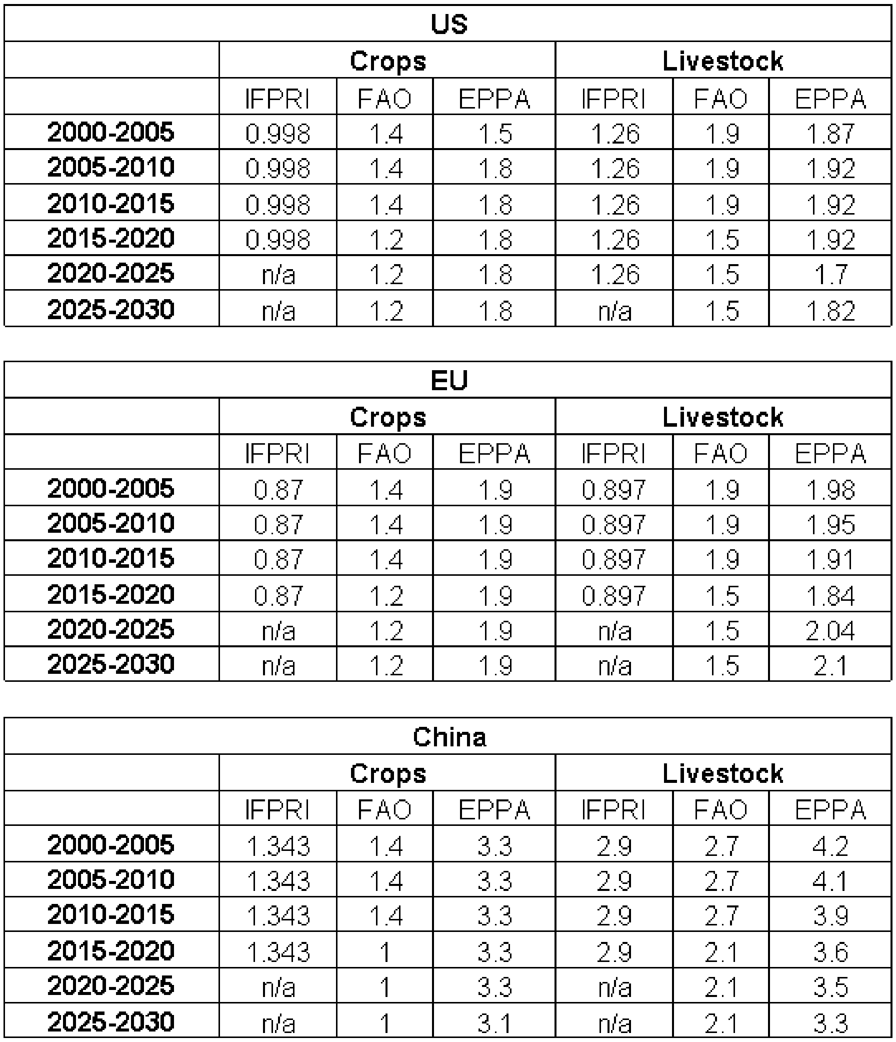
[2] Annual growth rates were calculated manually for FAO, as the report only lists productions for 1997, 2015 and 2030. Figures for the EU and the US were extracted from developed countries.

[3] Annual growth rates were calculated manually for IFPRI, as the report only list productions for 1997 and 2020. Figures for China was extracted from Southeast and East Asia.

Table 6: Annual growth rates projected by FAO, IFPRI, and MIT



US						
	Crops			Livestock		
	IFPRI	FAO	EPPA	IFPRI	FAO	EPPA
2000-2005	0.998	1.4	1.5	1.26	1.9	1.87
2005-2010	0.998	1.4	1.8	1.26	1.9	1.92
2010-2015	0.998	1.4	1.8	1.26	1.9	1.92
2015-2020	0.998	1.2	1.8	1.26	1.5	1.92
2020-2025	n/a	1.2	1.8	1.26	1.5	1.7
2025-2030	n/a	1.2	1.8	n/a	1.5	1.82

EU						
	Crops			Livestock		
	IFPRI	FAO	EPPA	IFPRI	FAO	EPPA
2000-2005	0.87	1.4	1.9	0.897	1.9	1.98
2005-2010	0.87	1.4	1.9	0.897	1.9	1.95
2010-2015	0.87	1.4	1.9	0.897	1.9	1.91
2015-2020	0.87	1.2	1.9	0.897	1.5	1.84
2020-2025	n/a	1.2	1.9	n/a	1.5	2.04
2025-2030	n/a	1.2	1.9	n/a	1.5	2.1

China						
	Crops			Livestock		
	IFPRI	FAO	EPPA	IFPRI	FAO	EPPA
2000-2005	1.343	1.4	3.3	2.9	2.7	4.2
2005-2010	1.343	1.4	3.3	2.9	2.7	4.1
2010-2015	1.343	1.4	3.3	2.9	2.7	3.9
2015-2020	1.343	1	3.3	2.9	2.1	3.6
2020-2025	n/a	1	3.3	n/a	2.1	3.5
2025-2030	n/a	1	3.1	n/a	2.1	3.3

The projections are relatively close, although the results from EPPA are consistently higher than those predicted from the other two models. They are much lower with the adjustments I have made than without, but this comparison suggests that additional attempts to improve EPPA's representation of food demand are needed. I return to some of these recommendations in the final chapter.

Chapter 3: The Economic Impact of Tropospheric Ozone on Agriculture in the US, EU, and China

Tropospheric ozone is an oxidizing agent that interferes with the ability of crops to produce and store food. It causes a reduction of photosynthesis and damages to reproductive processes (Mauzerall and Wang, 2001). Appendix D summarizes some of the observable damages on crops from ground level ozone. Previous research has shown that tropospheric ozone could reduce soybean seed yields by 41% at ambient carbon dioxide level in Massachusetts (Fiscus *et al.*, 1997), and the crop loss for soybeans and spring wheat might reach 20% to 30% in China by 2020 (Aunan *et al.,* 2000). Developing countries that are concerned about food production or relying on the agricultural economy may be particularly motivated to understand the impact of tropospheric ozone on agriculture.

Crops grow during the summer when photochemical ozone production is most elevated, creating sufficient amount to reduce crop yields (Mauzerall and Wang, 2001). Felzer *et al.* (2004) defines "ozone hotspots" as regions with high levels of ozone concentration that also coincide with high plant productivity (Figure 9). Many of the ozone hotspots are in the mid-latitudes (Figure 10), where major agricultural regions are located in the world, therefore ozone pollution will have a significant negative effect on future crop yields (Felzer, *et al.*, 2004). Ozone measurement is designated as AOT40, the accepted and standard measurement for vegetation exposure to ozone (Holland *et al.,* 2002). This index is a measure of the accumulated hourly ozone levels above a threshold of 40 parts per billion (ppb).

Figure 9: Mean of ozone level (AOT40) from June-July-August, 1998

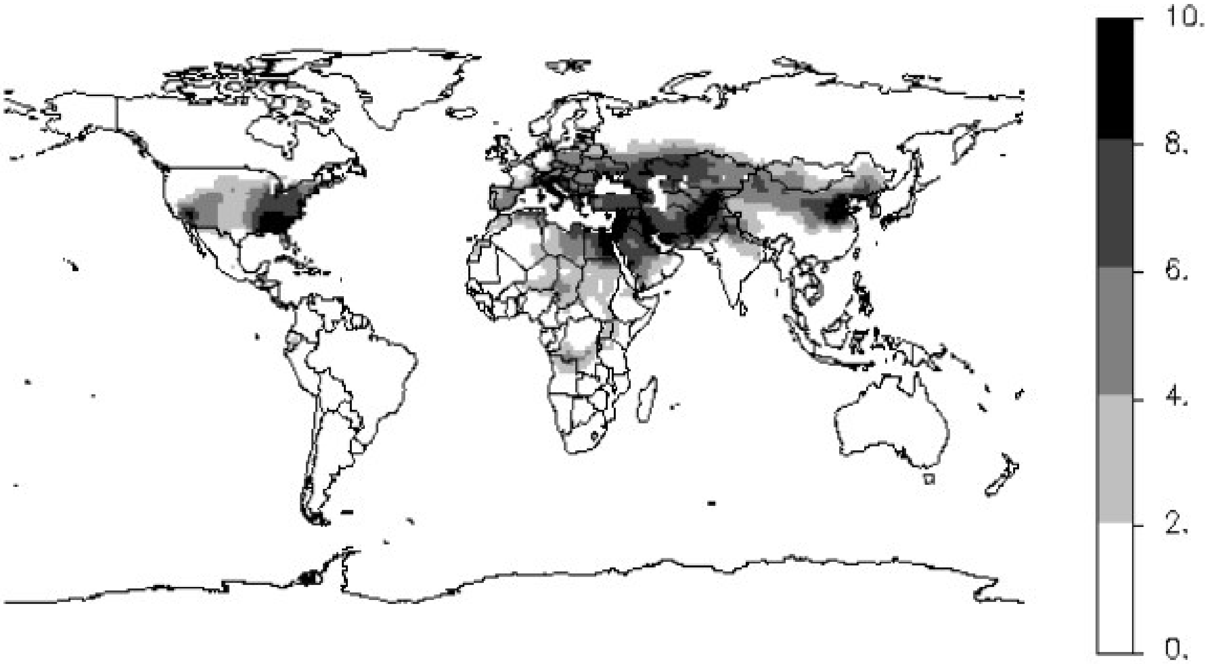
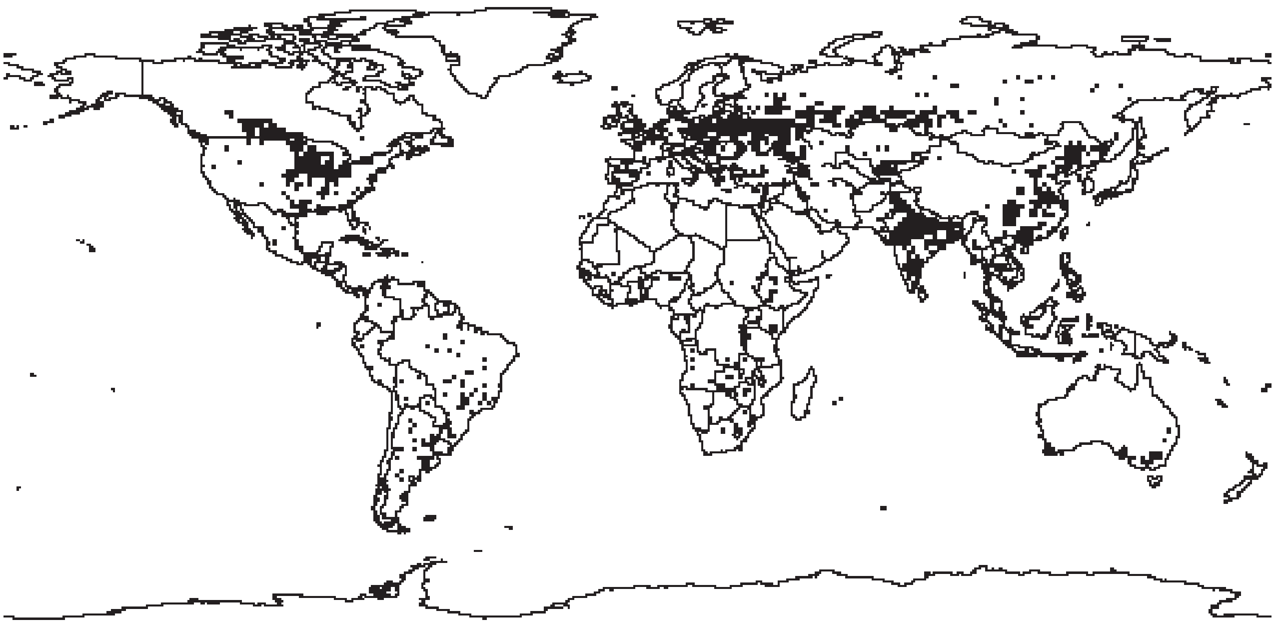


Figure 10: Major agricultural regions in the world in 1995



3.1 Research Interest

While much of previous research on the subject of ozone damage on crops has focused on the yield reduction, few papers examine the ozone damage in economic terms on a national level. Previous models that do assess the economic effects of ozone on crop yields have run into the problem of not being able to include changes in price over time, or not being to apply a general equilibrium model (Holland *et al.*, 2002). The EPPA model as a computable general equilibrium model avoids the above pitfalls. The EPPA model also includes multiple channels of market-based adaptation, including input substitution and trade, which allows us to examine how markets respond to the impact of ozone by mitigating the damage through adaptation.

My research extends previous research that analyzed the past and future effects of ozone on net primary production and carbon sequestration (Felzer, *et al.*, 2004). Specifically, I analyze the economic impact of tropospheric ozone on agriculture in the United States, the European Union and China. Felzer, *et al.* (2004) focused on these three regions because ozone pollution is largely a regional phenomenon and these regions incur the highest loss on their lands' net primary productivities (NPP) (Figure 11). Moreover, the ozone levels in these regions are projected to increase in the future (Figure 12).

Understanding the economic impact of tropospheric ozone on agriculture production is an integral part of the process of recognizing the consequences of air pollution in order to create more effective climate and air pollution policies. The economic analysis translates climatic effect and yields assessment into monetary values; the terms that policy makers could comprehend more explicitly, and decision makers could directly compare with other relevant data in the policy setting process. Additionally, developing countries do not currently participate in Kyoto Protocol, so they might be reluctant to devote resources on climate policy. Hence, putting the damage in economic terms may spur interests for developing countries to look more into the issue of ozone pollution.

Figure 11: Annual percent difference of NPP with nitrogen fertilization on croplands

