The Impact of Including Water Constraints on Food Production within a CGE Framework

by

Jonathan Early Baker

B.S., Davidson College (2006)
M.S., Purdue University (2008)

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Author ....
Engineering Systems Division
August 5, 2011

Certified by ....
John M. Reilly
Senior Lecturer, MIT Sloan School of Management
Thesis Supervisor

Certified by ....
Kenneth M. Strzepek
Research Scientist, MIT Center for Global Change Science
Thesis Reader

Accepted by ....
Dava J. Newman
Professor of Aeronautics and Astronautics and Engineering Systems
Director, Technology and Policy Program

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Abstract

This research explores the long-term relationship between water resources, irrigated land use change and crop production within a computable general equilibrium modeling framework. The modeling approach is developed on a variant of the MIT Emissions Prediction and Policy Analysis (EPPA) model that describes three agriculture sectors–crops, livestock and managed forestry–five land types–cropland, pasture land, managed forest land, natural grass land and natural forest land–and conversion among these land types. I further develop this framework by describing crop production as the aggregate production of crops grown on irrigated and non-irrigated cropland. Water resources, through the parameterization of regional irrigable land supply curves, limit conversion to irrigated cropland and thus constrain regional crop production.

Land use change, dynamics of irrigated land and regional water demand and crop production are investigated with the new model structure. Non-irrigated cropland is found be expanding faster than irrigated cropland. However, regionally, competition from biofuels for non-irrigated cropland may drive further expansion in irrigated cropland. Regarding water demand, most regions are withdrawing a very small share of their renewable water resource. Crop production levels are compared to results from a model that does not include water constraints. Global crop production declines a small amount with the most significant regional effect observed in the Middle East where regional water constraints have severely restricted the area by which irrigated cropland can expand. This result highlights the importance of considering water resource constraints in regions that experience, or might experience, shortages of water.

Thesis Supervisor: John M. Reilly
Title: Senior Lecturer, MIT Sloan School of Management

Thesis Reader: Kenneth M. Strzepek
Title: Research Scientist, MIT Center for Global Change Science

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Chapter 1

Motivation

1.1 Introduction

Irrigation currently accounts for approximately 70 % of the world's total water consumption (Berrittella et al., 2007) and as such, water and food production are inextricably connected. For example, Johansson et al. (2002) note that "Irrigated agriculture now occupies 18% of the total arable land in the world and produces more than 33% of its total agricultural production". The linkage between water and food supply is significant considering the concern regarding increased scarcity of global water resources. In a study investigating human appropriation of renewable freshwater, Postel et al. (1996) estimated that the proportion of available surface runoff used by humans would increase from approximately 54 % around 1995 to over 70 % by around 2025, though the authors note that this number might understate the reality on account of future potential changes in climate. Also, in an article addressing future water resources, Rogers (2008) cites that by 2050, "as much as three quarters of the earth's population could face scarcities of freshwater". Rosegrant et al. (2002) note that pressure on the world's water supply will increase on two fronts; a fast growing water demand from industrial and domestic uses as well as increase demand for irrigation due to a growing population. The integral link between water and food combined with increased water scarcity raises concerns about future food security (Rosegrant et al., 2002).

This research explores the long-term water scarcity-food security relationship. I introduce a computable general equilibrium modeling framework that allows for the exploration of how water constraints will impact food output and prices. The model includes changes in land use, specifically addressing irrigated and non-irrigated cropland. Regional water resources constrain the amount of irrigated cropland that can be created. Specifically, this research investigates the impact of including water resources on crop production, changes in land use, specifically cropland, and the implications for water demand based on increases in irrigated area.

1.2 Context

This research sits within a much larger body of economic literature addressing water. Griffin (2006) provides a nice introduction to the field of water resource economics as a whole. A wealth of the literature has focused on the impact of water allocation mechanisms (Johansson et al., 2002) and determining the economic value of water (Johansson, 2005). Knowing the economic value of water is an important component of policy analysis (Johansson, 2005; Young, 2005). According to Young, "Perhaps the most important use of irrigation water valuation is analysis of economic tradeoffs among water-using sectors in the face of growing deamnds for water in urban and environmental uses" (Young, 2005, p. 162).

Young (2005) describes several theoretical approaches as well as applications of these approaches in the specific context of agriculture in Chapter 5 of his text "Determining the Economic Value of Water". He classifies both inductive methods such as hedonics and econometric studies, and deductive methods such as the residual method (Young, 2005) which involves subtracting the "incremental value-added (cash and non-cash) of all production inputs (with the exception of irrigation water) from the value of the total output. . . The resulting value. . . can be assumed to be the value of irrigation water" (Johansson, 2005).

This research is aimed at assessing the impacts of global changes on the economic system and thus does not investigate the value of water per se. Broadly speaking, there are two types of economic analysis used for conducting such studies; partial and general equilibrium methods. Partial equilibrium models focus on one or a few sectors in an economy. As noted by Johansson (2005), partial equilibrium models are used for investigating the direct effects of a poilcy on the sector(s) in question but do not explore indirect effects of how changes in the sector under study may alter changes in sectors not studied. In their recent survey of partial and general equilibrium models addressing water policy, Dudu and Chumi (2008) note of partial equilibrium models that "The widely researched areas have been the use of water markets and pricing in an effort to manage water scarcity". One example of a partial equilibrium model designed to assess global scale issues is the International Food Policy Research Institute's, IFPRI, IMPACT model (International Model for Policy Analysis of Agricultural Commodities and Trade) (Rosegrant et al., 2008). IMPACT is a partial equilibrium model of the global agricultural market, projecting world food prices until 2050. The model also incorporates a physical water resouce module, and together, IMPACT has been used to study the connection between water scarcity and food security under different projections of global water availability (Rosegrant et al., 2002).

The research described here, though focusing on agricultural production in this particular analysis, is part of a larger effort aimed at describing the general effects of policies and shocks on the entire economy. The focus on the entire economy, therefore, suggests a general equilibrium approach.

1.3 General Equilibirum Modeling Approaches

1.3.1 Background

General equilibrium models consider all sectors of a particular economy. Such models are often referred to in the literature as computable general equilibrium (CGE) models as they tend to be solved with the aid of a computer. CGE models are built upon a base year data set, called a social accounting matrix or SAM, that describes the flows of goods and services in all economic sectors. The CGE problem is a constrained maximization problem for households and firms, where a representative consumer(s) maximize utility and representative firms maximize profits subject to the following three constraints: zero profit, market clearance and income balance. Zero economic profits is the result of the neoclassical assumption of perfect competition. Market clearance requires supply to equal demand. Finally, income balance requires that consumers only spend as much as their income allows.

Many CGE models today rely on nested constant elasticity of substitution, or CES, functions. By way of example, consider an output, O that requires two inputs, X_1 and X_2, with some elasticity of substitution between the inputs, σ. A CES function describing the production of O is shown below:

$$O = \left(aX_1^{\frac{\sigma-1}{\sigma}} + (a-1)\, X_2^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}} \tag{1.1}$$

If $\sigma = 0$, the CES function describes a Leontief production function where inputs are used in fixed proportions to generate output, O. If $\sigma = \infty$, the inputs are perfectly substitutable. The choice of σ can have a significant impact on model results.

CES functions can be nested to describe more complex production structures; for example, to allow different elasticities between different pairs of inputs. It may be that X_1 is actually an aggregate of inputs X_3 and X_4. The sub-production of X_1 can therefore be nested within the top level production of O as:

$$O = \left(a\left(\left(bX_3^{\frac{\rho-1}{\rho}} + (b-1)\, X_4^{\frac{\rho-1}{\rho}}\right)^{\frac{\rho}{\rho-1}}\right)^{\frac{\sigma-1}{\sigma}} + (a-1)\, X_2^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}} \tag{1.2}$$

where

$$X_1 = \left(bX_3^{\frac{\rho-1}{\rho}} + (b-1)\, X_4^{\frac{\rho-1}{\rho}}\right)^{\frac{\rho}{\rho-1}} \tag{1.3}$$

CES functions can be represented diagrammatically as nested trees. Eq. (1.2) is illustrated in tree form in Figure 1-1[1].

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[1] My thanks to Chris Gillespie's ESD.801 presentation for suggesting to me the presentation of

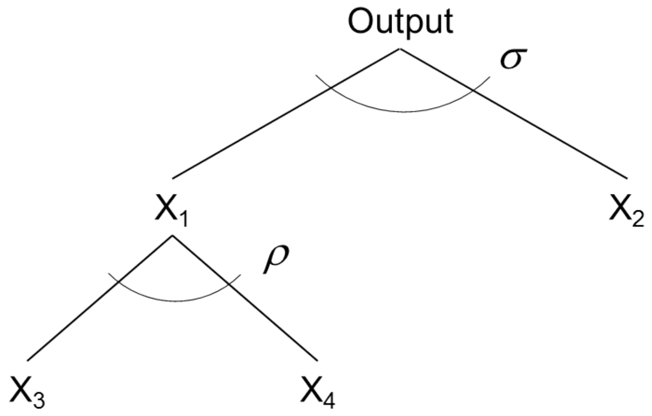

Figure 1-1: Illustration of CES tree diagram.

1.3.2 Regional CGE Approaches

Johansson et al. (2002) surveys the theory and various case studies of water pricing mechanisms and institutions for governing irrigation water allocation, presenting examples of both partial and general equilibrium approaches. Johansson (2005) then extends this survey, specifically focusing on approaches that aim to answer what is the value of irrigation water and how this value will change given various policy environments (again giving exmaples of partial and general equilibrium approaches). Dudu and Chumi (2008) present a survey of more recent developments, primarily of partial and general equilibrium models addressing water. The majority of the studies surveyed are regional in nature with countries tending to be the largest geographic extent of analysis. Following is a brief survey of several general equilibrium approaches addressing water.

Storm (1999) develops a CGE model of the Indian economy to investigate the impact of increased trade liberalization on food price security for various classifications of consumers. The model explicitly considers irrigated and non-irrigated land because yields for the two land types tend to be different (Storm, 1999). Nerlove (1956)

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nested CES production functions in mathematical and tree-diagram format.

proposes a method for determining crop acreage allocation based on the expectation that farmers have of relative crop prices in the future. Storm (1999) employs this approach to allocate agricultural land between irrigated and non-irrigated area by crop. Total agricultural land area is determined by investment in irrigation (Storm, 1999).

Seung et al. (2000) combine a recreational demand model with a regional dynamic CGE model of Churchill county, Nevada to assess the impacts of redistributing water from the agricultural sector to a recreational wetland area. The recreational demand model is used to estimate the increased expenditures due to increased recreation which are input to the CGE model. The study assumes that reducing water for agriculture will contribute to proportional reductions in land available for agriculture (Seung et al., 2000).

Strzepek et al. (2008) use a static CGE model with a land/water composite in the value added nest of agricultural output to study GDP in an Egypt with and without the High Aswan dam. Land and water are used in fixed proportions with crops requiring a fixed amount of water. Four land-water technologies are included for each crop. The model "chooses the least-cost land-water technology for each crop, given the "prices" of land and water. The model solves for land rental rates and the shadow price. . . of water" (Strzepek et al., 2008).