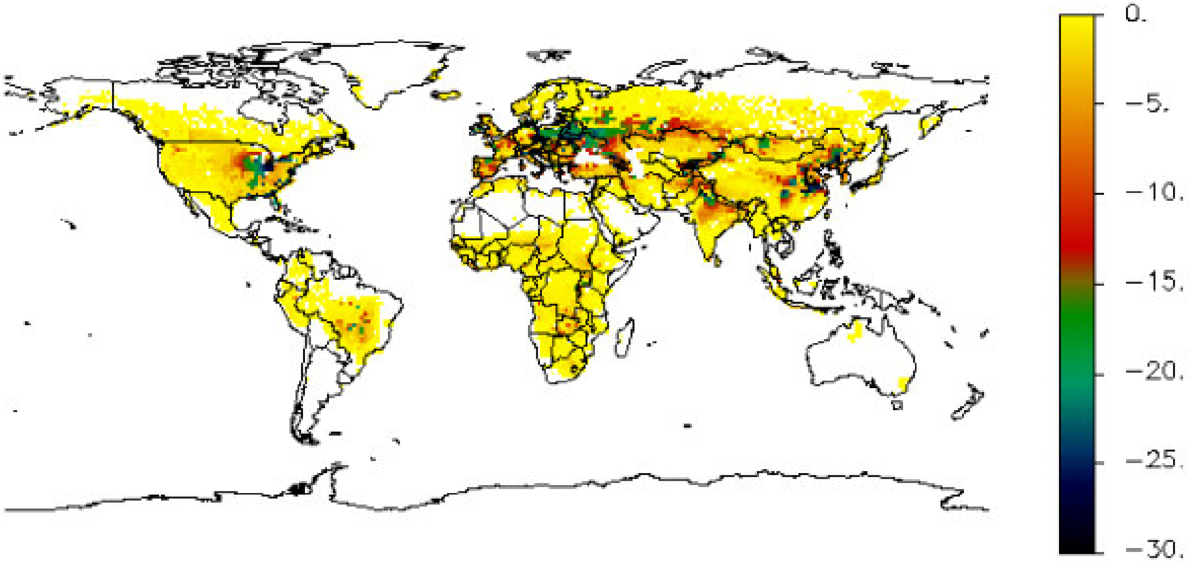
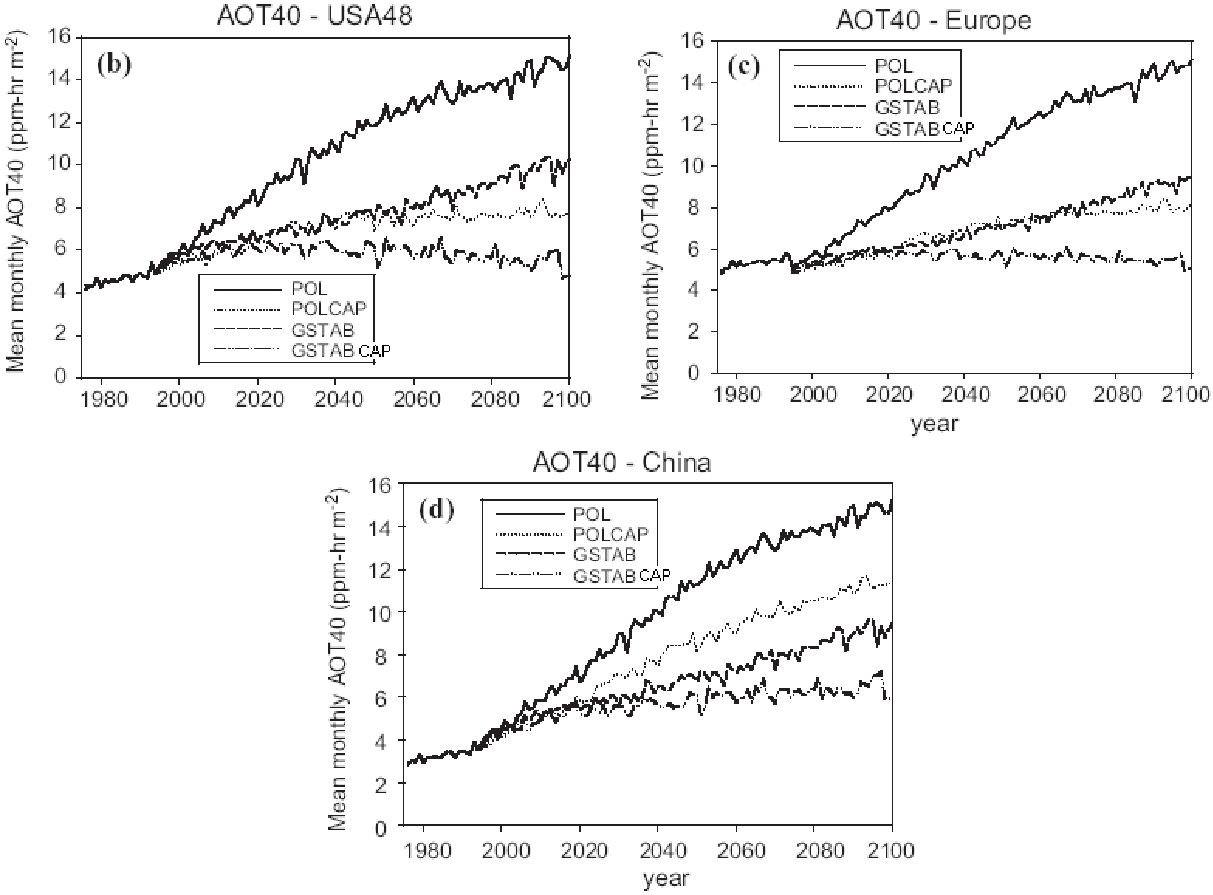


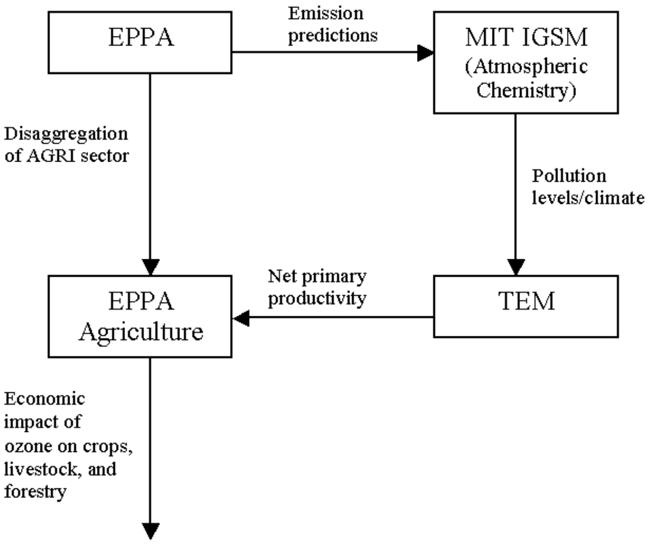
Figure 12: Mean monthly AOT40 in US, EU and China



3.2 Methods

The economic assessment was computed using net primarily productivity data obtained from the Terrestrial Ecosystem Model (TEM), which calculates NPP with inputs generated from MIT IGSM Model, thus completing the loop between IGSM and TEM (Figure 13). Because the process of generating NPP values is elaborated in Felzer, *et al.* (2004), only a summary is provided below to present a comprehensive explanation on the interactions between TEM and the EPPA model.

Figure 13: Interactions between the EPPA Agriculture Model and TEM

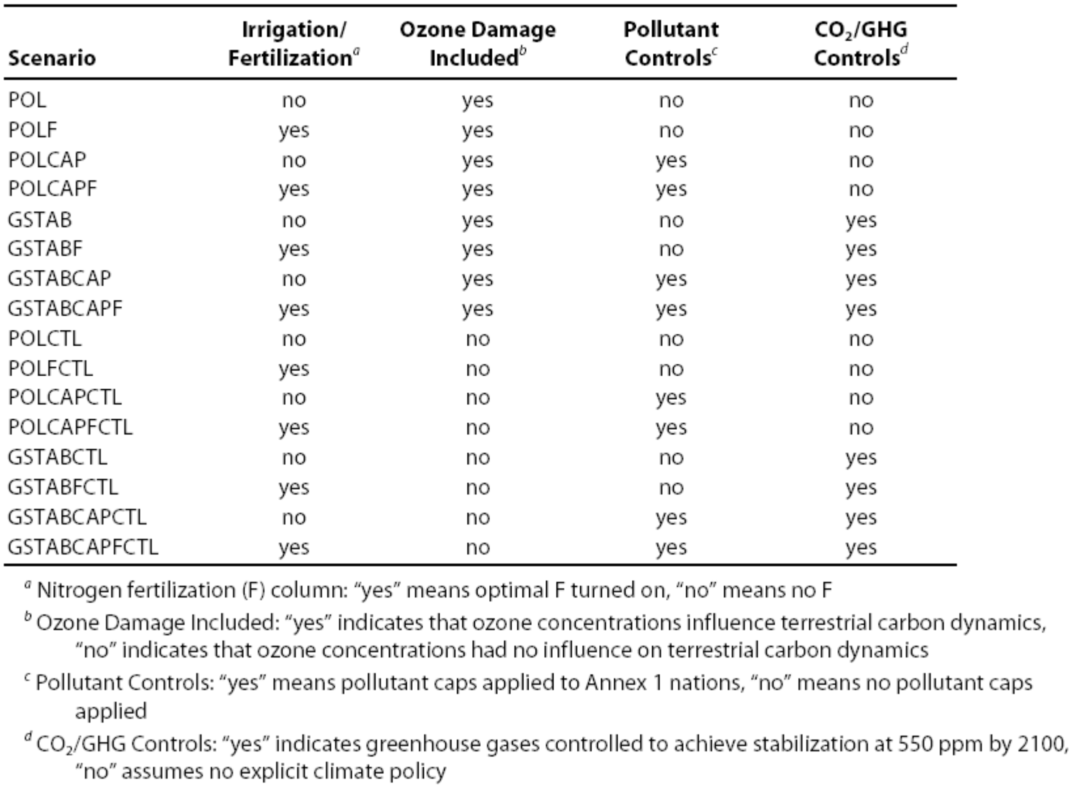


3.2.1 Obtaining Net Primary Productivity

The EPPA model produces emission projections for major greenhouse gases such as carbon dioxide, as well as other climate important substances, including carbon monoxide, nitrogen oxides, and non-methane volatile organic compounds (Babiker et. al. 2001). Though EPPA model does not project the emission level of ozone, it models emissions of ozone precursors (CO, NOx, CH4, NMVOCs). These gases form ozone through chemical reactions and sunlight. Modeling of the complex non-linear process of producing ozone is done in the atmospheric chemistry component of the MIT IGSM.

TEM then generates the net primary productivity by taking the outputs of pollution levels from MIT IGSM, in order to simulate the effects of greenhouse gases and ozone on vegetation. TEM is a spatial model, resolved a 2-degree by 2-degree latitude-longitude scale, and thus is able to capture spatial variation in ozone exposure. Different scenarios were created using TEM to capture the effects of climate policies or environmental policies. Specifically, a pollution case (POL) allows GHG and pollutant gas emissions to increase unabated, while the POLCAP sets a cap on the pollutant gases at 1996 level for Annex 1 nations to account for pollution controls. Other experiments include CTL that accounts for ozone control, and F for nitrogen fertilization. A detailed explanation of various scenarios is listed in Table 7 (Felzer *et al.,* 2004).

Table 7: Simulation of future scenarios



Scenario	Irrigation/ Fertilization[a]	Ozone Damage Included[b]	Pollutant Controls[c]	CO$_2$/GHG Controls[d]
POL	no	yes	no	no
POLF	yes	yes	no	no
POLCAP	no	yes	yes	no
POLCAPF	yes	yes	yes	no
GSTAB	no	yes	no	yes
GSTABF	yes	yes	no	yes
GSTABCAP	no	yes	yes	yes
GSTABCAPF	yes	yes	yes	yes
POLCTL	no	no	no	no
POLFCTL	yes	no	no	no
POLCAPCTL	no	no	yes	no
POLCAPFCTL	yes	no	yes	no
GSTABCTL	no	no	no	yes
GSTABFCTL	yes	no	no	yes
GSTABCAPCTL	no	no	yes	yes
GSTABCAPFCTL	yes	no	yes	yes

[a] Nitrogen fertilization (F) column: "yes" means optimal F turned on, "no" means no F

[b] Ozone Damage Included: "yes" indicates that ozone concentrations influence terrestrial carbon dynamics, "no" indicates that ozone concentrations had no influence on terrestrial carbon dynamics

[c] Pollutant Controls: "yes" means pollutant caps applied to Annex 1 nations, "no" means no pollutant caps applied

[d] CO$_2$/GHG Controls: "yes" indicates greenhouse gases controlled to achieve stabilization at 550 ppm by 2100, "no" assumes no explicit climate policy

3.2.2 Evaluating Economic Impact

We analyze the effect of ozone by pairing up scenarios with or without CTL to compare results. The NPP values associated with each scenario are region specific, so we could obtain data for the

United States, the European Union, China, and ROW (Rest of World). We then simulate four separate runs for every pair by adjusting the productivity factor on land in EPPA agriculture model exogenously. The four runs are:

- Business-As-Usual run with default land productivity.
- Land productivity adjusted for NPP with abundant greenhouse gases (CO_2, CH_4, etc) and with no ozone.
- Productivity adjusted for NPP with greenhouse gases as well as with ozone damage
- Counterfactual run to examine how many agricultural goods would have been produced if there had been no ozone damage.

The EPPA Agriculture Model evaluates economic impacts based on the above productivity values, enabling us to calculate potential yield loss and economic loss from tropospheric ozone damage.

3.3 Results

We have simulated the ozone damage on two different pairs of scenarios: POLCAPF/POLCAPFCTL, and GSTABCAPF/GSTABCAPFCTL. The purpose of the first pair is to examine the ozone damage when greenhouse gas emissions increase unabated with nitrogen fertilization, whereas the purpose of the second pair is to examine the ozone damage where a significant reduction in greenhouse gas emissions occurs by 2100, both with caps on air pollution. In particular, the second scenario assumes Kyoto Protocol restrictions on the emissions of both CO_2 and other greenhouse gases on Annex 1 nations in 2010 and on all nations starting in 2025; so atmospheric concentration of CO_2 will stabilize at about 550ppm by 2100. These scenarios also correspond to the AOT40 level in Figure 12 from Felzer *et al.* (2004), and the results from them will be explained separately

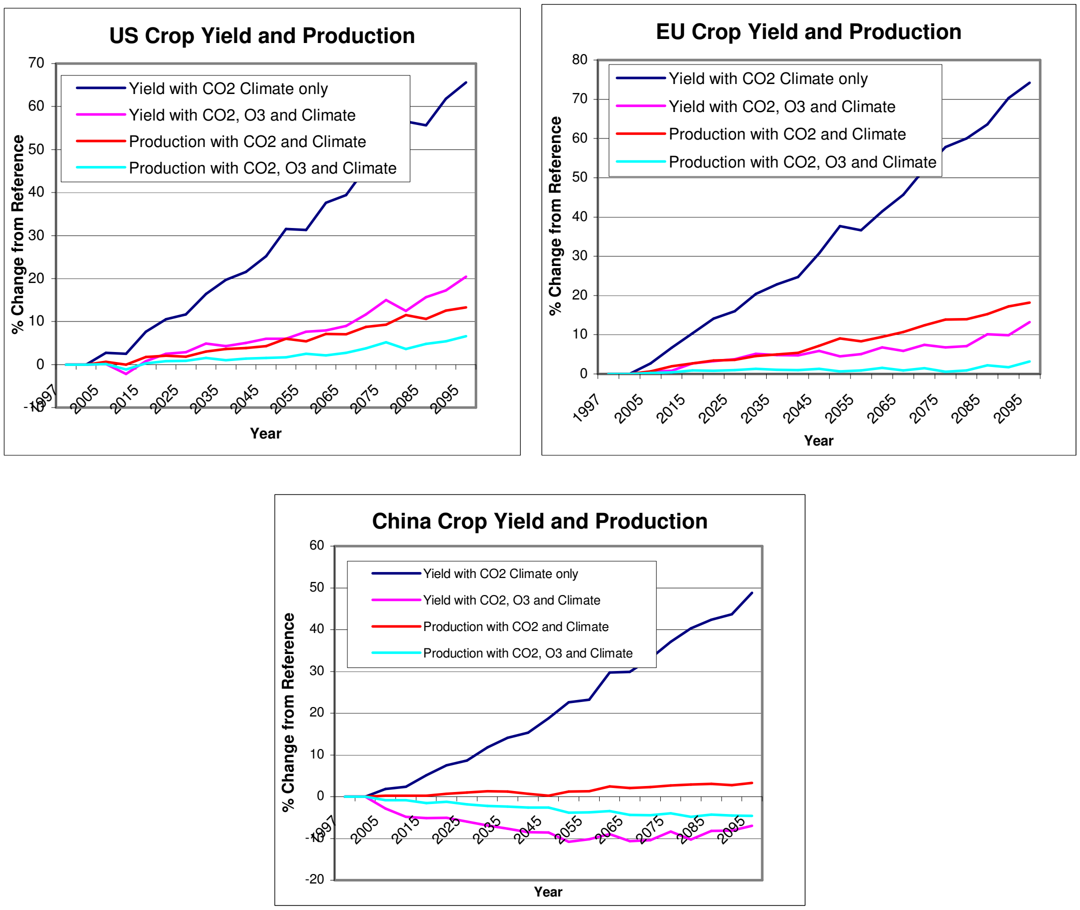
Because we have disaggregated the agriculture sector into three separate sectors (crops, livestock, forestry), it would be ideal to examine the ozone effect on all three sectors. Unfortunately, I only obtained NPP values for croplands, hence only the economic impact on crops would be quantitative. However, I applied the NPP values for livestock land and forestry land in my simulations. Even though the economic evaluations for those two sectors would not be accurate, they provide qualitative assessments on the impact of tropospheric ozone on the livestock and forestry sectors.

3.3.1 POLCAPF/POLCAPFCTL case

3.3.1.1 Crop Yield and Production

Figure 14 shows the yield change from scenarios with changes in climate, CO_2 and ozone. I have changed the land productivity associated with each combination in the EPPA Agricultural Model, in order to compute percentage change from the BAU run as a result of these land productivity (i.e. yield) changes.

Figure 14: Yield and production for crops in the US, EU and China



CO_2 and climate have significant positive impacts on the yields of the crops. The positive response in EU could be as high as 35% by 2050. However, the beneficial effects on yields due to climate and CO_2 are significantly undermined by ozone damage in all regions. Especially in China, the ozone damage was greater than the positive effect from climate and CO_2, so the yield becomes negative. This substantial decrease in yield occurs mostly likely because of particularly high ozone levels in major cropping areas of China.

At the same time, production effects are much smaller than the yield effects for all regions, in either the climate and CO_2 scenario or in the scenario that includes ozone damage. China is the only region that experiences production decreasing due to ozone. Economies adapt by reallocating resources away from crop production to other uses because food demands are not very responsive to falling food prices, even with productivities gains. In other words, even though the land is more productive and produces potentially higher yields, unresponsive demand accompanied by the decrease in food price would result in less of other inputs to be used in crop production. As a result, production changes considerably less than the yield.

3.3.1.2 Livestock and Forestry Production

The qualitative assessment of the production change for livestock is shown in Figure 15. The yield change is not available as the NPP values only entail to croplands. In general, livestock production will be affected by both the change in pasture and forage productivity, as well as by the change in crop production since much of crop production is livestock feed. However, because the feed and forage is not as large a share of inputs in the livestock sector as is the land input in crops since livestock activities are most likely capital and labor intensive, we do not see as big a production impact from ozone damage in livestock as in crops.

Figure 15: Production for livestock in the US, EU and China

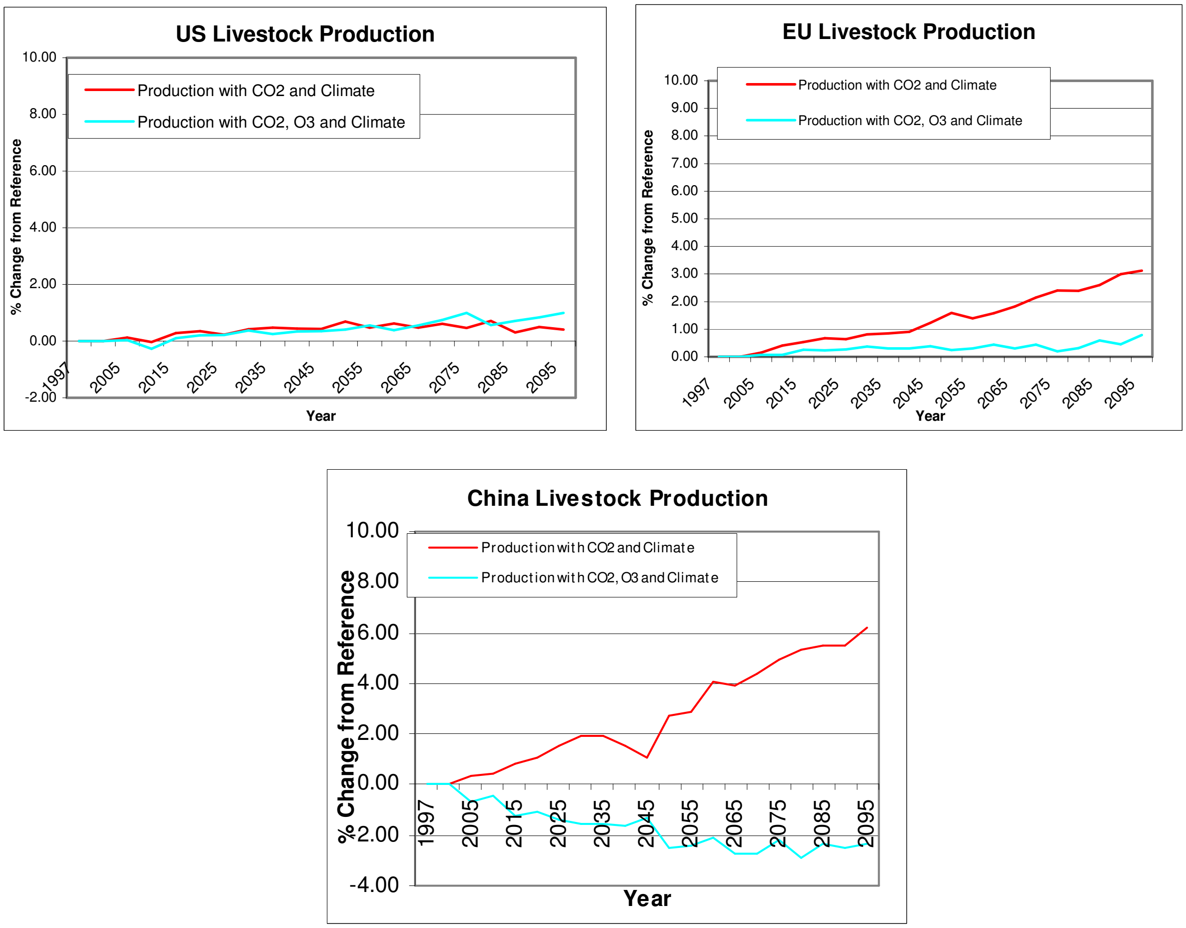
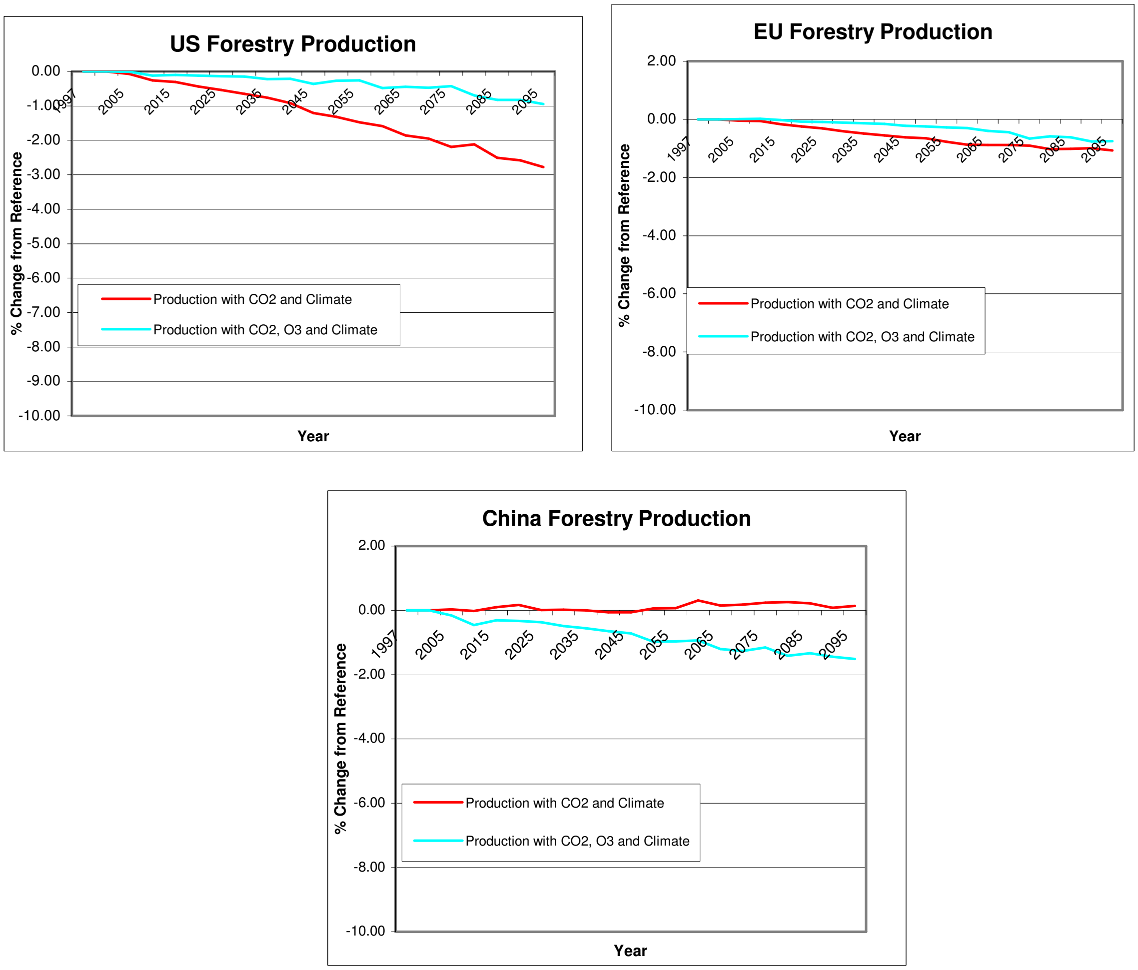


Figure 16 shows the forestry production change. Similar to the livestock sector, forestry production is not greatly affected by the ozone. As mentioned previously, "ozone hotspots" usually coincide with croplands, so it is highly probable that the forestry lands do not suffer from ozone pollution nearly as much as crop fields do.

Figure 16: Production for forestry in the US, EU and China

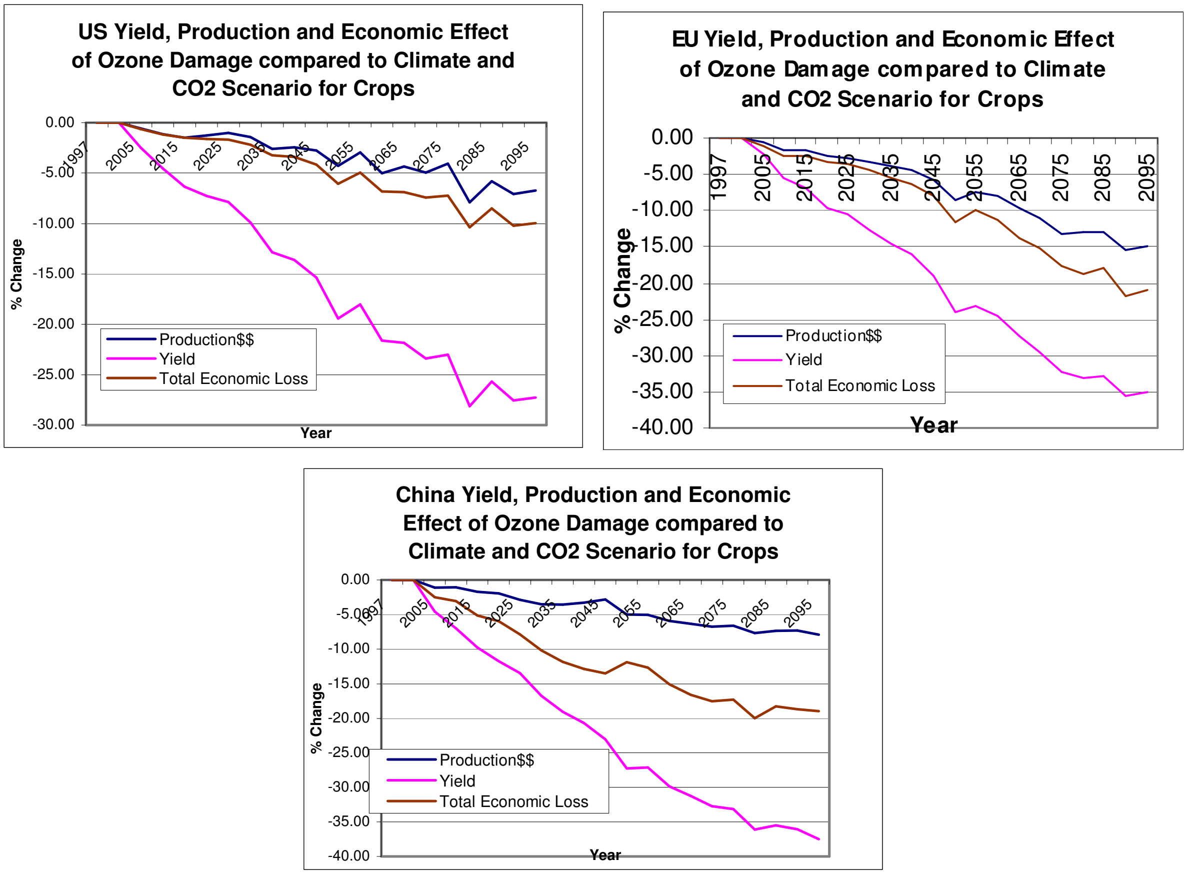


3.3.1.3 Economic Impact on Crops, Livestock and Forestry

Even though economies adapt to agricultural management and technologies that would not be affected by ozone pollution as much, the economic costs of ozone damage still exist in the form of consumption loss, compared to the case of CO_2 and climate effect (Figure 17). Yields decrease significantly because of tropospheric ozone. However, crop productions do not change accordingly, because of adaptations. The production loss in EU, US and China indicates that these regions lose competitive advantage due to ozone damage as it reduces production of crops, and relies on imports of crops.

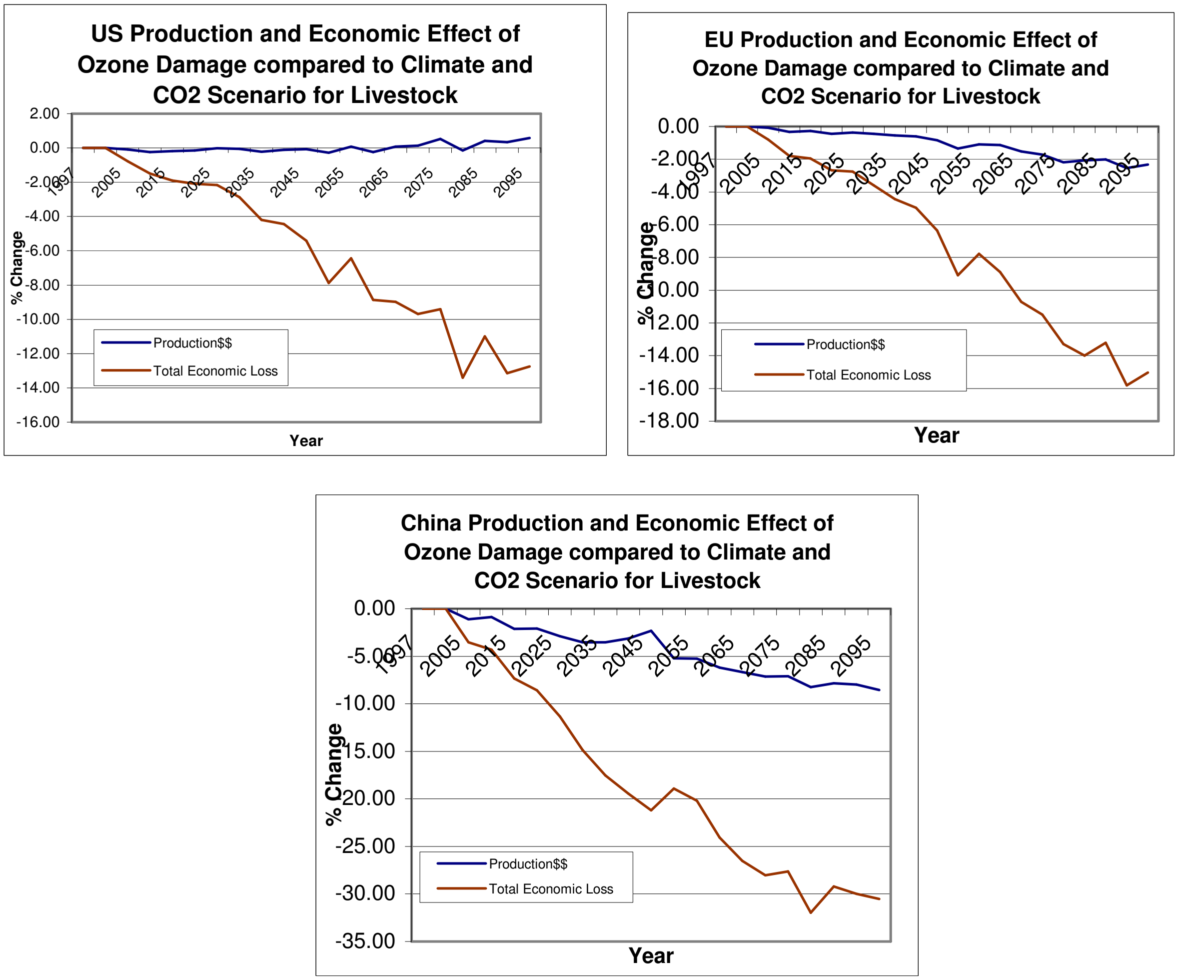
However, it would be incorrect to conclude that because crop production changes little even when there is a large impact on yields, so there is little economic effect. As shown in Figure 17), economic cost is less than the yield loss, but still rises to 15% of the value of crop production for the US. The economic effect is less than the yield effect because of adaptation, but much of the cost is reflected in changes in consumption of other goods. This is because demand for agriculture is very price-inelastic. Any potential cost due to adaptations will be reflected on the food price, and the burden will be passed onto the consumers. The EPPA Agriculture Model accurately simulates the reality that adaptation can counterbalance much of the initial yield impact, while also measuring the cost to the economy of making those adaptations.