Thurlow (2008) develops a detailed water specific SAM for South Africa, then used in Hassan and Thurlow (2011) in a static CGE analysis to analyze the effects of increased water trade liberalization within and among South African water management areas. Thurlow (2008) breaks out water as a factor of production in agriculture by subtracting the shadow value of water for a given crop from the capital value-added for each crop. Shadow value is calculated as the product of shadow price and water demand, which is a function of crop yield and shadow price is calculated based on a crop production function (Thurlow, 2008). Hassan and Thurlow (2011) describe land and water as factors of production, with water being a factor of production only for those crops that are irrigated. By including land as a factor of production for irrigated and non-irrigated crops, changes in irrigated and non-irrigated land can be assessed (Hassan and Thurlow, 2011).

1.3.3 Global CGE Approaches

The aformentioned CGE analyses, however, are all regional in nature. The literature describing global CGE models that address water resources is limited. This is, at least in part, due to the fact that water prices are typically absent from baseline data sets upon which CGE models are constructed, and data intensive techniques, as in Thurlow (2008) and Hassan and Thurlow (2011), are required to describe water in baseline SAMs.

However, since 70 % of the worlds water consumption is due to agriculture, "[a] complete understanding of water use is. . . impossible without understanding the international markets for food and other agriculture related products, such as textiles" (Berrittella et al., 2007). Berrittella et al. (2007) addresses this concern with the GTAP-W model by incorporating water as a factor of agricultural production and a water distribution sector in fixed proportions with other top level inputs in the context of a global static CGE model.

A later version of GTAP-W, described in Calzadilla et al. (2009, 2010b,a) explicity distinguishes between irrigated and rainfed agriculture. In this construction, water is included within a land/water aggregate similar to Strzepek et al. (2008), but land and water are not held in fixed proportions (Calzadilla et al., 2009, 2010b,a). The method for calculating the elasticity between irrigation and land is based on estimates of the price elasticity for water use (Calzadilla et al., 2009). The authors acknowledge that the water factor of production is in fact a water-captial aggregate, but GTAP-W does not explicitly describe this capital input, arguing that in the short term, irrigation capital is fixed (Calzadilla et al., 2009).

GTAP-W calculates the value of water based on the physical quantity of water, output and yield using data from the IMPACT model, a partial equilibrium model that projects world food prices and agricultural production (both irrigated and rainfed) and associated water use (Rosegrant et al., 2008; Calzadilla et al., 2009, 2010b,a). In so doing, GTAP-W is able to investigate the impacts of agricultural production on physical water useage in both irrigated agriculture and rain-fed agriculture (Calzadilla et al., 2009).

1.3.4 Global Land Use Change Models

In the long term, a primary driver of water use in agriculture is the area of land irrigated. As such, land use change may have a significant impact on regional water resources. For this reason, as mentioned above, this research addresses water constraints in the context of a global economic land use change model. Other authors have addressed land use change as well. Verburg et al. (2008) investigate land use change (including irrigated and non-irrigated land changes) in Europe from 2000 to 2030, combining the GTAP global CGE model with an integreated assessment model, IMAGE. The CGE model provides IMAGE with agricultural production and changes in land productivity while IMAGE provides the CGE model with land yields (Verburg et al., 2008). The output of this iterative process drives a spatially explicit land use change model, CLUE-s, for Europe (Verburg et al., 2008).

Agricultural land use in Verburg et al. (2008) is calculated globally by the CGE model described by van Meijl et al. (2006). Land is allocated to different crop types and is not disaggregated between irrigated and non-irrigated land. Conversion among land types (both agricultural and non-agricutural land) is described by a nested CET function. The model incorporates a land supply curve for agricultural land to reflect the fact that as more land becomes converted to agricultural land, rents increase on account of increasing agricultural land scarcity (van Meijl et al., 2006). Gurgel et al. (2008) also introduce a global land use change model, but employ a real cost of conversion approach rather than relying on a CET approach. As this research builds on the modeling framework of Gurgel et al. (2008), this framework is described more fully in the next chapter.

1.4 Contribution

While GTAP-W makes a valuable contribution to the relationship between global change and water resources, there are some limitations to the modeling framework. One is that the model is a static CGE model, and thus does not allow for a complete investigation of future changes without linking itself to another model to describe the dynamics. Another drawback is that the modeling framework assumes that agricultural land area is fixed; increases in irrigated land cause a decrease in non-irrigated land by the same amount, and vice versa (Calzadilla et al., 2009). No explicit land use change is incorporated. The study also assumes that any expansion in irrigation can occur without cost, the only constraint being the availability of water (Calzadilla et al., 2009). Furthermore, the assumption that the value of capital implicit in the irrigation water factor of production is fixed is not likely to be valid for longer term analysis.

The model developed by van Meijl et al. (2006) does model global land use change, but does not explicity describe irrigated and non-irrigated cropland and implications of water constraints. Additionally, Gurgel et al. (2008) note that formulating land use change with CET functions is inherently share presevering, and therefore in the long run, no major land use changes will be observed.

This research proposes an alternative method for investigating water constraints in the context of a global recursive dynamic CGE model with an explicit description of land use change that considers real cost of conversion among land types. The modeling framework projects out to 2100 and thus projects long term trends. The primary contribution of this research is the introduction of water constraints in a global CGE model through a description of an irrigable land supply curve parameterized by the conversion of non-irrigated cropland to irrigated cropland.

Chapter 2

EPPA-IRC: Introducing Water Resources in EPPA

2.1 The Emissions Prediction and Policy Analysis EPPA Model

The modeling framework upon which this research builds is the the MIT Emissions Prediction and Policy Analysis, EPPA, model which is described in Paltsev et al. (2005). EPPA is a recursive dynamic computable general equilibrium (CGE) model, describing the world economy in 16 geographic regions and 13 economic sectors. The base data set is the Global Trade Analysis Project, GTAP, data set, maintained at Purdue University. The most recent version of the database is documented in Narayanan and Walmsley (2008).

EPPA models the flows of goods and services within and among the regions and economic sectors, projecting a region's sectoral output, including emissions and prices, until 2100. EPPA was originally designed to investigate the relationship between the world economy and global emissions and climate change. EPPA is part of a larger modeling effort at MIT, the Integrated Global System Modeling, IGSM, framework. The IGSM framework is aimed at describing the entire earth system of which EPPA models the human impacts (Sokolov et al., 2005).

2.2 EPPA-LUC

The point of departure for this research is a variant of the EPPA model developed by Gurgel et al. (2008) that explicitly describes land use change in the agricultural sector, referred to here as EPPA-LUC. EPPA-LUC was developed to investigate the impact of a global second generation biofuels industry, specifically how such an industry might compete for food producing cropland (Gurgel et al., 2008). The version of EPPA-LUC described in Gurgel et al. (2008) employs the regional disaggregation and underlying base year data of the EPPA version described in Paltsev et al. (2005). The version of EPPA-LUC used in this research is based on the GTAP-7 database, which describes the world economy in 2004 (Narayanan and Walmsley, 2008). Additionally, the economic regions in the EPPA-LUC version used in this research are updated with respect to the regions documented in Paltsev et al. (2005) to describe in more detail developing economies, such as Brazil. See Figure 2-5 for the geographic resolution of the verison of EPPA-LUC used in this analysis. The regions used in this analysis are listed below in Table 2.1.

Table 2.1: EPPA regions.

Acronym	**Description**
USA	United States
CAN	Canada
MEX	Mexico
JPN	Japan
ANZ	Australia and Oceania
EUR	Europe
ROE	Rest of Europe and Central Asia
RUS	Russia
ASI	Dynamic Asia
CHN	China
IND	India
BRA	Brazil
AFR	Africa
MES	Middle East
LAM	Rest of Americas
REA	Rest of East Asia

In the original EPPA framework described in Paltsev et al. (2005), agriculture is described as one sector and uses an aggregate land type as a factor of production. Gurgel et al. (2008) disaggregated agriculture into a crops sector, livestock sector and forestry sector. Each agricultural sector uses a specific land type as a factor of production; the crops sector uses cropland, the livestock sector uses pasture land, and the forestry sector uses managed forest land (Gurgel et al., 2008). Gurgel et al. (2008) also introduce two types of natural land, natural grass land and natural–or unmanaged–forest land. The production structure for crops in each EPPA region in EPPA-LUC is shown below in Figure 2-1.

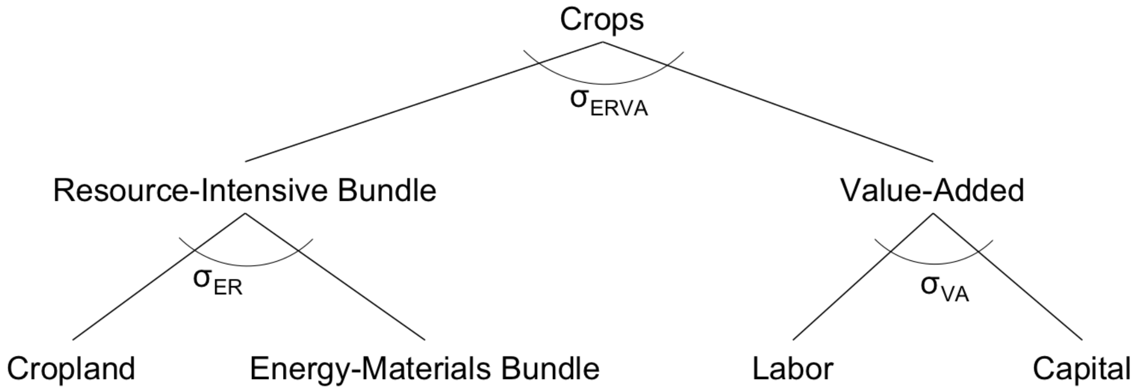

Figure 2-1: Crops production structure in EPPA-LUC (Gurgel et al., 2008).

In addition to disaggregating agricultural production into the production of crops, livestock and forestry and introducing land types associated with these production technologies, EPPA-LUC also describes land use change among the various land types (Gurgel et al., 2008). Certain rules govern these land transitions. For example, land of type x cannot be converted to itself, and all developed land can be abandoned to natural land (Gurgel et al., 2008). The land transitions that are allowed in EPPA-LUC are shown below in Table 2.2, where *Crop* refers to cropland, *Pasture* refers to pasture land, *Fors* refers to managed forest land, *NFors* refers to natural forestry and *NG* refers to natural grass land. It should be noted that while neither natural grass nor natural forest land can be directly converted to cropland, both types of natural land can indirectly be converted to cropland through pasture land (for natural grass) and managed forest land (for natural forest) (Gurgel et al., 2008).

Table 2.2: Land transitions allowed in EPPA-LUC (Gurgel et al., 2008).