Figure 17: Economic impact on crops



In the livestock sector, all the regions incur economic loss due to ozone damage. However, the US is the only region that has a positive production effect, which means that the US gains competitive advantage by increasing production and could export, while China and the EU depend on imports of livestock due to production losses. Even though only qualitative assessments are available for the livestock and forestry sectors, it is apparent that tropospheric ozone causes a negative economic impact on the livestock sector (Figure 18) to account for the cost of adaptations. Of the three regions, China suffers the most potentially because of the lack of appropriate adaptation technology and management, so the cost of adaptation is higher, and is transferred to consumers via price increase, causing widened consumption loss. The economic impacts from ozone pollution on the forestry can be found in Appendix E, as they are very similar to those for the livestock sector.

Figure 18: Economic impact on livestock



3.3.1.4 Consumption Loss

The total consumption losses due to ozone damage in US, EU, and China are indicated in Figure 19. Specifically, the economic loss in 2005 is US$7.4 billion dollars for the US, US$16.5 billion dollars for EU, and US$17.6 billion dollars for China. Table 8 lists the consumption loss for future years in the US, EU, and China. The consumption loss is aggregated from all sectors in EPPA, such as loss in the transportation sector or energy intensive sector. This is because a possible loss of crop yields could potentially cause other sectors in the economy to fall or rise, i.e. more inputs devoted to agriculture to adapt to ozone means less inputs available to produce other goods.

Figure 19: Consumption loss due to tropospheric ozone in POLCAPF scenario

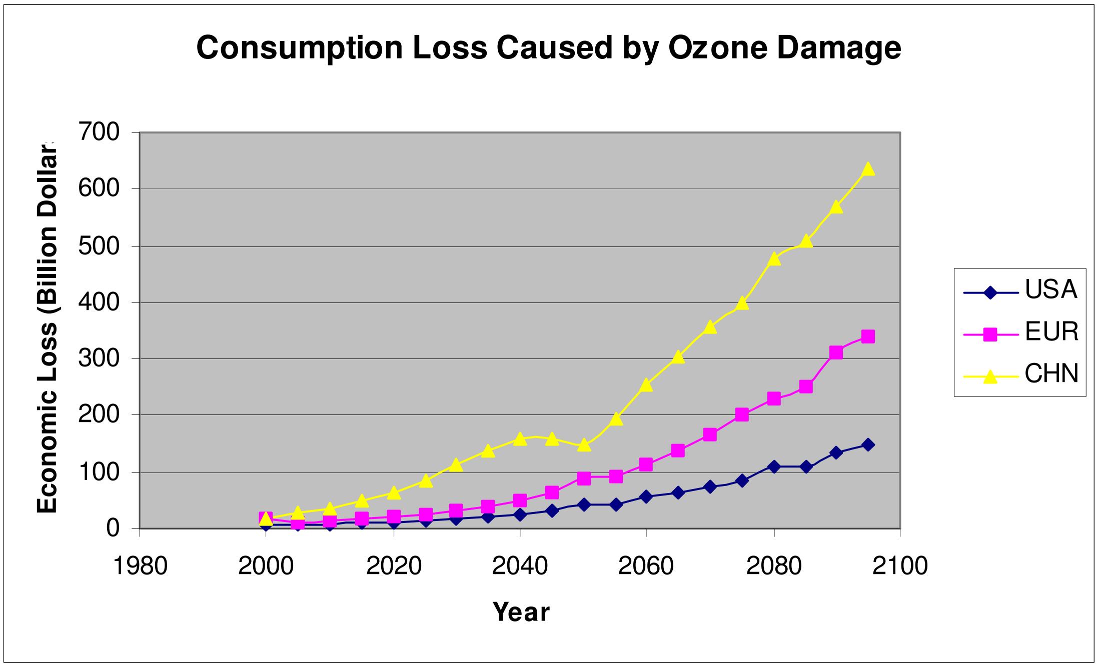


Table 8: Values of consumption loss from tropospheric ozone (billion)

	USA	EUR	CHN
2005	7.429	16.503	17.643
2010	6.24	11.637	27.527
2015	8.019	15.72	36.631
2020	9.667	17.637	48.046
2025	11.092	21.441	64.158
2030	12.871	24.715	85.176
2035	15.964	31.638	112.466
2040	21.097	39.751	138.826
2045	24.603	47.968	157.654
2050	31.201	63.064	159.866
2055	42.198	86.92	150.028
2060	44.079	90.826	195.004
2065	57.517	112.016	253.11
2070	64.585	139.415	302.884
2075	75.874	165.313	355.37
2080	84.022	200.38	401.246
2085	108.482	228.946	477.88
2090	110.227	250.836	510.615
2095	133.786	309.676	569.473
2010	147.79	338.682	635.571

3.3.2 GSTABCAPF/GSTABCAPFCTL case

Most of the assessments follow the same trend as those in POLCAPF/POLCAPF CTL. The only significant difference in this case is that because China is forced to constrain its emissions, economic impacts tend to level off after 2025. On the other hand, it is more valuable to compare results obtained from this case to the results from the previous case to gain more insights on the ozone impact. Therefore, I will illustrate the comparisons in this section, and figures for different sectors for all three regions are included in Appendix E.

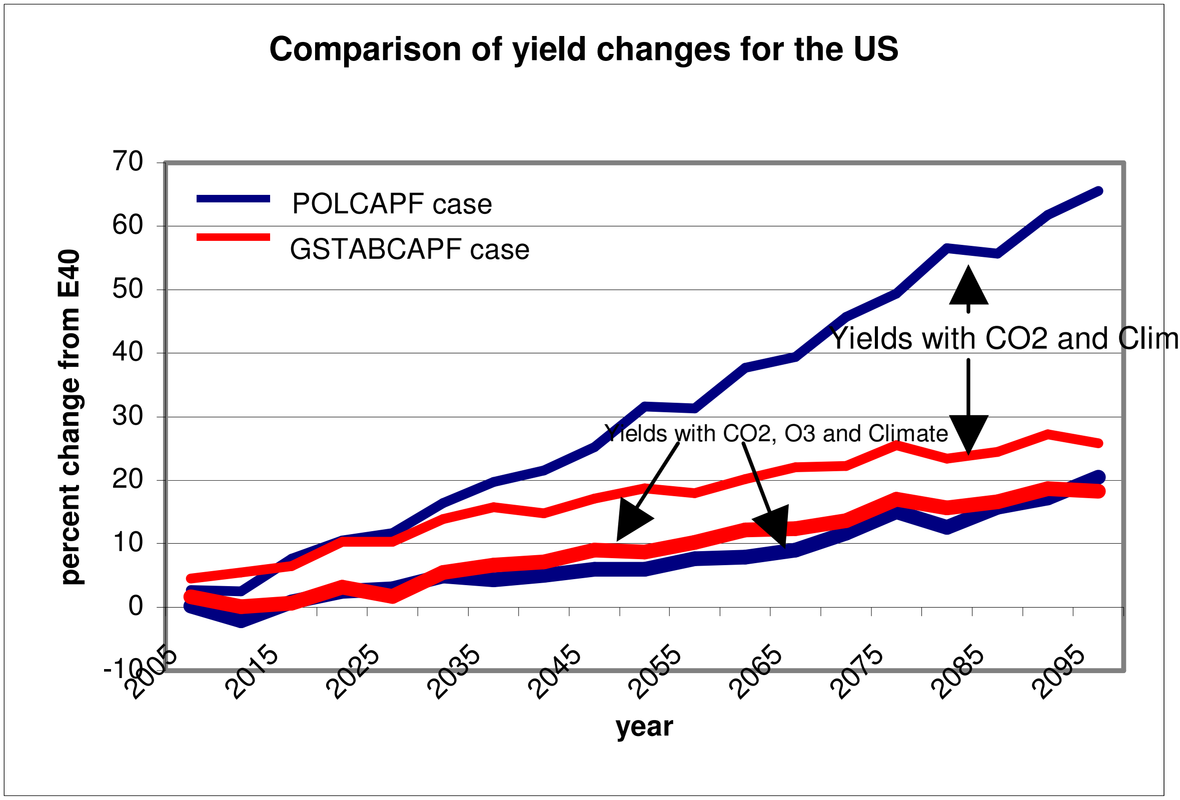
3.3.2.1 Crop Yield Changes Comparing with POLCAPF

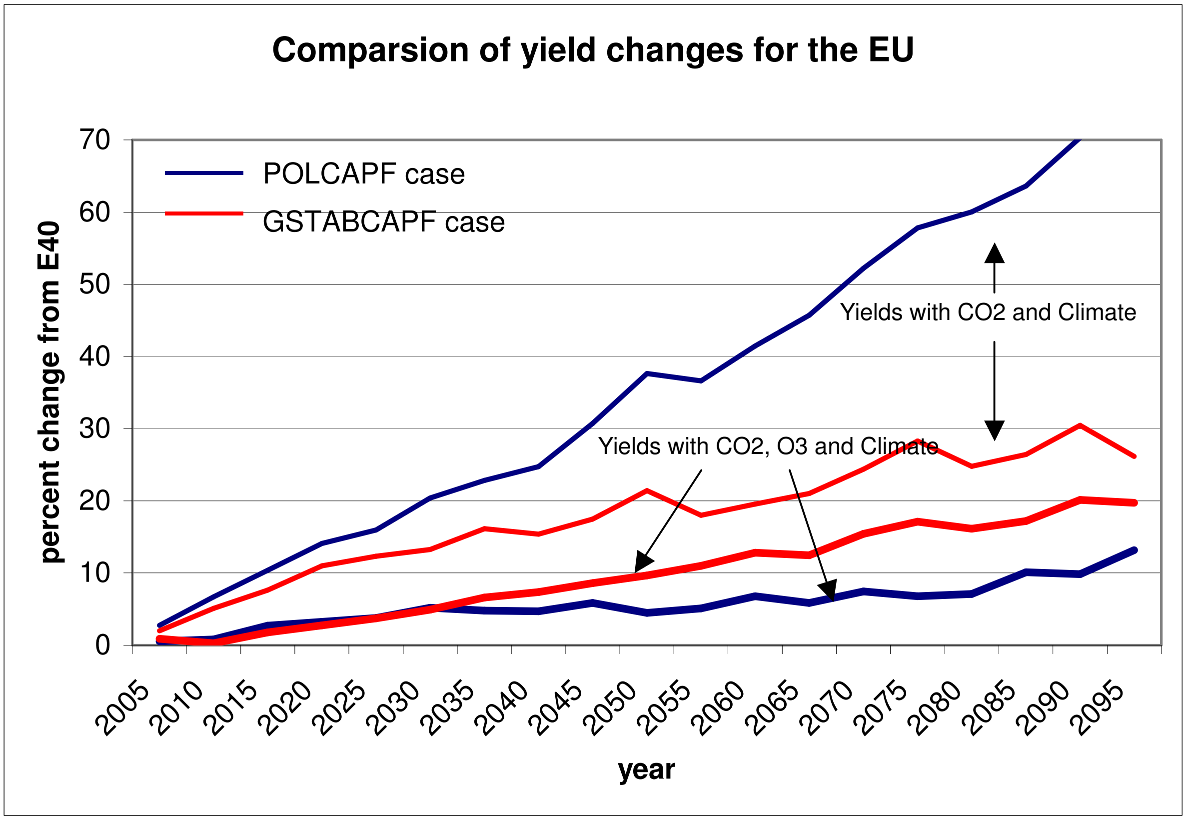
Figure 20 compares the yields change from GSTABCAPF/GSTABCAPF CTL and POLCAPF/POLCAPF CTL. The simulations with only CO2 and climate produce the highest yields for both scenarios, and POLCAPF with higher yield mostly because there are less greenhouse gases available in GSTABCAPF. However, the order is reversed when we consider ozone damage, which the yield with emissions constraints is higher than the yield without.

China is the only region that experiences negative yield due to ozone damage, when greenhouse gases emissions are not constrained.

Crop yields are closely related to the composition of the atmosphere. Ozone acts to counteract the benefits of agricultural management in both scenarios. Taking the ozone damage into consideration, the benefit of controlling greenhouse gases outweighs the positive fertilization effects. A possible explanation for this phenomenon is that policies constraining greenhouse gas emissions directly reduce fossil fuel activities, which in turn reduce the emissions of ozone precursors, resulting in lower ozone concentration in the atmosphere.

Figure 20: Yield comparison for POLCAPF and GSTABCAPF




Comparsion of yield changes for the EU
percent change from E40
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POLCAPF case
GSTABCAPF case
Yields with CO2 and Climate
Yields with CO2, O3 and Climate
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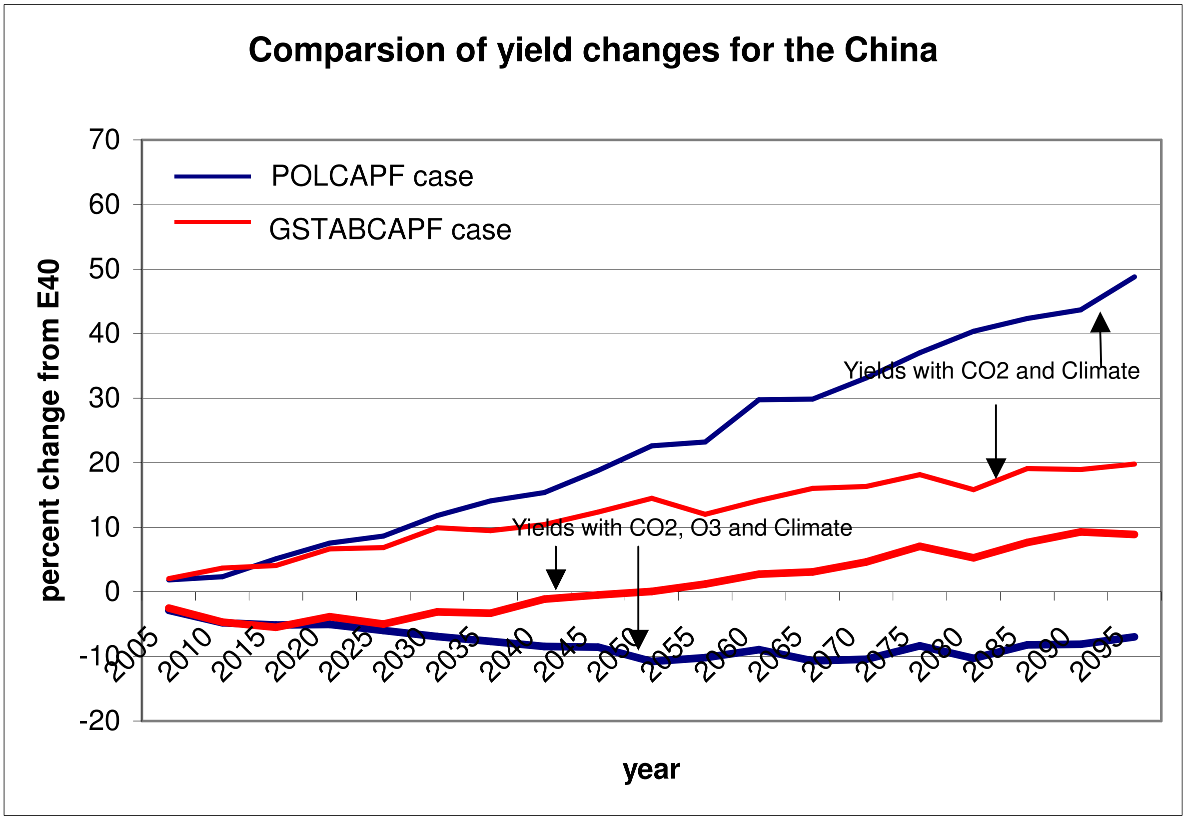
year


Comparsion of yield changes for the China
percent change from E40
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POLCAPF case
GSTABCAPF case
Yields with CO2 and Climate
Yields with CO2, O3 and Climate
2005
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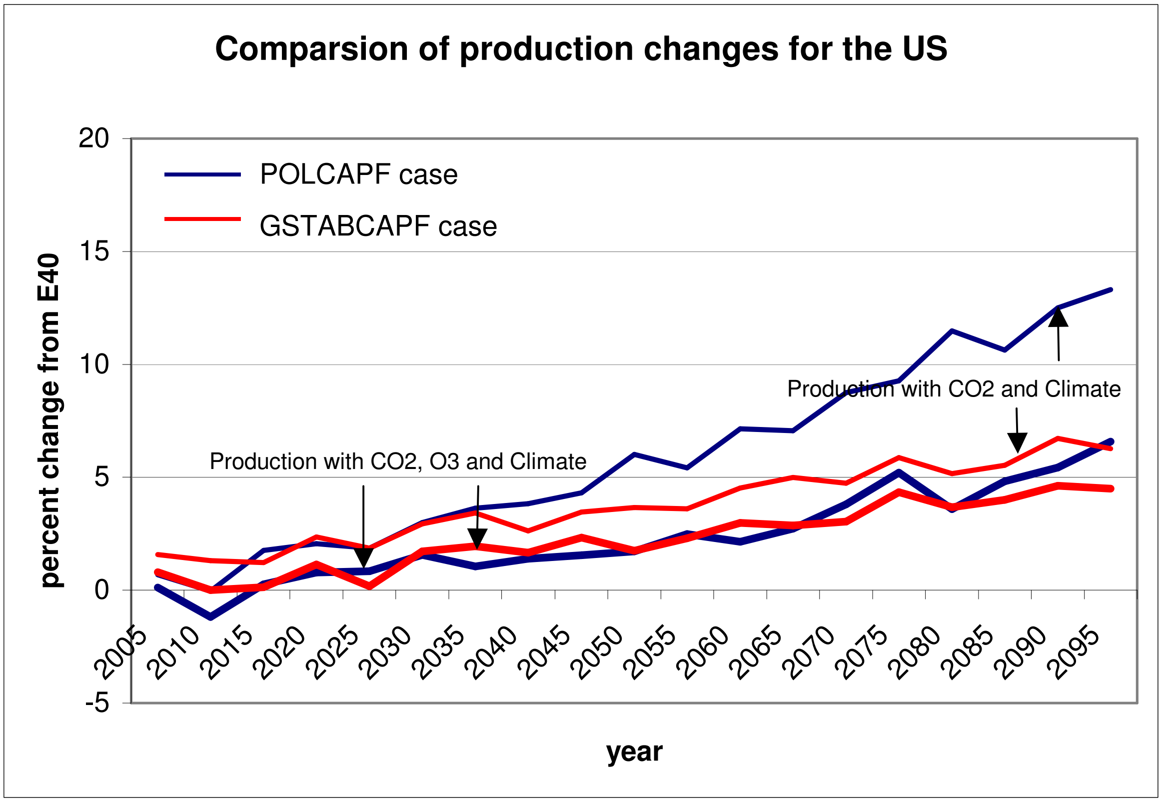
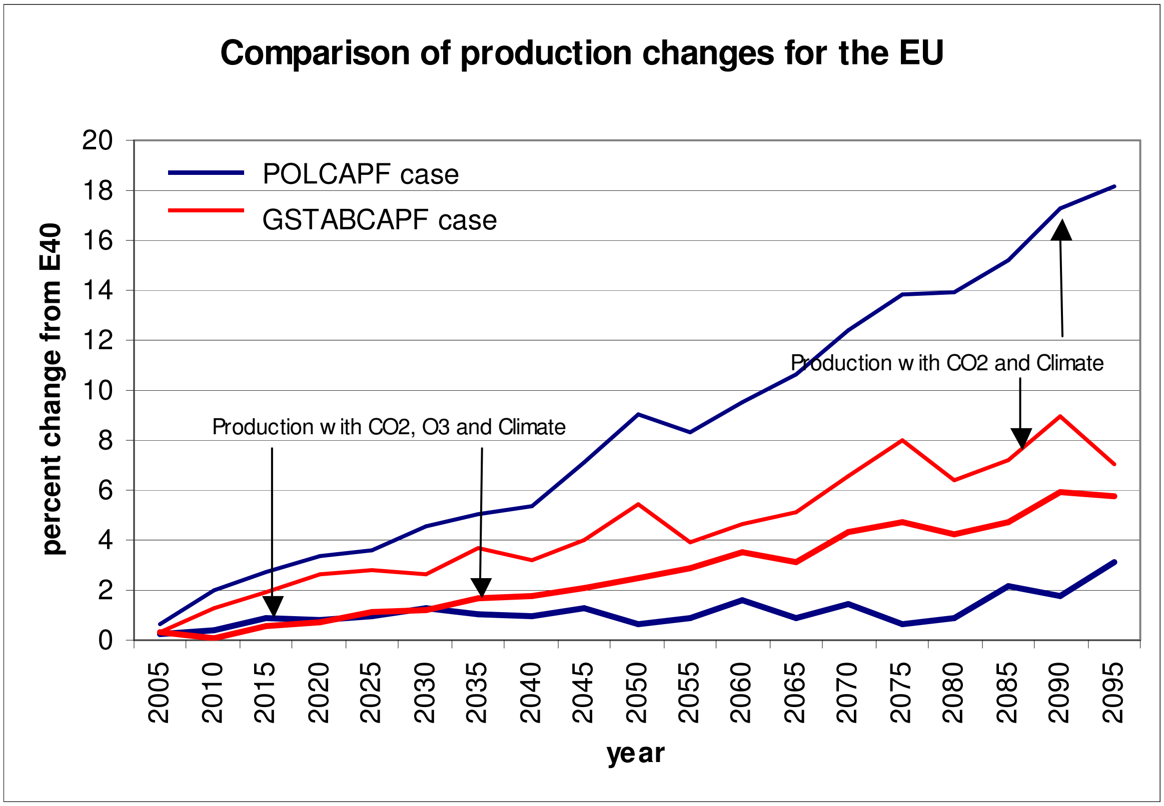
year

3.3.2.2 Production Change in Crops with Scenarios Comparison

The production changes are consistently less significant in GSTABCAPF for all regions. However, when comparing the production changes in GSTABCAPF with those in POLCAPF, it is interesting to note that when ozone pollution is included, all three regions have higher production changes in GSTABCAPF than those in POLCAPF. This is consistent with the yield changes in the previous section. It is highly possible because the tropospheric ozone level in GSTABCAPF is substantially lower than the level projected in POLCAPF indicated in Figure 12. Therefore, not much adaptation would be needed, hence reducing the cost of production, so production will increase as the cost of production is lowered. China is the only region that experiences negative production changes for crops, which also corresponds to the negative yields from Figure 21. This indicates that China may decrease its crops production as yields go decrease. It is likely that China will shift production away from crops and rely on imports to meet its demand

Figure 21: Production comparison for POLCAPF and GSTABCAPF




Comparison of production changes for the EU
percent change from E40
20
18
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14
12
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8
6
4
2
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POLCAPF case
GSTABCAPF case
Production w ith CO2, O3 and Climate
Production w ith CO2 and Climate
2005
2010
2015
2020
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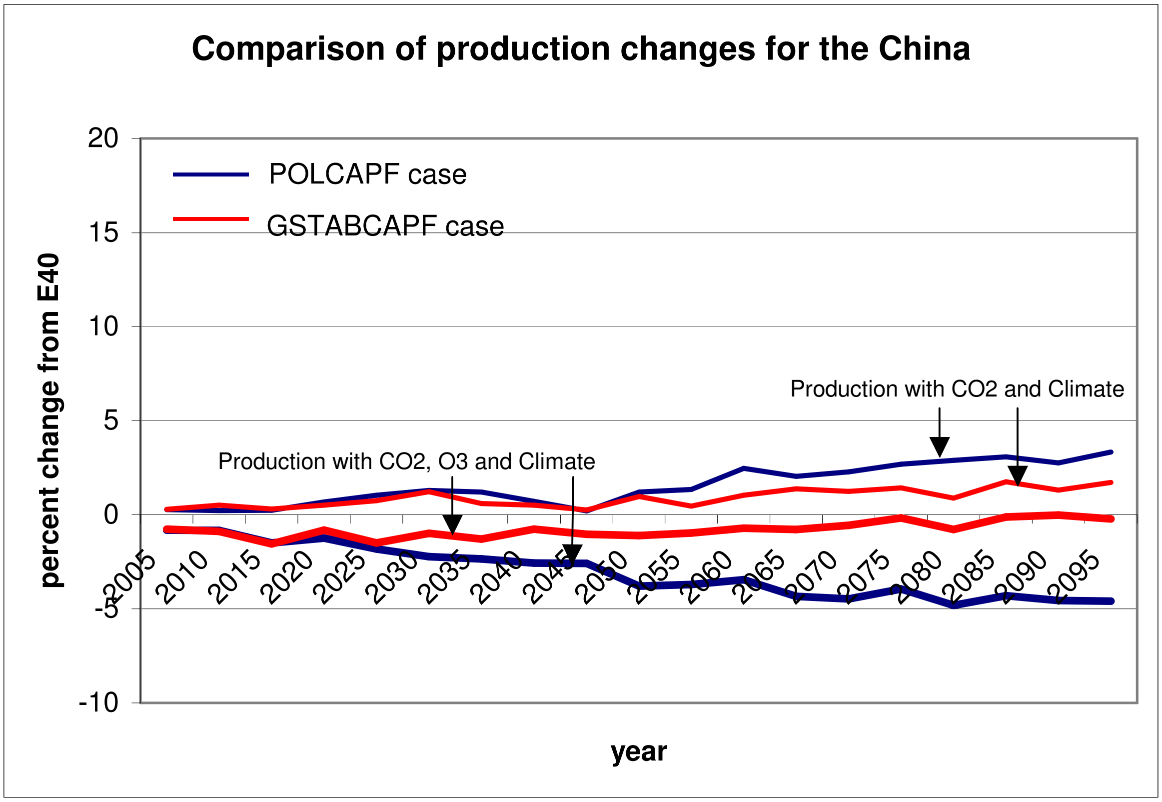
Comparison of production changes for the China
percent change from E40
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POLCAPF case
GSTABCAPF case
Production with CO2, O3 and Climate
Production with CO2 and Climate
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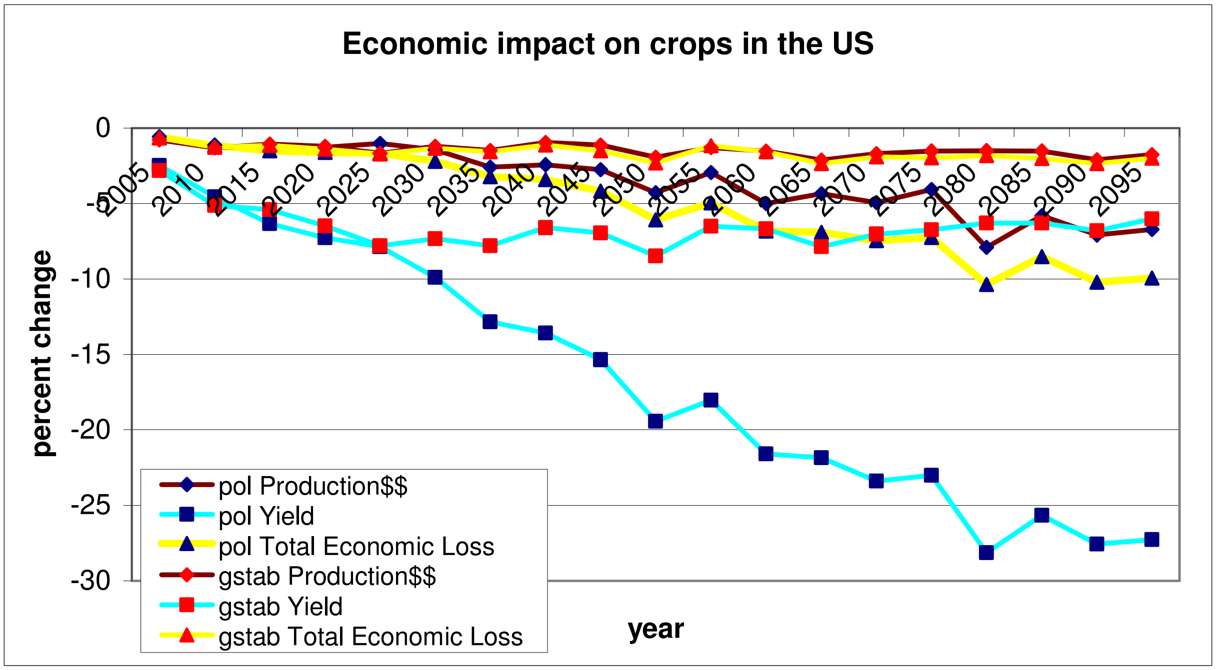
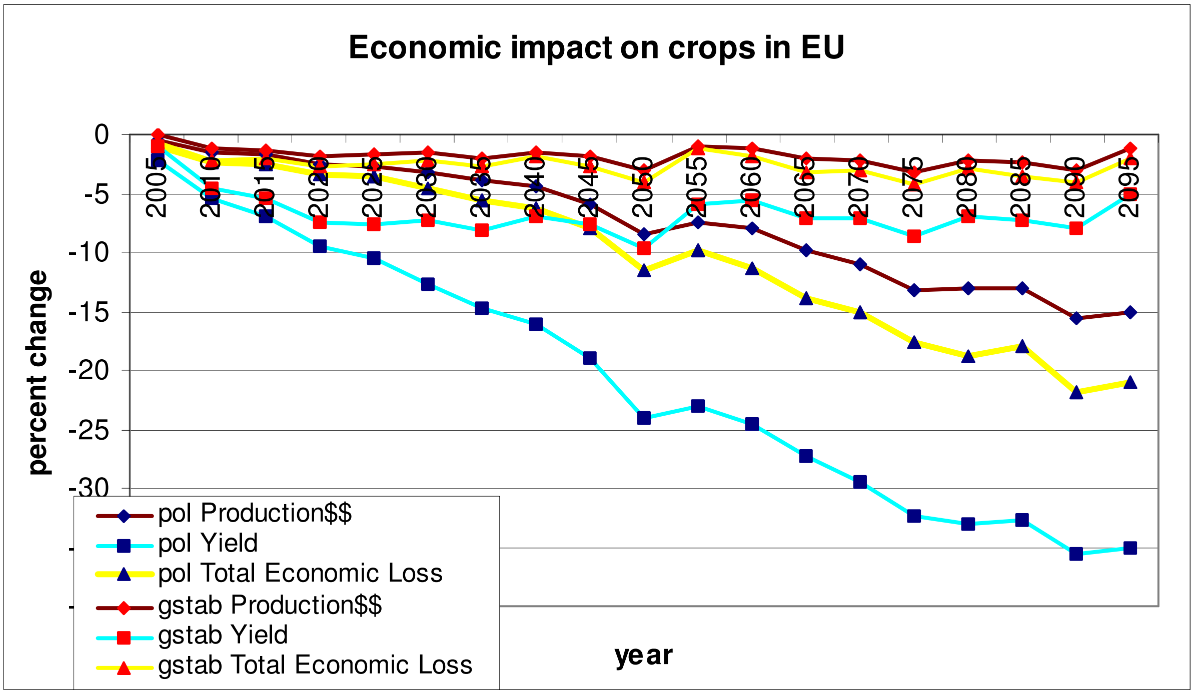
year

3.3.2.3 Economic Impact Comparison on Crops

In all three regions, the economic cost on production, yield, and consumption is significantly reduced when greenhouse gas emissions are constrained, though the economic cost of ozone damage still exits (Figure 22). This can be explained by adaptation, not just to ozone, but more importantly to greenhouse gas emission constraints. Policies imposing constraints on greenhouse gas emissions directly affect activities involving the combustion of fossil fuels, as they are the largest source of anthropogenic greenhouse gas emissions. At the same time, declines of fossil fuel combustions will reduce not only CO_2 and methane, but also the precursors of tropospheric ozone such as CO, NOx and NMVOCs. Therefore, the economic cost of ozone damage mitigates from adaptations to activities that reduce fossil fuel combustions.