	Transition To				
Transition From	*Crop*	*Pasture*	*Fors*	*NFors*	*NG*
Crop	X	yes	yes	yes	yes
Pasture	yes	X	yes	X	yes
Fors	yes	yes	X	yes	yes
NFors	X	X	yes	X	X
NG	X	yes	X	X	X

Land transitions are described explicitly in EPPA-LUC. “1 hectare of land of one type is converted to 1 hectare another type, and through conversion, it takes on the productivity level of the average for that type for that region” and in this way, total hectares of land are conserved (Gurgel et al., 2008). To ensure equilibrium in the base year, “the marginal conversion cost of land from one type to another” is “equal to the difference in the value of the types” (Gurgel et al., 2008). The land use change production block in EPPA-LUC is shown below in Figure 2-2.

In Gurgel et al. (2008), the fixed factor and additional timber output shown in Figure 2-2 is applied to the transition from natural forest land to managed forest land only. The fixed factor represents an observed land change response and slows conversion from natural forest to managed forest with respect to the case where no fixed factor is included (Gurgel et al., 2008).

In the model described by Gurgel et al. (2008) cropland implicitly includes irrigated cropland, and crop production likewise implicitly includes crops grown on irrigated and non-irrigated lands. There is, however, no connection to a region’s water resource in the conversion to cropland or in the production of crops. EPPA-LUC, therefore, could be thought of as a model describing crop production where irrigation is unconstrained by regional water resources.

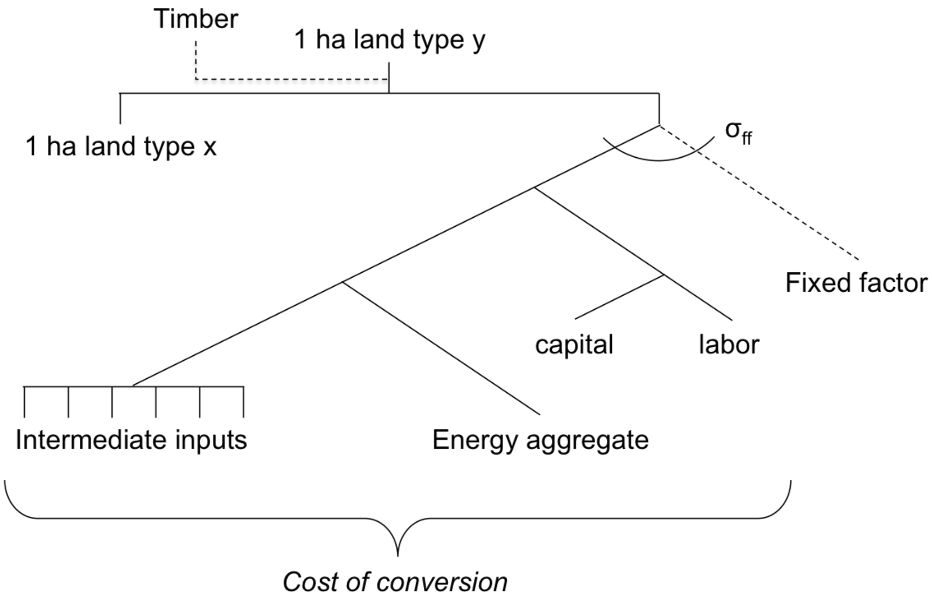

Figure 2-2: Land transition structure in EPPA-LUC (Gurgel et al., 2008).

2.3 EPPA-IRC: New Crop Production Structure

Irrigation plays a significant role in crop production, and water resources clearly have a significant impact on the amount of irrigation possible. To investigate the role that water resources have on crop production and land use, this research proposes a modeling framework where crop production is described as the aggregate production of irrigated and non-irrigated crops using irrigated and non-irrigated land respectively as factors of production. By constraining the conversion to irrigated cropland based on regional water availability, the new model framework proposed here, EPPA-IRC, introduces a description of constraints on crop production on account of regional water resources. EPPA-IRC thus builds on the model framwork developed by Gurgel et al. (2008) by further disaggregating crop production into irrigated and non-irrigated crop production, disaggregating cropland in to two new land types, irrigated and non-irrigated cropland, and finally describing land transitions to and among these two land types. The new crop production structure is shown below in Figure 2-3.

Note that the production structure of irrigated and non-irrigated crops follows the structure of the aggregate crop production of Gurgel et al. (2008) shown in Figure 2-1.

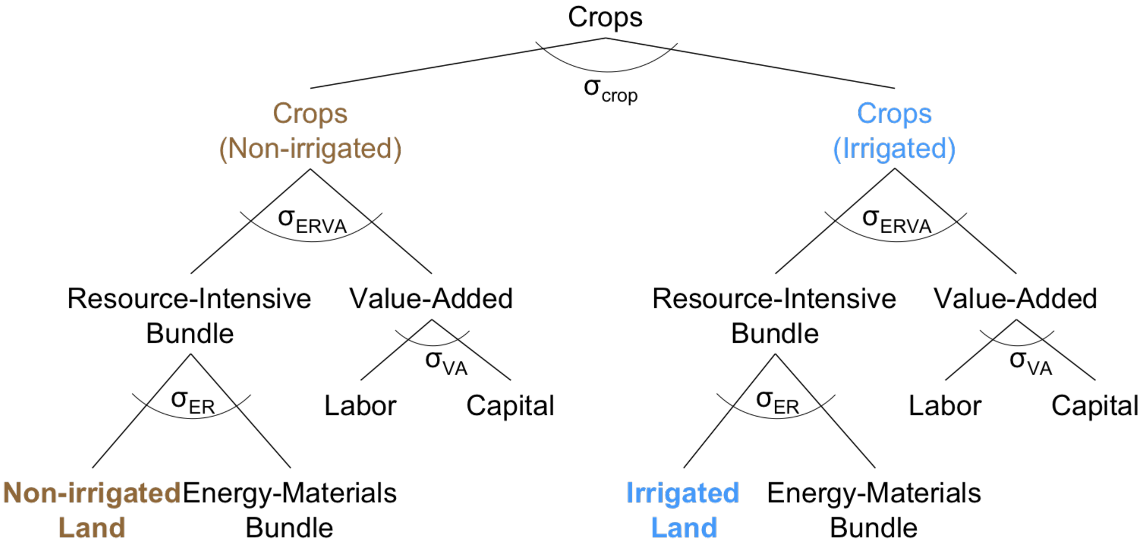

Figure 2-3: Crop production structure in EPPA-IRC.

To implement this structure into the model, the input shares for all inputs in both irrigated and non-irrigated crop production must be determined. Since the existing data combines irrigated and non-irrigated cropland, the implied level of input use, given the amount of production from irrigated and non-irrigated cropland, must sum to total input use in crop production for each input. The most important parameter in the production function illustrated in Figure 2-3 is the initial share of output from irrigated and non-irrrigated land. Also important, but secondary to the output share of irrigated production is the potential differential input shares and value of σ_{crop}.

2.3.1 Irrigated Output Share

To calculate the share of output from irrigated and non-irrigated land for the USA region, data from USDA Agricultural Research Service (ARS) is used. A 2001 publication of ARS reported that in 1997, the 16 % of US cropland that was irrigated produced 48 % of crop sales (ARS, 2001). Despite the discrepancy between the irrigated cropland coverage share estimate presented in Table 2.5 and that presented by the ARS, this research takes 48 % as the irrigated share of total crop production in the USA. For the remaining regions, the percentage of irrigated crop production is calculated based on data from the IMPACT model (Rosegrant et al., 2008).

IMPACT is a global, partial equilibrium model of the agricultural sector. Among its outputs are areas, yields and prices of various crop types grown on rain fed and irrigated lands (Rosegrant et al., 2008). The most recent version of IMPACT incorporates a water resources model linking water resources and agriculture (Rosegrant et al., 2008). The regional resolution of the water model, and also therefore the regional resolution of IMPACT, is a Food Producing Unit, which primarily follow major river basin delineations but also follow many major geopolitical boundaries (Rosegrant et al., 2008). The 281 FPUs are shown in Figure 2-4.

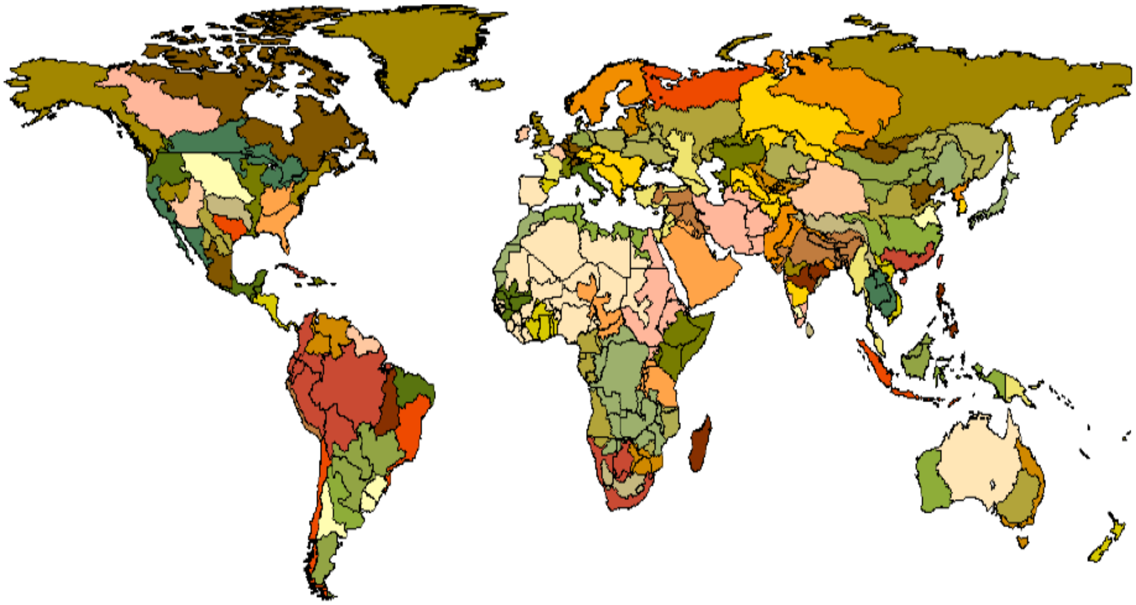

Figure 2-4: Food Producing Units (FPUs) used in IMPACT (source: Figure 2 in Strzepek et al. (2010)).

The FPUs must to be mapped to the EPPA regions so that IMPACT outputs can be used to develop parameters at the EPPA geographic resolution. The EPPA regions are shown in Figure 2-5. While most of the mapping is straightforward, some FPUs do not fit within EPPA region boundaries. For example, much of Russia is defined as part of the Rest of World (ROW) FPU. The ROW FPU, however, also includes Iceland, Greenland and Alaska. For the purposes of this analysis, the ROW FPU is assigned to the Russian (RUS) EPPA region[1]. Further details of the mapping are described in Appendix A.