Figure 22: Economic impact comparison for crops




Economic impact on crops in EU
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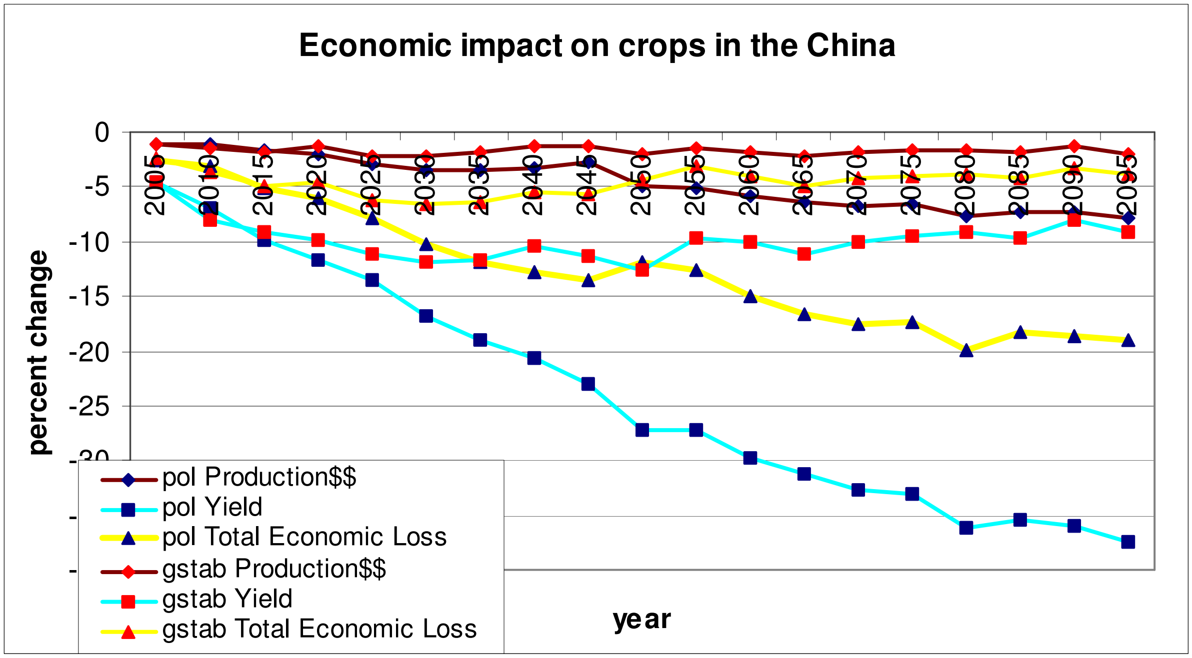
Economic impact on crops in the China
percent change
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3.3.2.4 Consumption Loss

Most of the results are very similar to the POLCAPF/POLCAPFCTL case, except for total loss in consumption due to ozone damage (Table 9). At the end of 2100, the consumption loss due to ozone drops almost 50% in this scenario compared with the previous case. The difference is significant because it demonstrates the importance of setting climate policies to control greenhouse gases emissions. Agricultural economy in developing countries such as China benefit substantially from climate policies that constrain the emissions of greenhouse gases, although they are not required to participate in currently emission restrictions in reality.

Table 9: Consumption loss comparison between POLCAPF and GSTABCAPF (billion)

	USA	USA	EUR	EUR	CHN	CHN
2005	7.429	7.297	16.503	17.012	17.643	17.502
2010	6.24	6.212	11.637	11.353	27.527	27.212
2015	8.019	8.087	15.72	15.787	36.631	37.863
2020	9.667	8.914	17.637	16.84	48.046	46.168
2025	11.092	10.472	21.441	19.984	64.158	59.883
2030	12.871	12.672	24.715	22.508	85.176	78.536
2035	15.964	13.631	31.638	25.008	112.466	96.717
2040	21.097	16.654	39.751	31.043	138.826	113.025
2045	24.603	17.799	47.968	32.888	157.654	119.774
2050	31.201	22.483	63.064	41.987	159.866	123.556
2055	42.198	29.097	86.92	55.609	150.028	101.95
2060	44.079	29.315	90.826	48.9	195.004	122.103
2065	57.517	35.595	112.016	60.812	253.11	157.518
2070	64.585	43.841	139.415	78.515	302.884	195.76
2075	75.874	47.414	165.313	88.838	355.37	213.61
2080	84.022	53.801	200.38	109.599	401.246	239.853
2085	108.482	58.887	228.946	111.174	477.88	265.312
2090	110.227	67.238	250.836	132.688	510.615	301.899
2095	133.786	78.256	309.676	155.18	569.473	314.186
2100	147.79	84.687	338.682	152.029	635.571	357.505

🟦 POLCAPF / POLCAPF CTL
🟧 GSTABCAPF / GSTABCAPF CTL

In addition to responding to greenhouse gas emissions, changes in the consumption level also correlate to the income level of the country. Agriculture is a relatively small sector in developed countries, so the tropospheric ozone will not impose as much damage as it does for developing countries, as agriculture is still a sizeable sector in developing countries. Therefore, the consumption loss is much greater in China than it is in the US or EU. Additionally, developed countries may be better equipped for adaptation potentially due to better technology. Therefore, they are able to reallocate resources away from activities that could be affected by ozone or other pollution. As an example, even though both EU and China started the consumption loss level at around 17 billion dollars, the difference increases over time, and China suffers roughly 60% more consumption loss than EU in 2050.

Chapter 4: Policy Analysis

Tropospheric ozone imposes negative impact on agriculture and on consumption, but constraining the emission levels of greenhouse gases can mitigate the damage from ozone. Results from my simulations may provide insightful details for future policy making. The relevant policies may involve climate, economics, and the environment. Each of the policy areas could affect the welfare of participating countries substantially, and they are explained separately.

4.1 Climate Policy

From the previous section on the damage of tropospheric ozone, it is obvious that the greenhouse gases impose mixed effects on crops. On one hand, having high concentration of CO_2 in the air will very likely induce positive response from crops because of the fertilization effect. On the other hand, combustion of fossil fuels that contributes to CO_2 emissions also causes emissions of ozone precursors, which directly affect the ozone level in the troposphere, and lead to yields reduction. Sirotenko *et al.* (1997) obtained similar outcomes that the tropospheric ozone consistently complicates carbon dioxide’s fertilization effect on crop yields in Russia.

However, by comparing results from scenarios of POLCAPF/POLCAPF CTL and GSTABCAPF/GSTABCAPF CTL, the significance of constraining greenhouse gases becomes apparent. In Figure 20, the yield from constraining greenhouse gas emissions with the ozone damage surpasses the yield of those without constraints in all regions. This finding reinforces the importance of Kyoto Protocol and also manifests indirect benefits for countries that constrain greenhouse gases emissions. Therefore, although developing countries may not have much incentive to regulate greenhouse gas emissions because they are not in the Protocol, my results have shown that the potential economic loss could be rather large if greenhouse gases emissions increase. For example, the consumption loss from tropospheric ozone is 50% higher for China in 2055 when greenhouse gases emissions are not controlled (Table 8). Furthermore, even with ozone damage, China is the only region that experiences negative yield change when it does not set constraints on emissions of greenhouse gases. Therefore, potential policies that propose an earlier entrance date for developing countries into Kyoto will find these findings useful.

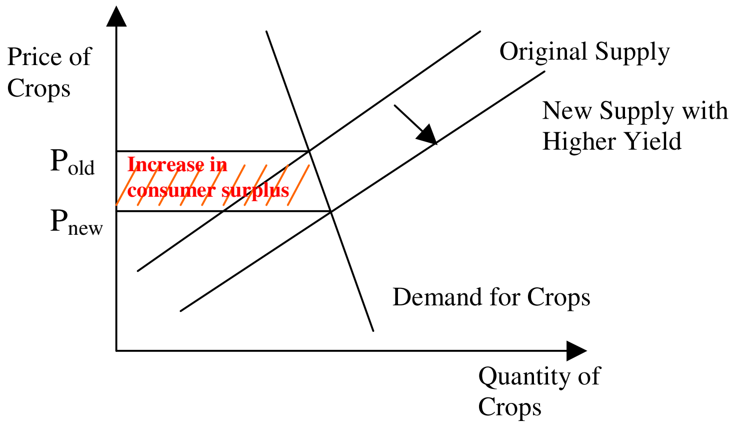
On the other hand, countries that do experience ozone damage on agriculture could consider constraining their greenhouse gases emissions as an alternative method for mitigating the negative impact. The reduction of tropospheric ozone will not only alleviate ozone's negative impact on the economy, but will also increase carbon uptake in the ecosystem, as fewer crops would be damaged by ozone (Felzer *et al.*, 2004). The direct impact of ozone on climate as a greenhouse gas will also be controlled.

More flexible climate policies can be introduced to mitigate the damage from tropospheric ozone as well. Governments could address the issue of ozone pollution by limiting the emission of carbon monoxide and nitrogen oxide, while giving more time for developing nations to limit carbon dioxide, which could improve crops yield in the short run. For example, EPA in 1998 issued a rule that will significantly reduce regional emissions of nitrogen oxides in 22 states and the District of Columbia, and in turn, reduce the regional transport of ozone.

4.2 Economic Policy

Global climate usually affects agriculture on regional levels with various effects. The small positive effect on production for crops compared with substantial increase in yields in the US and EU shows that these economies adapt to the climate change by reallocating resources away from crop production to other uses. Crops are essential commodities for survival but have very low demand price elasticity, thus consumers are unresponsive to falling prices, even though supply increases due to higher yields. As a result, without an increase in demand, the productions of crops are not stimulated to increase. However, there is an increase in consumer surplus because the price has fallen, and resources are freed for use in other sectors (Figure 23).

Figure 23: Supply and demand for crops with higher yields



On the other hand, China may experience negative yields due to ozone damage, and result in negative production effect. It is very likely that China will be dependant on imports of crops to satisfy the demand from its the population. Additionally, as projected by FAO and IFPRI, when income grows, the demand for livestock may bypass the demand for crops in the future for developing countries. The negative production effect for crops shown here may be compounded by potential negative production effect for livestock. My results qualitatively demonstrate that this is a conceivable scenario in China. Hence, the welfare for the agricultural economy in China might suffer in the future from ozone damage as the sector relies more on imports. The analysis presented here may serve as a preliminary guideline for policy makers to identify the consequences of ozone damage on issues such as international trade and economic welfare.

4.3 Environmental Policy

The control of tropospheric ozone concentrations in the United States has been motivated primarily by the need to protect human health. Only in the past two decades was tropospheric ozone concentration linked to declining crops productivities (Mauzeall and Wang, 2001). Statistics show that the US spent just under 50 billion dollars on health expenses due to ozone exposure in 2000 (Yang *et al.*, 2004). From my simulations, if I aggregate the economic cost on consumption from crops, livestock and forestry, the loss would be around 2.8 billion dollars, roughly 5% of the health care expenditure due to ozone exposure. Therefore, it would be useful to evaluate the stringency of current ozone standard taking into account of the damage on agriculture.

In my analysis, adaptation has been attributed to a number of scenarios to explain the nominal changes in agriculture production. Although the specific strategies of adaptation are not explicitly stated, they could include: shift in sowing dates, different crop varieties, more efficient irrigation or water supply systems, etc. Unfortunately, many of these adaptation methods have profound consequences on the environment. For example, a study found that increased pressure on groundwater resources in the aquifer region around San Antonio, Texas would threaten endangered species dependent on spring flows supported by the aquifer (Reilly *et al.*, 2001). Similarly, a new species of crops that would produce higher yields might require a different type of chemicals that could release more greenhouse gases. Therefore, even though the implications of adaptations are beyond the scope of this thesis, it is important to keep in mind the potential environmental impacts associations with different adaptation strategies.

Chapter 5: Conclusion

Much research has been done in the past on the damage to agriculture from the climate and tropospheric ozone, but most of them do not include an economic assessment of the damage. My research has confirmed the speculations that tropospheric ozone negates the positive fertilization effects from carbon dioxide on crops. I have also provided economic analysis on the negative impact from ozone pollution. Furthermore, I compared simulation results from two different scenarios, where the emissions level for greenhouse gases was constrained in one case, but uncontrolled in another. The findings uncover additional benefit of constraining greenhouse gas emissions, which it reduces the damage on production, yield and consumption from ozone pollution.

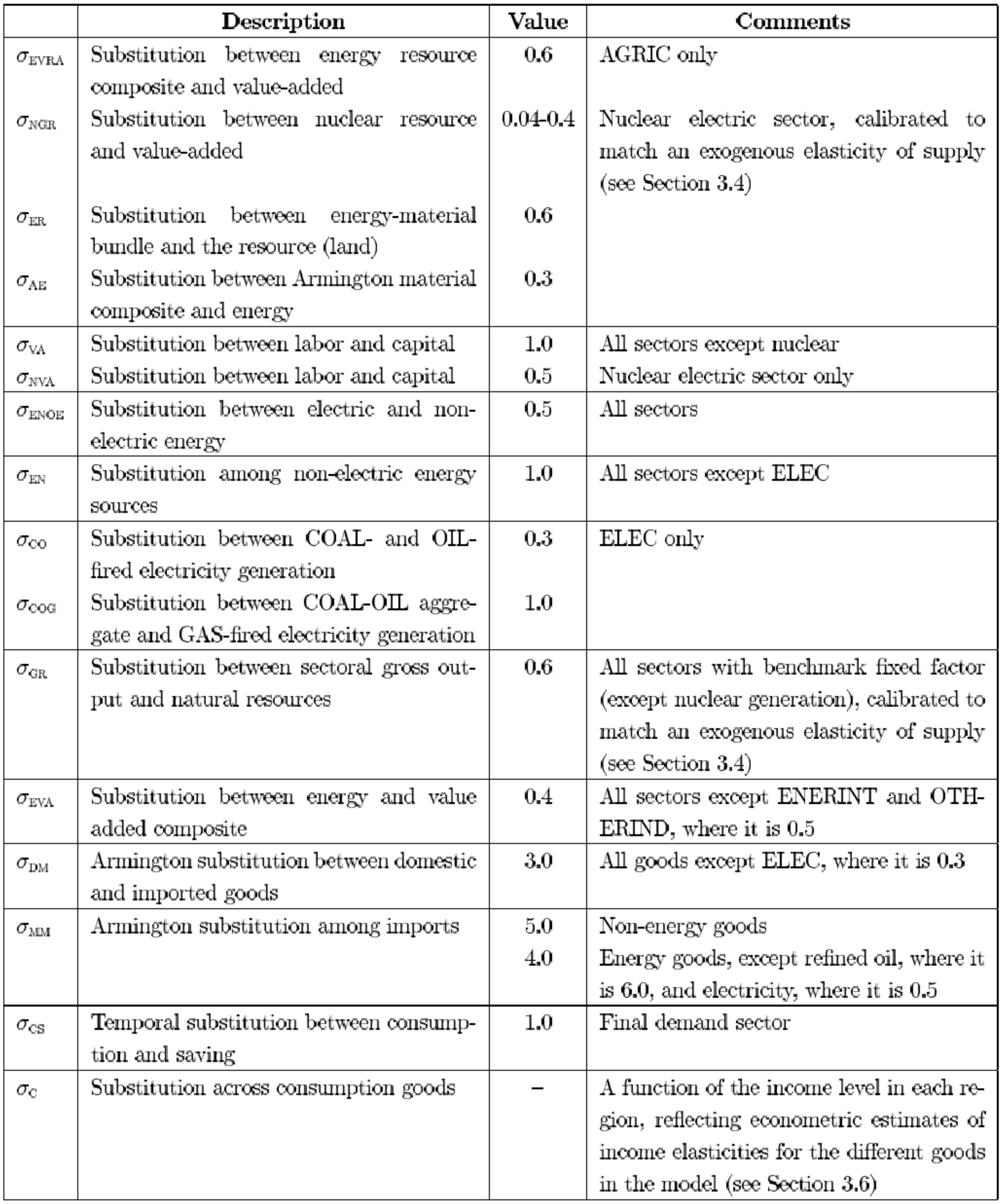
The experiment was simulated on three regions, the United States, the European Union, and China, where the ozone pollution level is the highest, and the damage on agricultural land is the greatest. The results have not only revealed how different regions would adapt to the ozone pollution, but have also provided guidelines for future policy making involving climate, economics, and environment.