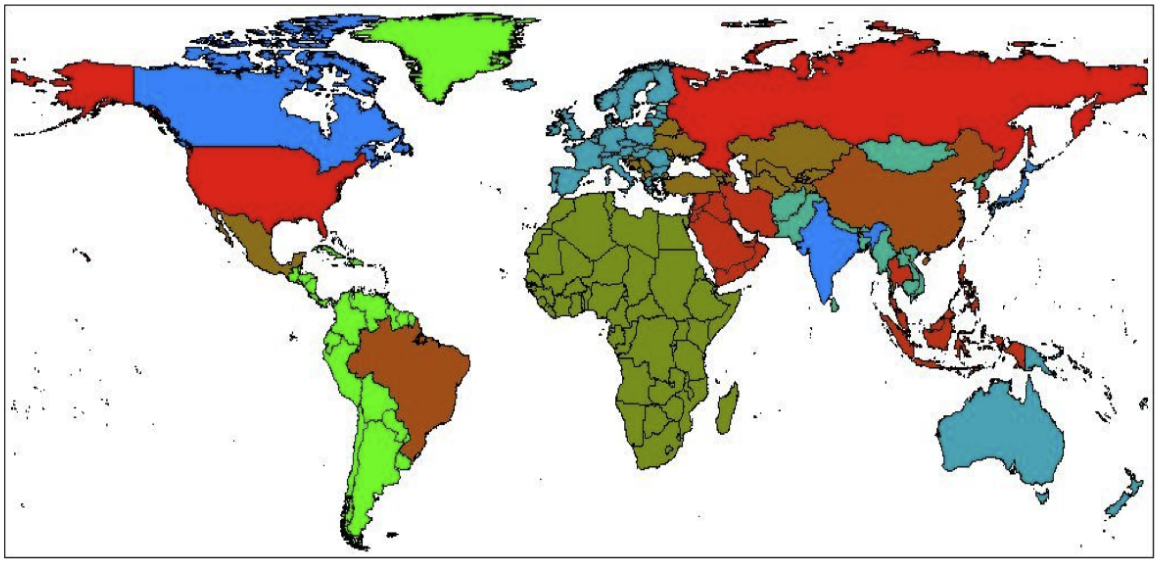

Figure 2-5: EPPA regions.

To calculate the irrigated share of total crop production in all regions other than the USA, yields, area and prices from IMPACT are considered[2]. First, the total production of all irrigated and non-irrigated crops, c, within a given FPU, i, is calculated. Total crop production is then multiplied by the crop specific world market price, wmp_c, giving the total value of irrigated crops by crop type, Eq. (2.1), non-

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[1] This will skew parameters associated with the RUS EPPA region. For example, the percentage of non-irrigated area is likely higher with this mapping since the non-irrigated areas of Iceland, Greenland and Alaska are incorporated into non-irrigated areas of Russia.

[2] This method is similar to that used by the GTAP-W model (see Calzadilla et al. (2009, 2010b,a)).

irrigated crops by crop type, Eq. (2.2) and all crops by crop type, Eq. (2.3).

$$value_{ci}^{irrigated} = \left(area_{ci}^{irrigated} * yield_{ci}^{irrigated}\right) * wmp_c \tag{2.1}$$

$$value_{ci}^{nonIrrigated} = \left(area_{ci}^{nonIrrigated} * yield_{ci}^{nonIrrigated}\right) * wmp_c \tag{2.2}$$

$$value_{ci}^{total} = value_{ci}^{irrigated} + value_{ci}^{nonIrrigated} \tag{2.3}$$

Summing Eq. (2.1), Eq. (2.2) and Eq. (2.3) over crop types, c, and FPU's, i, for a given EPPA region, j, allows for a calculation of the irrigated share of total crop production in each EPPA region.

$$prodShare_{j}^{irrigated} = \frac{\sum_{c}\sum_{i} value_{cij}^{irrigated}}{\sum_{c}\sum_{i} value_{cij}^{total}} \tag{2.4}$$

$$prodShare_{j}^{nonIrrigated} = \frac{\sum_{c}\sum_{i} value_{cij}^{nonIrrigated}}{\sum_{c}\sum_{i} value_{cij}^{total}} \tag{2.5}$$

The GAMS script used to calculate the above is presented in Appendix A. The results of Eq. (2.4) and (2.5) are presented in Table 2.3 below, along with the results for the USA described above.

2.3.2 Other Parameters

The crop production structure in Figure 2-3 allows the model to describe differential input shares of capital, labor, energy and land in irrigated versus non-irrigated crop production. The focus of this research has been on correctly parameterizing the irrigated land value share for the USA region. The method for calculating the irrigated land value share is described below.

Table 2.3: Output value shares for all regions.

EPPA Reg	**Irrigated Share [%]**	**Non-irrigated Share [%]**
USA	48	52
CAN	15	85
MEX	49	51
JPN	54	46
ANZ	24	76
EUR	29	71
ROE	35	65
RUS	05	95
ASI	48	52
CHN	29	71
IND	54	46
BRA	7	93
AFR	11	89
MES	80	20
LAM	21	79
REA	62	38

Irrigated Land Value Share The irrigated share of total returns to cropland is calculated for the USA based on rents and coverage data provided by the USDA National Agricultural Statistics Service, NASS. Though rents have been reported yearly since 1994, irrigated acerage is only tracked every 5 years. The year in which NASS reports both irrigated acreage and rents that is closest to the base year in the version of EPPA used in this research is 2002. State level land rents and coverages comes from the USDA surveys and the 2002 USDA Census of Agriculture, both provided by the NASS QuickStats online tool[3]. Using the rents and coverage data, the average irrigated cropland rents as a percentage of total cropland rents, $rent_{share}^{irrigated}$, can be calculated:

$$rent_{share}^{irrigated} = \frac{rent_{total}^{irrigated}}{rent_{total}^{all}} \tag{2.6}$$

Total irrigated cropland rents, $rent_{total}^{irrigated}$, and total cropland rents (the sum of irrigated and non-irrigated rents), $rent_{total}^{all}$, are calculated based on reported state rents

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[3] http://quickstats.nass.usda.gov/

and the associated harvested irrigated cropland and non-irrigated cropland coverage in that state:

$$rent_{total}^{irrigated} = \sum_{i=states} \left(land_i^{irrigated} * rent_i^{irrigated} \right) \tag{2.7}$$

$$rent_{total}^{nonIrrigated} = \sum_{i=states} \left(land_i^{nonIrrigated} * rent_i^{nonIrrigated} \right) \tag{2.8}$$

$$rent_{total}^{all} = rent_{total}^{irrigated} + rent_{total}^{nonIrrigated} \tag{2.9}$$

Irrigated land rents, however, are not reported for every state reporting irrigated land coverage. Some states report no rents, and some states report an aggregate rent that does not distinguish between irrigated and non-irrigated rents. For example, Florida reports irrigated and non-irrigated land coverage, but only reports non-irrigated rents. To avoid losing an excessive amount of data, the following rules are applied to those states that report aggregate land rent.

- **Irrigated rents:** assign aggregate rents to irrigated croplands in a state if the irrigated cropland in that state accounts for $\geq 90\%$ of the total cropland in that state

- **Non-Irrigated rents:** assign aggregate rents to non-irrigated croplands in a state if the non-irrigated cropland in that state accounts for $\geq 90\%$ of the total cropland in that state

Eq. (2.7) and Eq. (2.8) only account for those states that specifically report irrigated or non-irrigated land rents, or those states where an aggregate land rent has been classified as irrigated or non-irrigated based on the two rules described above[4].

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[4] For those states that only report either irrigated or non-irrigated rent, yet report coverage data for both, only the land where both rent and coverage data exist is considered. Irrigated land coverage not associated with any rent is ignored. After assigning aggregate land rents to either irrigated or non-irrigated land based on the rules described above, the remaining land not considered by Eq. (2.6) is 19 % of irrigated cropland and 4.4 % of non-irrigated cropland. In total, 6.2 % of all cropland is not considered

The irrigated share of total returns to cropland for the USA is calculated to be 22 %. A GAMS script was written to calculate the above. The code and access to the supporting NASS data are presented in Appendix B.

Other Input Shares In the absence of specific data regarding the share of capital, labor, intermediates and energy inputs in irrigated production, this research assumes that the irrigated share of the total value of these inputs used in crop production in the USA is the same. This share is calculated using a straightforward alegebraic relationship shown below, which ensures that the zero profit condition in irrigated and non-irrigated crop production in the USA is satisfied:

$$in_{shr}^{irrigated} = \frac{O^{irrigated} - Lnd^{irrigated}}{I^{total}} \tag{2.10}$$

where $O^{irrigated}$ is the value of irrigated output, $Lnd^{irrigated}$ is the returns to irrigated land, and I^{total} is the total value of capital, labor, intermediates and energy inputs used in crop production (both irrigated and non-irrigated) in the USA. Solving Eq. (2.10) results in $in_{shr}^{irrigated} = 53.103\%$.

Lacking better data for the remaining EPPA regions, I assume the irrigated and non-irrigated input shares of capital, labor, land, intermediates and energy in irrigated and non-irrigated production are equal. This aspect of the model parameterization needs further attention and is a subject of future work.

Parameterizing σ_{crop} The final parameter to be calculated in Figure 2-3 is σ_{crop}. In principle, a specific crop grown on non-irrigated cropland should be perfectly substitutable with the same crop grown on irrigated cropland. Mathematically this implies $\sigma_{crop} = \infty$. EPPA, however, describes a single crop product which is an aggregate of the eight crop types described in the GTAP database (Narayanan and Walmsley, 2008). Different crops have different values, and some higher valued crops, such as fruits, are often irrigated (depending upon the region) whereas other lower valued crops, such as feed corn, are often not irrigated. Due to the aggregate nature of crop production in EPPA, an infinite σ_{crop} would ignore the fact that specific crop types are not necessarily cultivated or harvested in equal proportions on irrigated and non-irrigated land and would thus cause an unrealistic shift to irrigated crops and consequentially an unrealistic conversion to irrigated cropland. It often makes economic sense not to irrigate if water is either highly scarce or if the cropland is highly fertile without irrigation, such as the corn belt in the midwestern United States.

Without disaggregating the crops sector further, any calculation of σ_{crop} is little more than an educated guess. In order to reflect the fact that for most crops, it matters little whether the crop was irrigated or not, but at the same time to prevent a bang-bang conversion to irrigated lands, a relatively high but non-infinite value of 1 is chosen for σ_{crop}. Sensitivity is performed about this assumption and model results are found to be relatively robust to the choice of σ_{crop}[5]. Resolving crop production into more specific crop types is an area deferred to future work.

2.3.3 Irrigated and Non-irrgated Cropland Rents

Irrigated and non-irrigated land rents are calculated based on the irrigated and non-irrigated share of regional returns to land and the irrigated and non-irrigated area share of total cropland coverage. Irrigated and non-irrigated shares of regional returns to land have been determined based on the parameterizations described above. To calculate the irrigated area share for the USA in the base year, data from the USDA is once again used[6]. Data on irrigated land coverages (both total and harvested) and total cropland coverage comes from the 2002 USDA Census of Agriculture provided by the NASS QuickStats online tool[7].

NASS reports total cropland, harvested irrigated land as well as total irrigated land. For this analysis, total irrigated cropland is calculated based on harvested irrigated land rather than total irrigated land since harvested land is sure to be

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[5] Crop production and price levels for $\sigma_{crop} = 10$ and $\sigma_{crop} = 0.1$ are compared to crop production and price levels for $\sigma_{crop} = 1$ in each EPPA region in 2100. The largest difference in production is 18 %. The largest difference in prices is 12 %. Most of the variation in production and price levels is less than 5 %. This suggests that model results are relatively robust to the choice of σ_{crop}.

[6] As noted above, however, the base year for this version of EPPA is 2004. Irrigated land coverage, however, is not kept yearly by the USDA. The closest year to 2004 for which the USDA has data is 2002.

[7] http://quickstats.nass.usda.gov/

cropland, and I want to avoid including some irrigated land that may not in fact be cropland[8]. Harvested irrigated land and total cropland are reported in Table 2.4. The irrigated share of total cropland area in the USA is reported in Table 2.5. Note that when calculating the share of irrigated cropland area, all harvested irrigated land is considered, not just harvested irrigated land for which rent data exists.

Table 2.4: USA cropland coverage, 2002.

USA Cropland Coverage	**Acres**
Total Harvested Irrigated	53,427,990 Acres
Total	434,164,900 Acres

For the remaining EPPA regions, irrigated area shares are calculated using data from IMPACT. The irrigated and non-irrigated areas for each EPPA region can be calculated by a summation of the land types (irrigated and non-irrigated) over all crop types, c, for all FPUs, i, in a given EPPA region, j:

$$area_j^{irrigated} = \sum_c \sum_i area_{cij}^{irrigated} \tag{2.11}$$

$$area_j^{nonIrrigated} = \sum_c \sum_i area_{cij}^{nonIrrigated} \tag{2.12}$$

$$area_j^{total} = area_j^{irrigated} + area_j^{nonIrrigated} \tag{2.13}$$

The irrigated and non-irrigated area share of total cropland area is calculated using Eq. (2.14) and Eq. (2.15) below. The original cropland coverage data from EPPA-LUC, as well as the recalculated irrigated and non-irrigated cropland areas, based on irrigated and non-irrigated shares of total cropland area, are shown below in Table 2.5 for all EPPA regions.

$$land_{share_j}^{irrigated} = \frac{area_j^{irrigated}}{area_j^{total}} \tag{2.14}$$

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[8] Harvested irrigated land is a value slightly less then the reported total irrigated land.

$$land_{share_j}^{nonIrrigated} = \frac{area_j^{nonIrrigated}}{area_j^{total}} \tag{2.15}$$

Table 2.5: Cropland coverage and land area shares, 2000; original cropland coverage from Hurtt et al. (2006).

		Recalculation			
EPPA Reg	**Original [Km^2]**	**Irrigated**		**Non-irrigated**	
		%	**[Km^2]**	**%**	**[Km^2]**
USA	1,866,001	12.3	229,518	87.7	1,636,483
CAN	528,091	11	58,502	89	469,589
MEX	218,711	29	63,346	71	155,365
JPN	46,972	77	35,967	23	11,005
ANZ	355,887	20	72,389	80	283,498
EUR	1,423,064	28	398,510	72	1,024,554
ROE	1,328,500	27	357,017	73	971,483
RUS	1,679,784	19	312,706	81	1,367,078
ASI	714,357	38	270,826	62	443,531
CHN	1,995,123	26	522,172	74	1,472,951
IND	1,770,475	42	742,416	58	1,028,059
BRA	746,218	4	30,893	96	715,325
AFR	1,609,073	7	108,838	93	1,500,235
MES	137,964	45	62,477	55	75,487
LAM	836,984	13	104,865	87	732,119
REA	859,731	56	480,506	44	379,225

Based on the irrigated and non-irrigated cropland coverages presented in Table 2.5, the aggregate returns to land from GTAP and the irrigated and non-irrigated share of returns to land, rents per hectare for irrigated and non-irrigated cropland are calculated and presented below in Table 2.6.

The rents illustrate what one would expect; irrigated rents are higher than non-irrigated rents. This pattern is true except for JPN and RUS[9]. To prevent unantici-

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[9] In JPN and RUS, the share of irrigated output (Table 2.3) is less than the share of irrigated area (Table 2.5). This leads to the odd behavior in rents for these two regions. The imperfect mapping between FPU regions and the RUS EPPA region is one possible reason for irrigated rents being less than non-irrigated rents in RUS. Additionally, the IMPACT data, when aggregated over EPPA regions, indicates that the irrigated yield in these two regions, JPN and RUS, is less than the non-irrigated yield. This is also true for the ASI EPPA region. In RUS, this behavior could be due to the imperfect mapping between FPU regions and the RUS EPPA region. The odd behavior in yields for JPN and ASI could perhaps be due to the fact that in JPN and ASI, much of the irrigated cropland is paddy rice.

Table 2.6: Cropland rents per hectare [2004 US $/ha].

Region	Non-Irrigated	Irrigated
USA	133.4	268.3
CAN	42.2	61.3
MEX	180.4	420.0
JPN	4105.6	1451.1
ANZ	62.8	76.3
EUR	335.8	354.3
ROE	44.1	66.1
RUS	36.1	8.1
ASI	358.4	543.9
CHN	162.0	189.4
IND	198.6	320.3
BRA	61.6	109.0
AFR	54.9	96.4
MES	62.6	295.2
LAM	129.4	235.9
REA	128.7	162.9

pated land transitions, for the purposes of this analysis, transition from non-irrigated cropland to irrigated cropland in the JPN and RUS EPPA regions is not allowed.

2.4 EPPA-IRC: Introducing Water Constraints through Land Use Change

With the disaggregation of crop production into irrigated and non-irrigated components, water resource constraints could be described in one of two ways. First, water could be included as a factor of irrigated crop production, as done in Berrittella et al. (2007)[10]. The advantage of this approach is that it allows the model to explicitly describe crop-water requirements. Thus for each crop, or crop type, a certain amount of water would be required with an associated shadow price. This is the approach of Thurlow (2008). This approach, however, requires a significant amount of data which is difficult to come by for the entire globe. In Berrittella et al. (2007), the

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[10] One would not include rain fall as a factor of non-irrigated crop production since, as noted by Calzadilla et al. (2010b), rain water is free.

authors note that the data for developing crop water requirements are “little more than informed guesses”, reflecting the difficulty in developing this kind of data for global models.

Another approach would be to describe water as a factor of production in the production of irrigated cropland. Though data is still something of a limiting factor, the data requirements are not as intensive as with the approach described above. Furthermore, a straightforward connection can be made between irrigated cropland coverage and the regional water resource. For these reasons, the second approach is adopted for including water resources in EPPA. Thus the basic method for introducing water resources in EPPA is to explicitly describe irrigated and non-irrigated cropland and the conversion to irrigated cropland. As described above, irrigated and non-irrigated cropland are then used as factors of irrigated and non-irrigated crop production. Irrigated crop production, therefore, implicitly includes the value of water in the value of irrigated cropland. If the conversion to irrigated cropland is highly constrained due to limited water resources, irrigated crop production will likewise be constrained since there will be a lesser amount of irrigable cropland upon which to cultivate crops[11]. The model structure for the conversion of cropland to irrigated cropland follows from the land use change structure developed by Gurgel et al. (2008) (Figure 2-2) and is shown below in Figure 2-6.

Following the method of Gurgel et al. (2008) describing land transitions in EPPA-LUC, the land conversion from non-irrigated to irrigated cropland occurs through one hectare of non-irrigated cropland being converted to one hectare of irrigated cropland, with the difference in land rents equaling the cost of conversion.

Often, without irrigation, land values are negligible. One might like to capture this fact by describing two types of transitions to irrigated cropland; transition from very arid land to irrigated cropland and the transition from non-irrigated cropland to irrigated cropland for the purposes of increasing the non-irrigated cropland's pro-

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[11] Water availability will also impact non-irrigated crop production, primarily through precipation. The water resources so described in this research focus only on those water resources used in irrigation. It is a matter of future work to describe the impact of precipitation changes on non-irrigated crop production.

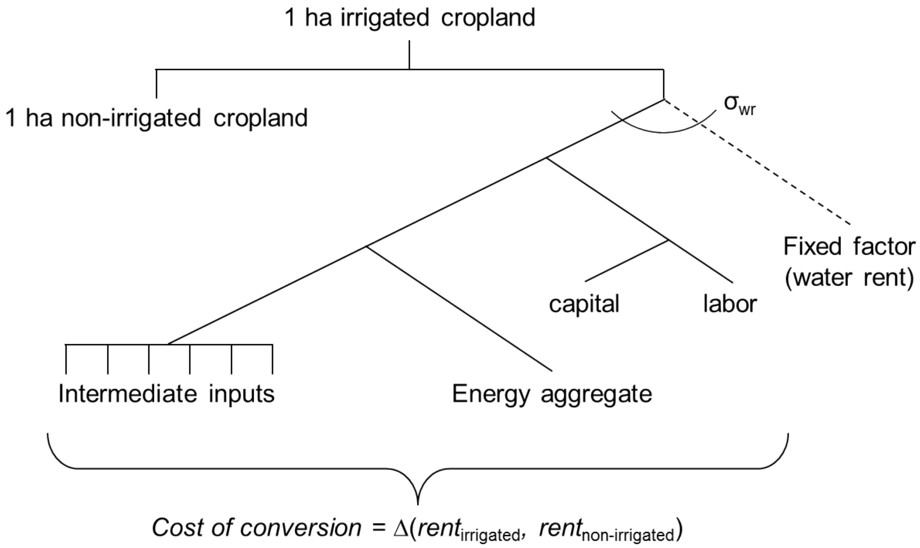

Figure 2-6: Production structure for the transition to irrigated cropland.

ductivity. Fischer et al. (2002), however, estimate that of the arid land unsuitable for dry land cultivation, "assuming availability of water resources,. . . only about 1.8 % of these dry zones, were assessed as potentially very suitable and suitable. . . for cereal crops under irrigation". For this reason, this research assumes that only non-irrigated cropland can be converted to irrigated cropland. The new land conversion matrix is shown in Table 2.7, where *IR crop* refers to irrigated cropland and *NIR crop* refers to non-irrigated cropland. Note that irrigated cropland can transition back to non-irrigated cropland and, like managed forest, pasture land and non-irrigated cropland, can also be abandoned to natural land[12].

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[12] Note that if it ever becomes profitable to transition from irrigated cropland back to non-irrigated cropland, the implicit assumption is that the irrigated cropland being converted is not otherwise arid land that could not be cultivated without irrigation. Under the current model structure, however, if irrigated cropland such as that found in much of California can no longer be irrigated, EPPA would convert this land to non-irrigated cropland instead of arid scrub land. Thus, non-irrigated cropland would be created where in reality, it could not exist. An appropriate treatment of this situation is left for future work.