The model I have used to derive my results is a special version of the MIT EPPA Model for which the original agriculture sector has been disaggregated to model the behavior of crops, livestock and forestry. One of the main drawbacks of the EPPA model is that it implements CES production and consumption functions that are homogeneous degree of one. The model fails to reflect the Engel's law.

A different implementation, AIDADS, is able to incorporate Engel's law into the demand system. Currently the AIDADS is not implemented in EPPA Agriculture model. I only predicted the values of food budget share using formulas from AIDADS, but the dynamic of solving the income elasticity is yet to be completed. Therefore, future research could continue with the current interaction between ADIDAS and CES and hopefully integrate the AIDADS system into EPPA. The advantage of ADDADS is that the demand system is more sophisticated than CES, and it would be useful to compare how sectors are predicted to grow using AIDADS.

Appendix A

Default Values of Key Substitution Elasticities (Babiker *et al.,* 2001)



	Description	Value	Comments
σ_{EVRA}	Substitution between energy resource composite and value-added	0.6	AGRIC only
σ_{NGR}	Substitution between nuclear resource and value-added	0.04-0.4	Nuclear electric sector, calibrated to match an exogenous elasticity of supply (see Section 3.4)
σ_{ER}	Substitution between energy-material bundle and the resource (land)	0.6	
σ_{AE}	Substitution between Armington material composite and energy	0.3	
σ_{VA}	Substitution between labor and capital	1.0	All sectors except nuclear
σ_{NVA}	Substitution between labor and capital	0.5	Nuclear electric sector only
σ_{ENOE}	Substitution between electric and non-electric energy	0.5	All sectors
σ_{EN}	Substitution among non-electric energy sources	1.0	All sectors except ELEC
σ_{CO}	Substitution between COAL- and OIL-fired electricity generation	0.3	ELEC only
σ_{COG}	Substitution between COAL-OIL aggregate and GAS-fired electricity generation	1.0	
σ_{GR}	Substitution between sectoral gross output and natural resources	0.6	All sectors with benchmark fixed factor (except nuclear generation), calibrated to match an exogenous elasticity of supply (see Section 3.4)
σ_{EVA}	Substitution between energy and value added composite	0.4	All sectors except ENERINT and OTHERIND, where it is 0.5
σ_{DM}	Armington substitution between domestic and imported goods	3.0	All goods except ELEC, where it is 0.3
σ_{MM}	Armington substitution among imports	5.0 4.0	Non-energy goods Energy goods, except refined oil, where it is 6.0, and electricity, where it is 0.5
σ_{CS}	Temporal substitution between consumption and saving	1.0	Final demand sector
σ_{C}	Substitution across consumption goods	–	A function of the income level in each region, reflecting econometric estimates of income elasticities for the different goods in the model (see Section 3.6)

Appendix B

Economic Derivation of Elasticity of Substitution for CES Functions

A typical CES utility function has the form of:

$$u = u(x, y) = (x^{\rho} + y^{\rho})^{1/\rho}$$

An indifference curve is then given:

$$u = const = (x^{\rho} + y^{\rho})^{1/\rho} \Leftrightarrow u^{\rho} = x^{\rho} + y^{\rho} \Leftrightarrow y = (u^{\rho} - x^{\rho})^{1/\rho}$$

Marginal rate of substitution is then calculated as:

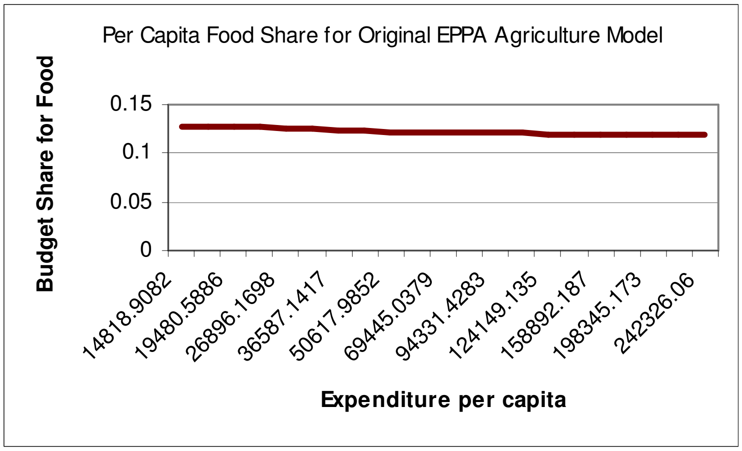
$$MRS = -\frac{dy}{dx} = -\frac{1}{\rho}(u^{\rho} - x^{\rho})^{\frac{1}{\rho}-1}(-\rho)x^{\rho-1} = (\frac{y}{x})^{1-\rho}$$

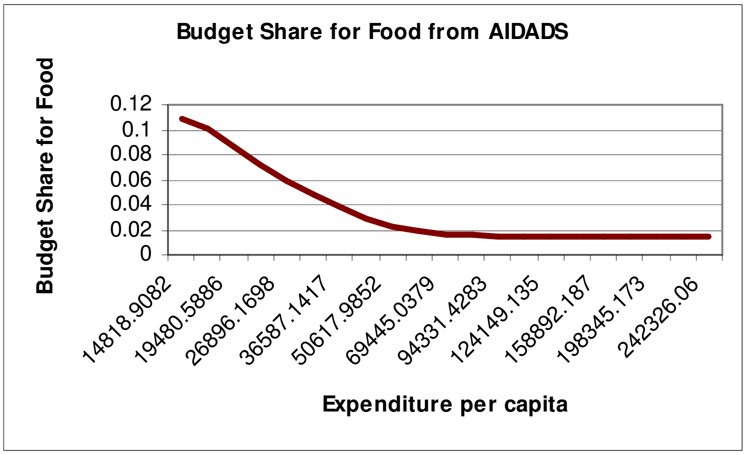
We then use substitution of variables, since in our calculation MRS is a function of (*y/x*). We denote X = MRS, and Y = y/x. We obtain for the elasticity of substitution:

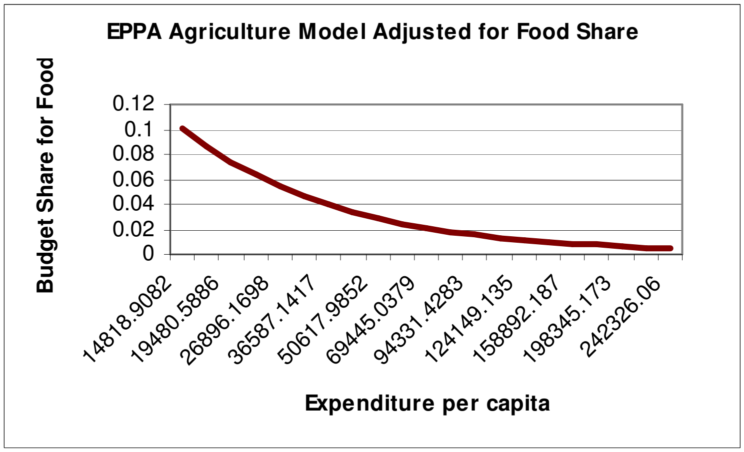
$$\eta = \frac{dY}{dX}\frac{X}{Y} = \left(\frac{1}{1-\rho}X^{\frac{1}{1-\rho}-1}\right)\frac{X}{\left(X^{\frac{1}{1-\rho}}\right)} = \frac{1}{1-\rho}$$

Appendix C

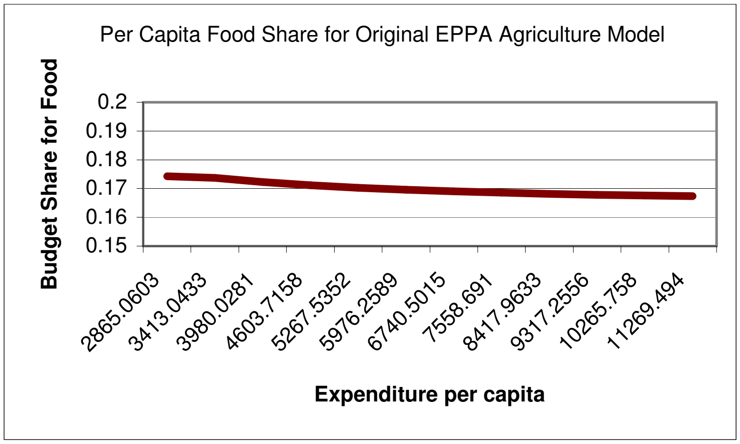
AIDADS Estimates for EPPA – European Union

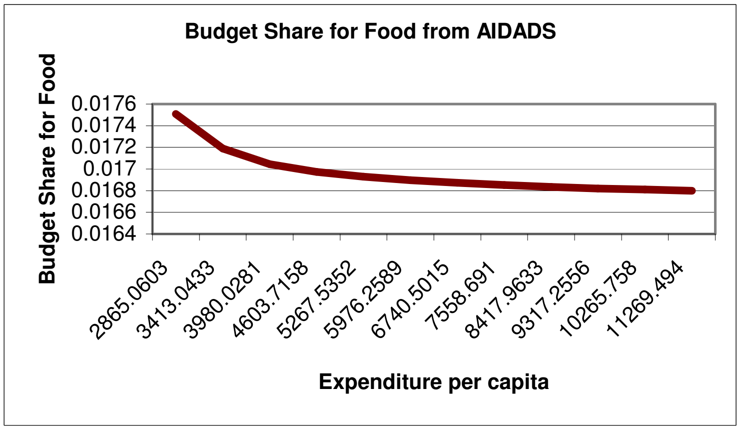


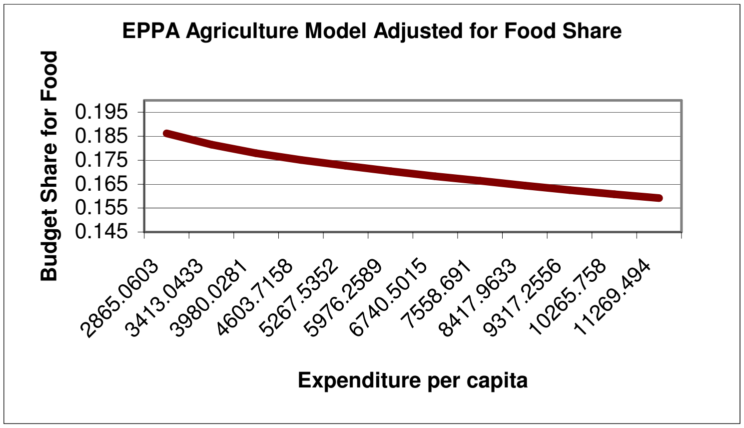




AIDADS Estimates for EPPA – China







Appendix D

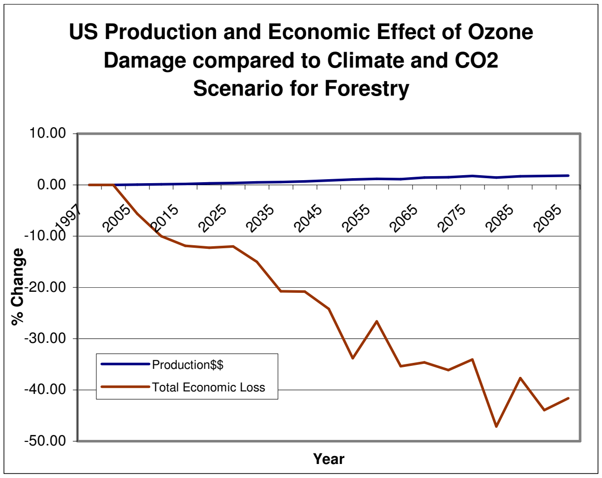
Economic Derivation of Elasticity of Substitution for CES Functions

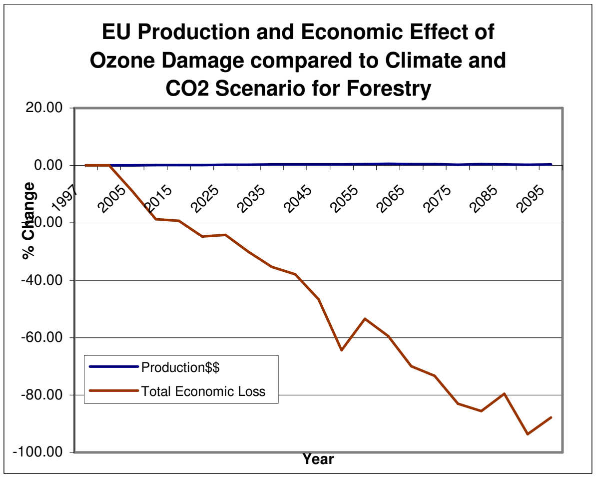
Plant Characteristic	**Effect of elevated surface level O3**
Photosynthesis	Decreased in most species
Leaf conductance	Decreased in sensitive species and cultivars
Water-use efficiency	Decreased in sensitive species
Leaf area	Decreased in sensitive species
Specific leaf weight	Increased in sensitive species
Crop maturation rate	Decreased
Flowering	Decreased floral yield, fruit set and yield, delayed fruit set
Dry matter production and yield	Decreased in most species
Sensitivity between cultivars (within species)	Frequently large variability
Drought stress sensitivity	Plants become less sensitive to O3 but sensitive to drought
Mineral stress sensitivity	Plants become more susceptible to O3 injury