In addition, Fischer et al. (2002) note that the amount of currently uncultivated land that could benefit from irrigation is very regionally dependent (see Table 5.9 in Fischer et al. (2002)). At certain regional resolutions, therefore, the possibility of converting arid land to irrigated land should not be ignored. A proper treatment of this conversion from arid land to irrigated cropland is left for future work.

Table 2.7: Land transitions allowed in EPPA-IRC.

	Transition To					
Transition From	*NIR crop*	*IR crop*	*Pasture*	*Fors*	*NFors*	*NG*
NIR crop	X	yes	yes	yes	yes	yes
IR crop	yes	X	X	X	yes	yes
Pasture	yes	X	X	yes	X	yes
Fors	yes	X	yes	X	yes	yes
NFors	X	X	X	yes	X	X
NG	X	X	yes	X	X	X

2.4.1 Connection of Regional Water Resources to Irrigable Land Supply Curves

Water resources enter the model through the conversion to irrigated land via the parameterization of regional irrigable land supply curves. This research postulates that in each region, there is a maximum supply of irrigable land dependent on the regional water availability. Consider the following equilibrium equations for non-irrigated and irrigated crops, respectively:

$$P_{nir} = yield * area * p_{unit} - cost_{prod} - rent_{land} = 0 \tag{2.16}$$

$$P_{ir} = yield * area * p_{unit} - cost_{prod} - (rent_{land} + capital_{irrigation}) = 0 \tag{2.17}$$

where total profit from non-irrigated and irrigated crop production, P_{nir} and P_{ir} respectively, are zero under the assumption of perfect competition, p_{unit} is the unit price of a particular crop, $cost_{prod}$ is production cost, $rent_{land}$ are land rents and $capital_{irrigation}$ refers to irrigation capital which implicitly includes the returns to water. In order for irrigation to be worthwhile, an increase in $yield$ must offset the increase in $capital_{irrigation}$ in Eq. (2.17). This concept is illustrated in Figure 2-7.

Figure 2-7 illustrates the total potential cropland in a region and the land's associated yield without irrigation. There will be some land that is very productive and no real benefit from irrigation is possible. This is represented by the "Highly productive non-irrigated land". The remaining land could benefit from some irrigation. In order for it to be economical to make the irrigation investment, however, the discounted

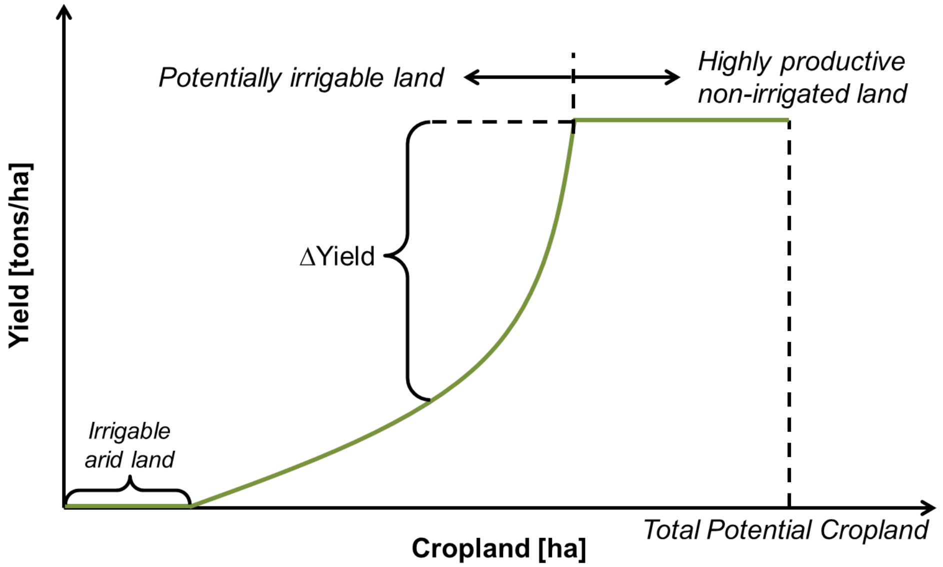

Figure 2-7: Conceptualization of remaining irrigable land.

present value of production under the increase in yield, $\Delta Yield$, due to irrigation over the life of the irrigation equipment must be greater than or equal to the present value of production on the same land without irrigation. If the difference between production values is strictly greater, the difference is the implied value of water.

It may not be worthwhile to irrigate land that is inherently productive unless water is sufficiently abundent and accessible. As water resources become constrained in a region, and thus as water becomes more expensive to supply, it becomes increasingly uneconomical to irrigate less and less productive land. In the limit, where water resources do not exist, the cost of irrigation becomes effectively infinite and no land is irrigated. The maximum supply of irrigable land is therefore related to water scarcity in a given region.

The increase in irrigated land area up to the maximum supply of irrigated land can be described by an irrigable land supply curve, illustrated in Figure 2-8. The irrigable land supply curve is described by three parameters; the maximum supply of irrigable land discussed above, the elasticity of irrigated land supply and finally the scarcity rents on the water resource.

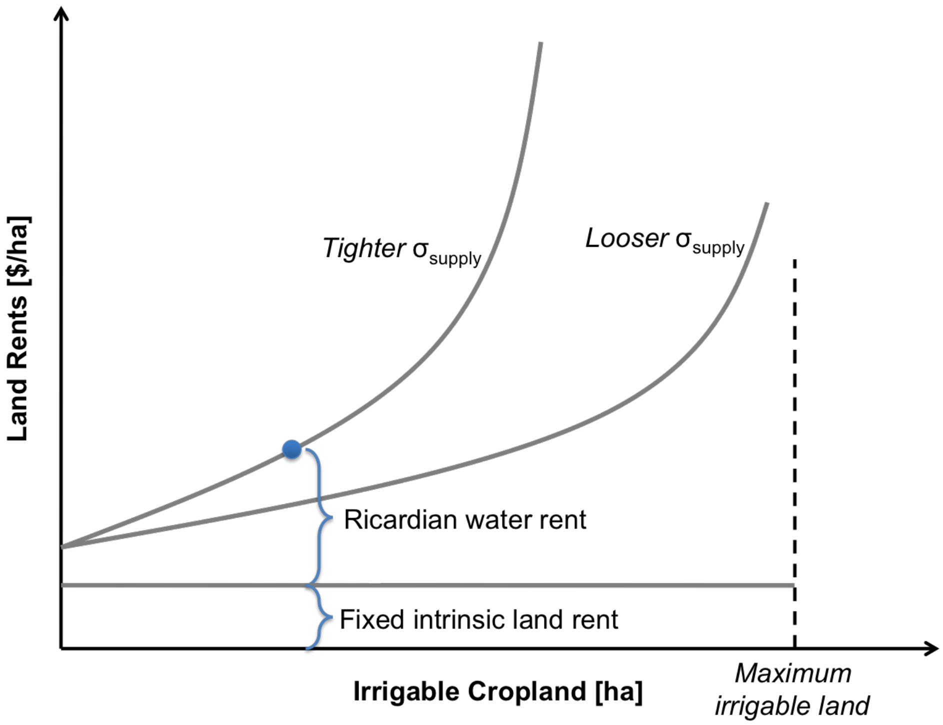

Figure 2-8: Illustrative example of an irrigable land supply curve.

Elasticity of Irrigated Land Supply The elasticity of irrigated land supply is a measure of the supply response of irrigated area to land rents and parameterizes the steepness of the irrigable land supply curve. A very steep curve implies a tight, or low elasticity of irrigated land supply, and suggests that relatively small increases in irrigated area occur as a response to increases in land rent. A shallower curve implies a loose, or high elasticity of irrigated land supply and suggests that relatively large (compared to a tighter elasticity of irrigated land supply) increases in irrigated area occur as a response to increases in land rent. Insofar as water resources determine the decision to irrigate, for regions that have limited water resources, rents on water will rise faster as more cropland is irrigated compared to regions with more abundent water resources. This implies that water scarce regions should have relatively tight elasticities of irrigable land supply[13].

Water Resource Scarcity Rent One can conceive of the returns to irrigated land as the sum of the intrinsic return to the land without irrigation and the return to the water resource applied to the land. The return to water, or water resource rent, is based on the Ricardian notion of land rents (Young, 2005, p. 62-63). Assuming that the intrinsic value of land is relatively fixed, the current water resource rent determines where a region is located on the irrigable land supply curve. As regions increasingly irrigate more cropland, and thus employ increasing amounts of water, water becomes more scarce, the water resource rent increases and regions will move up along the irrigable land supply curve.

Thus the irrigable land supply curve is a reflection of regional water scarcity by describing the maximum supply of irrigable land, supply response of irrigated cropland to changes in land rents (and by implication changes in water rents), and the water resource rent[14]. The two most important parameters for describing water resource constraints are the maximum supply of irrigable land in a given region as well as the supply elasticity of irrigated land. The calculation of these two parameters, as well as an estimate of the share of water scarcity rent in irrigated cropland, are discussed below.

2.4.2 Estimating Potential Irrigable Cropland

The maximum supply of irrigable land as conceived of in this research is the theoretical limit to irrigation imposed by physical water resources. WRI (2007) provides information regarding renewable water supplies and withdrawals at the country level. The WRI data, along with the current irrigated coverage presented in Table 2.5, is used to estimate the maximum increase in irrigable land allowed for by regional water

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[13] There are, of course, factors other than water resources that influence the supply response of irrigated land to changes in land rents and therefore the elasticity of land supply is not solely a measure of water scarcity, but is at the very least influenced by water scarcity.

[14] In van Meijl et al. (2006) the authors apply the concept of a land supply curve in agriculture, but do not distinguish between irrigated and non-irrigated land, instead describing the relationship between total agricultural area and land rent.

resources.

WRI reports values for total renewable water resources, RWR_{tot}, total withdrawals around the year 2000, WW_{tot}, and the percent of total water withdrawals used in agriculture, $WW_{ag}^{\%}$ all at the country level. I use these data to calculate water withdrawals used in agriculture, WW_{ag}, and available renewable water resources, RWR_{avbl}, in each country. WW_{ag} and RWR_{avbl} are then aggregated to EPPA regions[15].

$$WW_{ag} = WW_{tot} * WW_{ag}^{\%} \tag{2.18}$$

$$RWR_{avbl} = RWR_{tot} - WW_{tot} \tag{2.19}$$

I assume that all available renewable water resources, RWR_{avbl}, can be allocated to agriculture. The additional amount of irrigable land allowed for by regional water resources in each EPPA region, ΔIrr_{max}, is calculated using the regional available water resource and the land irrigated per unit of water:

$$\Delta Irr_{max} = \left(\frac{area_{irr}^{2004}}{WW_{ag}} \right) * RWR_{avbl} \tag{2.20}$$

where area $area_{irr}^{2004}$ is the irrigated area in the base year presented in Table 2.5. The results of this analysis are presented below in Table 2.8. The last column in Table 2.8 shows the percent by which current irrigated cropland can expand.