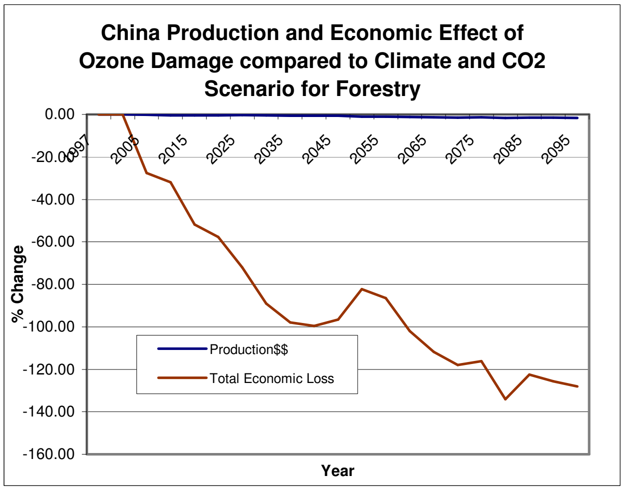
Appendix E

The POLCAPF/POLCAPF CTL case

Economic Impact of Ozone on Forestry

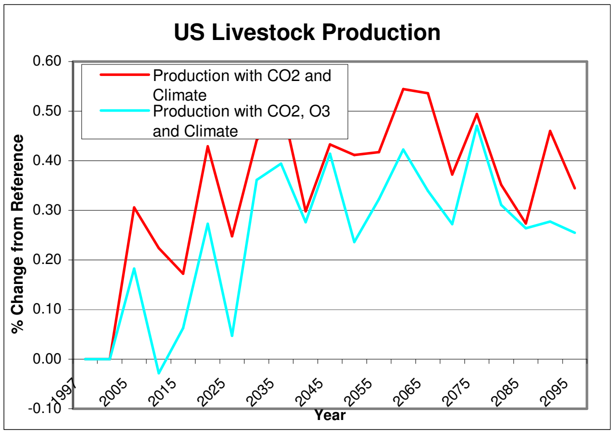


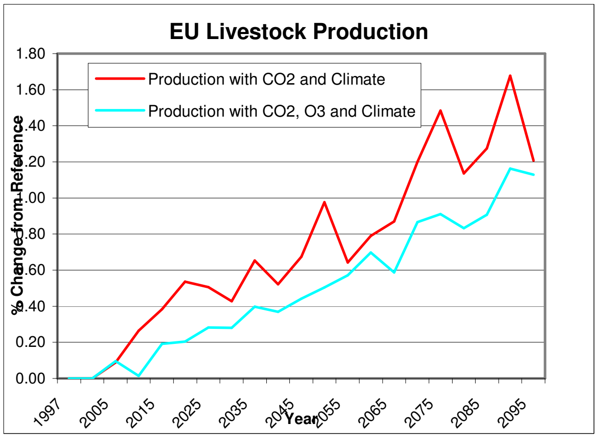


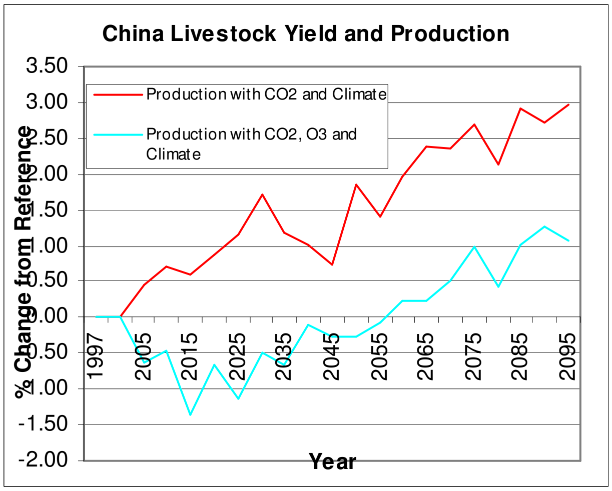


The GSTABCAPF/GSTABCAPF CTL case

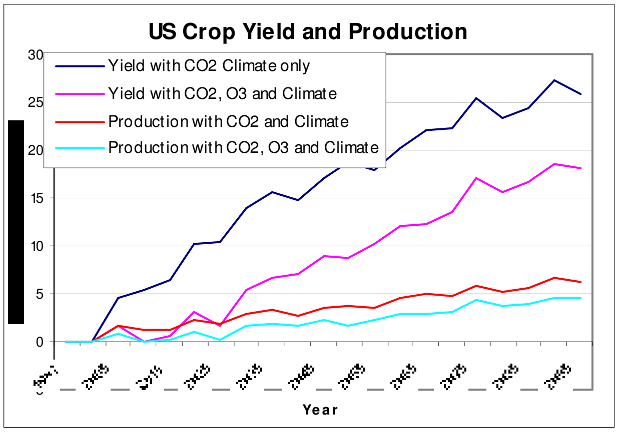
Production for Livestock in the US, EU and China

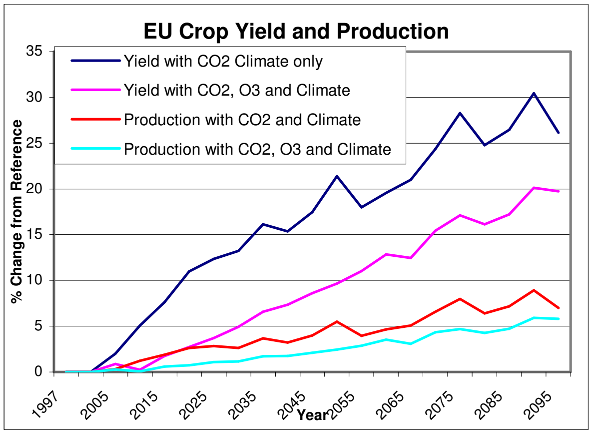


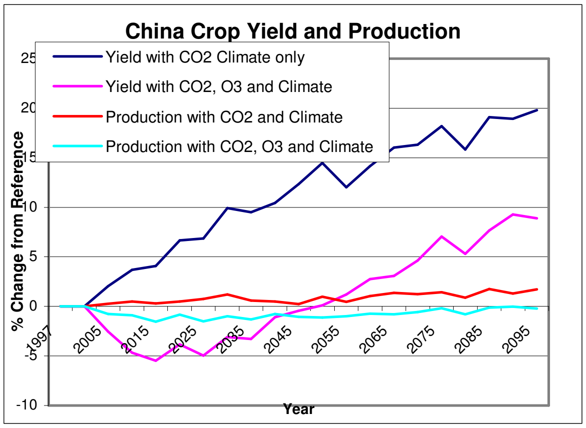




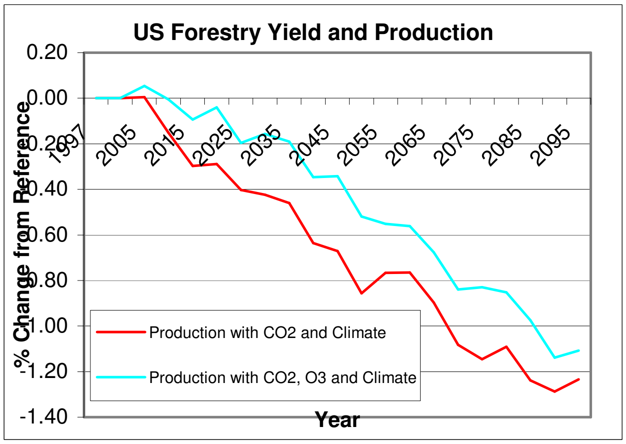
Yield and Production for Crops in the US, EU and China

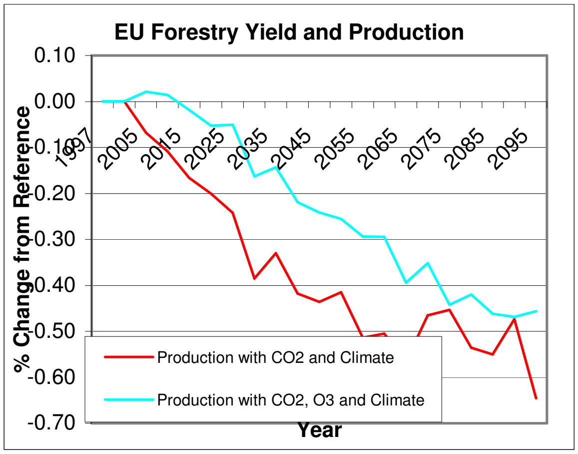


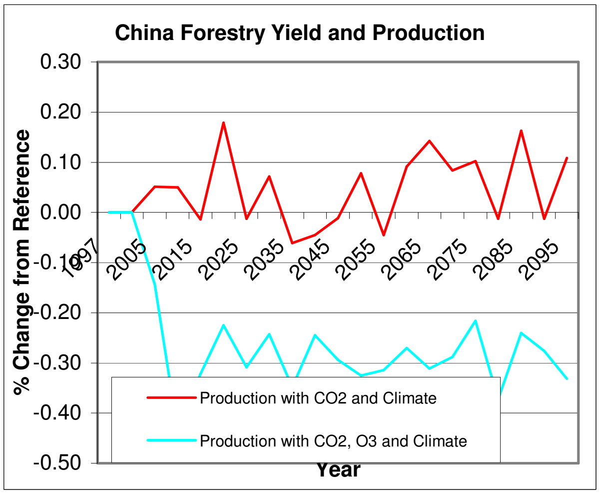




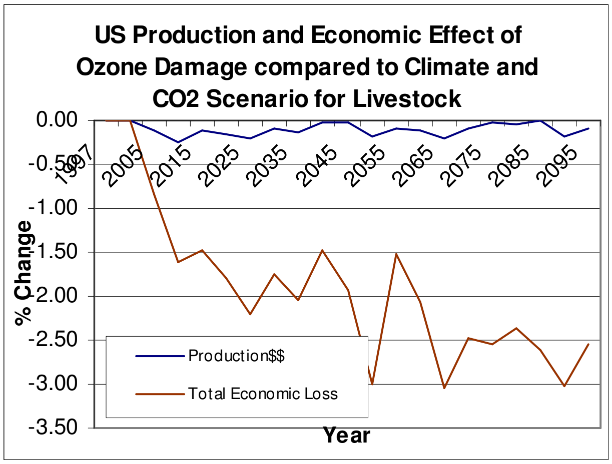
Production for Forestry in the US, EU and China

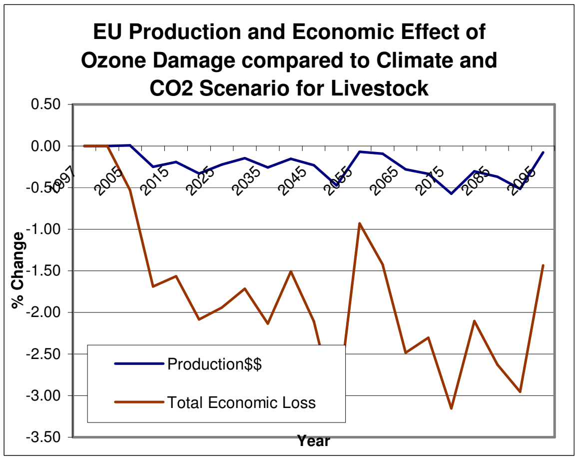


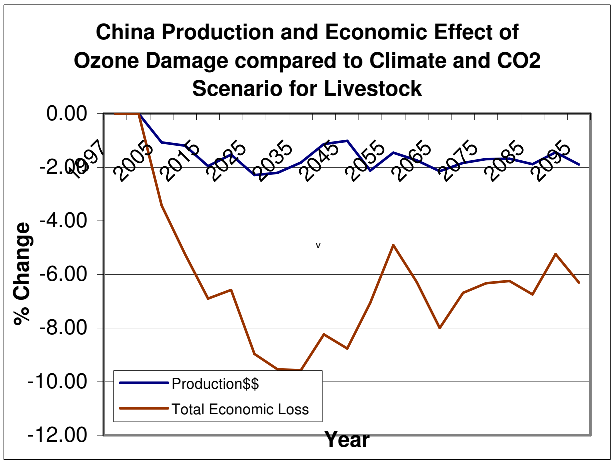




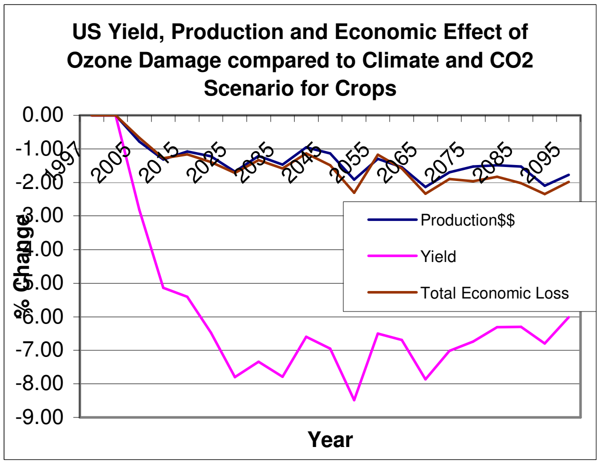
Economic Impact of Ozone on Livestock

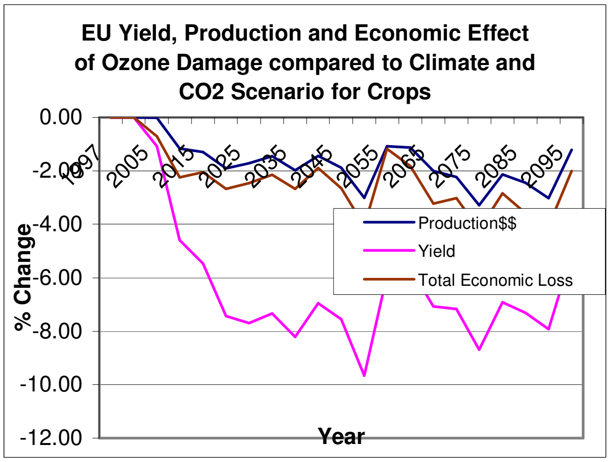


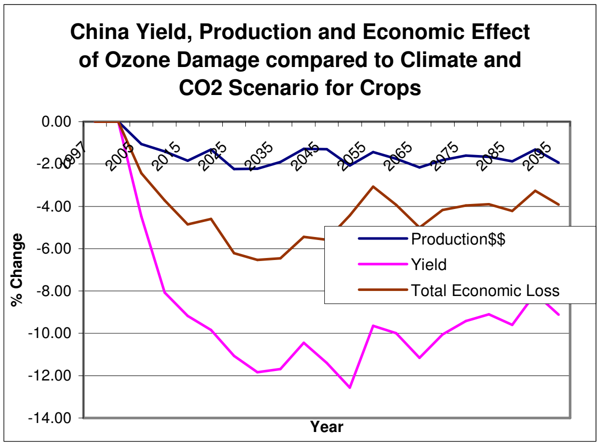




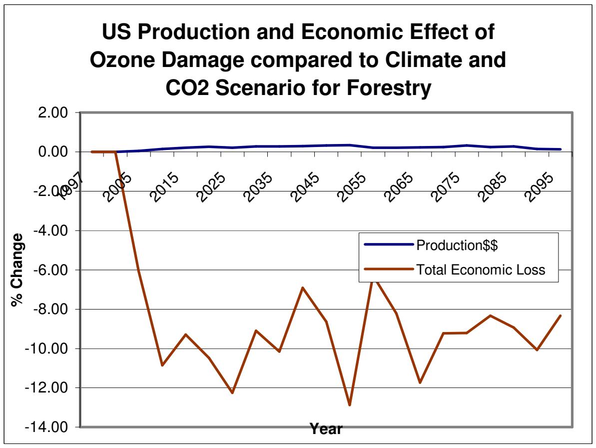
Economic Impact of Ozone on Crops

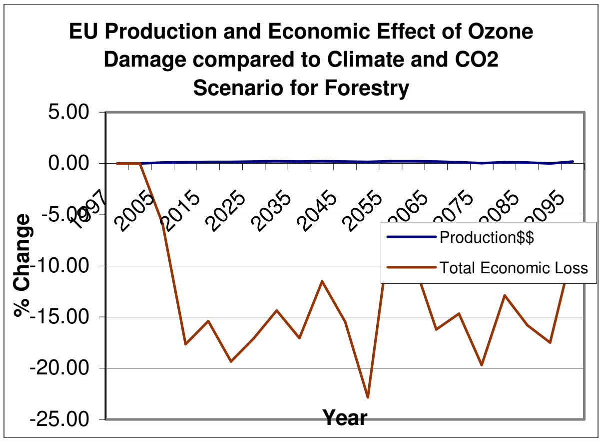


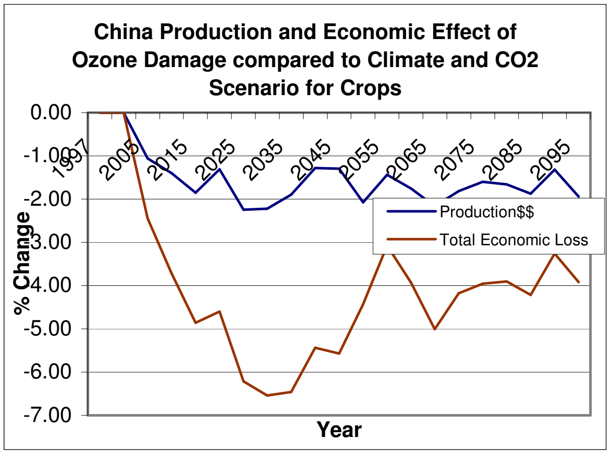




Economic Impact of Ozone on Forestry







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