For Canada, Europe, Russia, dynamic Asia, the rest of Americas and the rest of East Asia regions, the addition of the maximum increase in irrigated land, ΔIrr_{max}, to the current irrigated land coverage, $area_{irr}^{2004}$, yields an irrigated area greater than the total amount of land (this includes cropland, pasture land, managed and unman-

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[15] It should be noted that some EPPA regions span continents (see Figure 2-5). As such, Greenland's renewable water resources are included in the entire rest of Americas region. But the water resources of Greenland, which has no irrigation (WRI, 2007), are not realistically available to the remaining rest of Americas countries. The water resources of Greenland are, therefore, removed from the rest of Americas' renewable water resource. Similar issues exist in other regions that contain or are comprised of islands (for example, Madagascar in Africa). A full treatement of this issue, however, is left for future work.

Table 2.8: Regional renewable water resources, withdrawals and the maximum allowable increase in irrigated land.

	RWR_{tot}	WW_{tot}	WW_{ag}	RWR_{avbl}	$area_{irr}^{2004}$	ΔIrr_{max}	**% Change**
	[Km^3]				**[Km^2]**		[%]
USA	2,071	479.3	196.5	1591.7	229,518	1,859,082	810
CAN	2,902	46.0	5.5	2856.0	58,502	30,288,497	51773
MEX	457	78.2	60.2	379.0	63,346	398,591	629
JPN	430	88.4	54.8	341.6x	35,967	224,075	623
ANZ	1,693	26.2	18.9	1667.1	72,389	6,390,615	8828
EUR	2,656	288.5	96.1	2367.6	398,510	9,815,895	2463
ROE	1,164	245.7	193.3	917.9	357,017	1,694,903	475
RUS	4,507	76.7	13.8	4430.6	312,706	100,379,750	32100
ASI	4,377	226.2	193.7	4151.0	270,826	5,804,925	2143
CHN	2,829	630.3	428.6	2198.8	522,172	2,678,872	513
IND	1,897	645.8	555.4	1250.9	742,416	1,671,986	225
BRA	8,233	59.3	36.8	8173.7	30,893	6,868,033	22232
AFR	5,570	213.7	183.1	5356.5	108,838	3,184,125	2926
MES	255	168.6	152.6	86.4	62,477	35,365	57
LAM	9,842	127.8	90.6	9714.6	104,865	11,248,143	10726
REA	4,720	416.5	376.8	4303.9	480,506	5,488,665	1142

aged forest land, natural grass lands and other lands not considered in the land use change model; i.e. all land) in these regions. This result implies that if physical water availablility were the only constraining factor in conversion to irrigated land, conversion to irrigated cropland would not be constrained. Although, given that I have also included a supply elasticity describing the cost of creating irrigated land as irrigated area expands, that there is enough water in a large region to potentially irrigate the entire region does not mean that it would realistically be economic to do so. The supply elasticity is described in the following section.

Future work, using the water module component of Strzepek et al. (2010) could be used to consider growth in water use from competing uses, and revise over time the potential irrigable land based on water resources available for irrigation versus other purposes.

2.4.3 Estimating Irrigated Land Supply Elasticity

The supply elasticity for irrigated cropland, ε_{supply}, is calculated using irrigated land coverage data and rents from the USDA. Data of harvested irrigated land coverage and irrigated land rents from the USDA National Agricultural Statistics Service (NASS)[16] are used to calculate the elasticity of irrigated land supply between 1997 and 2007.

$$\varepsilon_{supply} = \frac{\%\Delta land^{irrigated}}{\%\Delta rent^{irrigated}} \tag{2.21}$$

The GAMS script used to calculate ε_{supply} as well as further details of the calculation are presented in Appendix B. The result of these calculations yields $\varepsilon_{supply} = 0.23$[17].

To calculate ε_{supply} for all other EPPA regions, this research follows Gurgel et al. (2008) by assuming that the percent change in irrigated land rents for the USA can be used as a proxy for percent changes in irrigated land rents for the world. Percent changes in USA irrigated land rents are calculated using data from NASS. Percent changes in irrigated land coverage for all EPPA regions are calculated from data developed by Freydank and Siebert (2008). This data is a country wide database describing area equipped for irrigation from 1900 through 2003 (Freydank and Siebert, 2008). In this research, I assume that percent changes in area equipped for irrigation approximates percent changes in area actually area irrigated.

The data developed by Freydank and Siebert (2008) reports through 2003, and thus the range of years covered by both this data and the NASS coverage data is 1997 to 2002. Therefore, ε_{supply} for all EPPA regions other than the USA is calculated using Eq. (2.21) where $\%\Delta land^{irrigated}$ represents percent changes in irrigated land coverage between 1997 and 2002 using the data developed by Freydank and Siebert (2008) and $\%\Delta rent^{irrigated} = 16.3\%$ and represents the percent change in irrigated rents for the USA between 1997 and 2002 as calculated by the NASS data.

Table 2.9 shows the percent change in area equipped for irrigation between 1997

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[16] http://quickstats.nass.usda.gov/

[17] An alternative approach for calculating ε_{supply} is proposed, but not fully worked out, in Appendix C.

Table 2.9: Percent change in area equipped for irrigation (Freydank and Siebert, 2008).

Region	**% Δ '97-'02**	ε_{supply}
CAN	9.17	0.56
MEX	3.86	0.24
JPN	-	-
ANZ	5.40	0.33
EUR	0.67	0.04
ROE	0.83	0.05
RUS	-	-
ASI	2.56	0.16
CHN	2.98	0.18
IND	12.79	0.78
BRA	14.66	0.90
AFR	4.99	0.31
MES	4.40	0.27
LAM	0.94	0.06
REA	4.96	0.30

to 2002 and the resulting ε_{supply} for all EPPA regions other than the USA[18].

Following Hyman et al. (2002) and Gurgel et al. (2008), the elasticity of substitution, σ_{wr}, in the production structure of irrigated cropland, Figure 2-6, is calculated based on the elasticity of land supply, ε_{supply}, and the share of the fixed factor in the production of irrigated cropland, α_{ffwr}.

$$\sigma_{wr} = \frac{\varepsilon_{supply}}{1 - \alpha_{ffwr}} \tag{2.22}$$

The share of the fixed factor, α_{ffwr}, is described in the following section.

2.4.4 Parameterizing the Fixed Factor

The fixed factor in the production structure of irrigated cropland (Figure 2-6) represents the water resource rent in the production of irrigated cropland and thus represents a region's location on the irrigable land supply curve. The fixed factor is

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[18] The data developed by Freydank and Siebert (2008) indicates that area equipped for irrigation in JPN and RUS has decreased, which would imply a negative elasticity of irrigated land supply. Recall, however, that transitions to irrigated land in JPN and RUS are not considered in this analysis. Thus it is unnecessary to determine ε_{supply} in these two regions.

included in the model as an endowment that decreases over time as more irrigated cropland is created until the maximum amount of irrigable land is reached.

To parameterize the fixed factor, the share of the the water resource rent in the production of irrigated cropland must be determined. This is a challenge since studies that investigate the value of water used in irrigation often include in this calculation the implicit value of capital used for irrigation. Take, for example, two studies described by Young (2005), Torell et al. (1990) and Faux and Perry (1999).

Torell et al. (1990) conducted a hedonics study of the value that irrigation water adds to cropland in the Ogallala Aquifer region in the United States. The authors conclude that the average value of water as a share of irrigated farmland between 1979 and 1986 in this region is 48 % (Torell et al., 1990). The authors note, however, that this value also includes irrigation equipment, and therefore does not represent the intrinsic value of water used for irrigation only (Torell et al., 1990).

Faux and Perry (1999) present a hedonic analysis[19] of the value of water for 5 land classes in Treasure Valley, Oregon. 225 sales between 1991 and 1995 are used in the study. The authors calculate the value of a water-land quality aggregate by taking the difference between the value of irrigated land and non-irrigated land per acre (similar to Torell et al. (1990)). Based on Table 5 of Faux and Perry (1999), I calculate that the share of water in total land value is 58 % [20].

Taking the estimate of 48 % from Torell et al. (1990) as place to start, I assume that the intrinsic value of water in irrigated cropland is lower since the 48 % implicitly includes irrigation capital. Furthermore, the Ogallala region investigated by Torell et al. (1990) is very dry and one would therefore expect water used in irrigation to have a relatively high value. For this reason, the value share of the water used in

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[19] Of this study, Young mentions that "Because water quantity is not reported for the individual sales observations and is not an independent variable in their hedonic equation, this effort cannot, strictly speaking, be labeled a hedonics property value study for irrigation water value" (Young, 2005, p. 180). Accordingly, Young (2005) terms the study a "quasi-hedonic" study.

[20] This is the value of water for the lowest land quality. The authors explain that contingent on water being mobile between land parcels, the value of water-land quality for the lowest quality land is the value of water (Faux and Perry, 1999). The difference between this value, and higher water-land qualities for higher quality land would then be due to the soil characteristics rather than water (Faux and Perry, 1999). I have assumed that water is mobile amongst land parcels.

irrigation for the entire US would be lower still than the intrinsic value of water for the Ogallala region.

For the purposes of this research, a value of 10 % is chosen. Fixed factor shares for the rest of the world are paramaterized based on the assumed USA share of 10 %, and the ratio of irrigated to non-irrigated land rents. Thus, the share α_{ffwr}^{REG} for any region, REG, other than the USA is:

$$\alpha_{ffwr}^{REG} = \frac{\alpha_{ffwr}^{USA}}{rr_{USA}} * rr_{REG} \tag{2.23}$$

where rr_{REG} defines the ratio of irrigated to non-irrigated rents in any EPPA region, REG. The rational for this approach is the assumption that the difference in irrigated and non-irrigated land values is proportional to the value of water. Thus when parameterizing based on US data, it makes more sense to scale by the proportion of the ratio of irrigated to non-irrigated land rents in each region, than to scale by the proportion of irrigated land rents alone. Based on a 10 % share in the USA, the land rent ratios and Eq. (2.23), the fixed factor shares for all EPPA regions are given below in Table 2.10. Table 2.10 also shows the elasticity of land supply, ε_{supply}, calculated based on the method described by Eq. (2.21), and the subsitution elasticity, σ_{wr}, calculated based on the method described by Eq. (2.22).

2.4.5 The Fixed Factor Depletion Model

The initial supply of the fixed factor is determined by irrigated cropland rents in the base year and the share of the fixed factor in irrigated land production presented in Table 2.10[21]. The fixed factor endowment is depleted in a manner proportional to the growth of irrigated cropland and is limited by the maximum potential increase in irrigable cropland. The fixed factor is updated based on the following relationship:

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[21] No land use change occurs in the base year and therefore only the zero profit condition is enforced for the land use change production blocks. Another consequence of land use change not occuring in the base year is that relative land production levels are not necessarily 1, and thus the fixed factor as described above may not appropriately reflect the initial fixed factor supply. In order to initialize the fixed factor supply to an appropriate level, the fixed factor as calculated by base year irrigated land rents and the share of the fixed factor in these rents is scaled by relative irrigated land production in the second period of the calculation, which is the first period that land use change occurs.

Table 2.10: Fixed factor share, elasticity of land supply, ε_{supply}, and resulting subsitution elasticity, σ_{wr}.

EPPA Reg	**Share of Fixed Factor**	ε_{supply}	σ_{wr}
USA	0.10000	0.23	0.26
CAN	0.07210	0.56	0.61
MEX	0.11578	0.24	0.27
JPN	0.01758	-	-
ANZ	0.06049	0.33	0.35
EUR	0.01500	0.04	0.04
ROE	0.07447	0.05	0.06
RUS	0.01120	-	-
ASI	0.07547	0.16	0.17
CHN	0.05813	0.18	0.19
IND	0.08018	0.78	0.85
BRA	0.08800	0.90	0.99
AFR	0.08732	0.31	0.34
MES	0.23443	0.27	0.35
LAM	0.09062	0.06	0.06
REA	0.06295	0.30	0.32

$$ffirr_{T+1} = ffirr_T * \frac{area_T - area_{T0}}{\Delta Irr_{max}} \tag{2.24}$$

where $ffirr_{T+1}$ is the updated fixed factor supply, $ffirr_T$ is the initial endowment or current time period's fixed factor supply, $area_T$ is the irrigated land area after the model solution of period T, $area_{T0}$ is the irrigated cropland area in the base year and ΔIrr_{max} is the maximum amount by which irrigated cropland can increase in any given region.

If irrigated cropland area decreases or remains the same from one period to the next, the fixed factor supply remains unchanged between these periods. If irrigated cropland area increases above the maximum supply of irrigable cropland, then the fixed factor supply is set to zero. A supply of zero will force the price of the fixed factor to become near infinite, thus preventing any more conversion to irrigated cropland. The underlying idea is that conversion to irrigated cropland should cease when a region's water supply becomes prohibitively expensive to access. An illustrative example of the fixed factor depletion model as described by Eq. (2.24) is shown below in Figure 2-9.

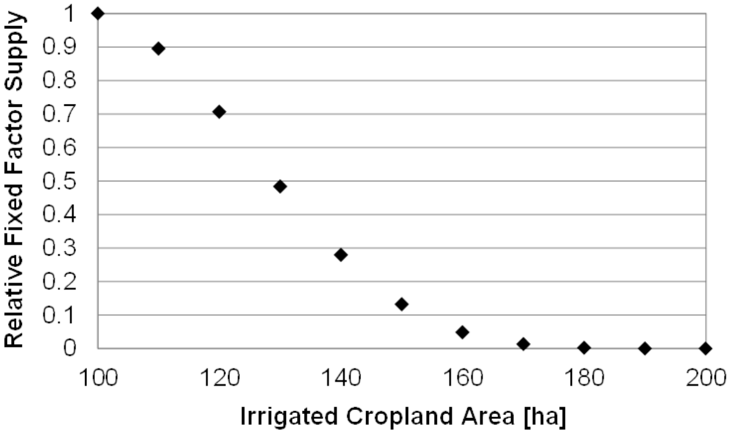

Figure 2-9: Illustration of the fixed factor depletion model.

If the production structure of irrigated cropland changes (for example though a change in technology) throughout time, then, as the fixed factor endowment is depleted and the share of the fixed factor in production changes, σ_{wr} must necessarily be updated based on Eq. (2.22). If, however, the production structure remains constant throughout the simulation timeframe, σ_{wr} will remain constant. I assume no changes in the land supply curve, nor any changes in the structure of the production of irrigated land. Therefore, σ_{wr} remains constant.

2.4.6 Other Calculations

Satisfying Zero Profit Conditions In order for the land transition block shown in Figure 2-6 to satisfy zero profit conditions, the sum of the input quantities must be equal to the output quantity in the base year. The transition to irrigated cropland adopts the same construction as the transition to cropland in EPPA-LUC, i.e. the value of intermediates, energy, labor and capital inputs is equal to the difference in land rents multiplied by an appropriate scaling factor (Gurgel et al., 2008). With the inclusion of the fixed factor representing the water resource rent, the inputs for capital, labor, intermediates and energy must be scaled yet again such that the sum of the input quantities for capital, labor, intermediates, energy *and* the fixed factor equal the difference in land rents between irrigated cropland and non-irrigated cropland. The additional scaling factor, μ is defined as follows:

$$\mu = 1 - \frac{\alpha_{ffwr}^{REG} * rent_{irr}^{REG}}{K + L + Int + E} \tag{2.25}$$

where K, L, Int and E represent input quantities to capital, labor, intermediates and energy respectively. To avoid negative values of μ, the method of Eq. (2.23) is not followed for Europe[22]. An α_{ffwr} of 0.015 is enforced since it is this value that yields a μ for Europe somewhat similar to the μ's of other developed regions. The values for μ are presented in Table 2.11.

Table 2.11: Adjustment factor μ.

	μ		μ
USA	0.801	ASI	0.779
CAN	0.768	CHN	0.598
MEX	0.797	IND	0.789
JPN	–	BRA	0.798
ANZ	0.660	AFR	0.797
EUR	0.713	MES	0.702
ROE	0.776	LAM	0.799
RUS	–	REA	0.700

Other Land Conversion Structures Additional land conversion structures from irrigated cropland to natural land and non-irrigated cropland is included as well. However, these "abandonment" transitions do not require any special formulation and follow the same structure as described in Gurgel et al. (2008).

Land Inputs to Biomass Production In EPPA-LUC, bio-electricity and bio-oil production compete with agriculture for cropland (Gurgel et al., 2008). This

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[22] It is clear that if the denominator in Eq. (2.25) is smaller than the numerator, $\mu < 0$ which is impossible since a production technology cannot use a negative amount of input. Depending on the region, however, $\mu < 0$ is possible mathematically if the ratio of irrigated to non-irrigated rents is relatively close to 1, as is the case in Europe.

research reasons that it would make little sense to grow biomass crops on irrigated cropland and therefore bio-electricity and bio-oil only compete with agriculture for non-irrigated cropland. Under this construction, however, biomass production will be in even greater competition for non-irrigated cropland than under the EPPA-LUC construction, since EPPA-LUC implicitly considers both irrigated and non-irrigated cropland in one aggregate cropland land type.

Chapter 3

Simulation Results

This chapter investigates land use, the dynamics of irrigated land, regional water demand and crop production using the model introduced in Chapter 2.

3.1 Model Scenario

The model is run from the base year, 2004, through 2100 driven exogenously by a global population that grows by 64 % from approximately 6 billion to 9.9 billion. The population data is shown in Figure 3-1. Most regions follow the global trend of more or less steady growth through 2100. Europe, Russia, and the rest of Europe and Central Asia however, all experience declining population. In China, population rises sharply until around 2040, then begins to decline. However, the rate of population growth through 2040 is greater than the rate of population decline such that in 2100, the population in China is still greater than the population in China in 2004. In Japan, population declines until 2050 and then begins to recover afterwards, but does not reach the 2004 population level, leading to a net decrease between the base year and 2100. In the USA and Canada, the population reaches a plateau around 2050.

Table 3.1 shows the increase in regional population from 2004 through 2100, $\%\Delta_{pop}$, and the percent of global population, $\%GP$, in each region in 2004 and 2100. In the base year, population is concentrated in China and India, with both countries

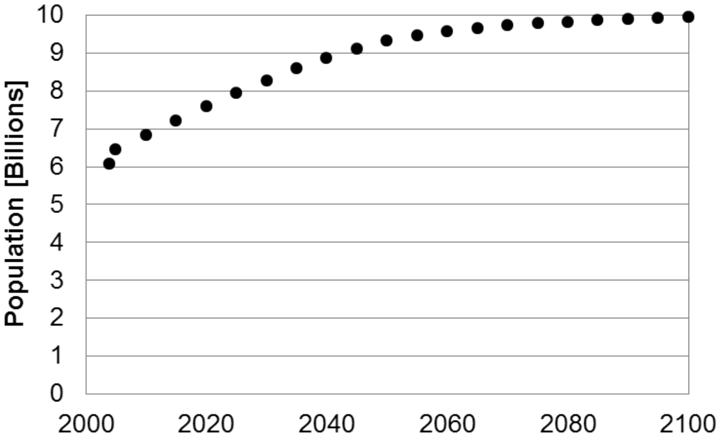

Figure 3-1: Global population growth.

comprising nearly 38 % of the global population. In 2100, however, the population shifts towards Africa, which constitutes 25 % of the global population, up from 13 % in the base year.

Table 3.1: Regional population growth and the percent of global population in each region.

	$\%\Delta_{pop}$	$\%GP_{2004}$	$\%GP_{2100}$		$\%\Delta_{pop}$	$\%GP_{2004}$	$\%GP_{2100}$
USA	38.6	4.7	4.0	ASI	57.8	3.5	3.4
CAN	29.9	0.5	0.4	CHN	4.1	21.2	13.4
MEX	60.9	1.6	1.6	IND	62.9	16.7	16.5
JPN	-6.0	2.1	1.2	BRA	60.8	3.5	3.4
ANZ	43.6	0.4	0.3	AFR	215.3	13.1	25.2
EUR	-25.9	6.4	2.9	MES	170.5	2.9	4.7
ROE	-33.9	1.6	0.6	LAM	70.1	6.9	7.2
RUS	-21.0	4.8	2.3	REA	107.0	10.2	12.8

Population growth is accompanied by income growth, with the model projecting global GNP increasing by approximately a factor of 8 from US 2004 \$40 trillion to US 2004 \$321 trillion. Regionally, all regions experience a rise in GNP per capita, however at different growth rates. Table 3.2 presents regional GNP per capita in the base year and 2100 and the percent change in GNP per capita. China experiences the largest growth of GNP per capita, growing from US 2004 \$14,000 per capita to

US 2004 \$53,000 per capita. India, the rest of Europe and Central Asia and Russia also experience large growth rates in GNP per capita.

Table 3.2: Regional GNP per capita in thousand US 2004 dollars.

	$GNPPC_{2004}$	$GNPPC_{2100}$	%Δ		$GNPPC_{2004}$	$GNPPC_{2100}$	%Δ
USA	41.2	194.7	373	ASI	7.9	47.5	502
CAN	31.6	183.5	481	CHN	1.4	53.5	3643
MEX	6.9	30.1	334	IND	0.6	13.7	2063
JPN	36.4	154.7	325	BRA	2.9	17.9	525
ANZ	33.0	161.1	389	AFR	1.0	2.7	173
EUR	32.8	196.4	498	MES	4.9	16.3	234
ROE	5.6	67.6	1109	LAM	2.0	11.8	476
RUS	1.9	19.8	914	REA	0.4	2.9	547

Energy prices are projected to grow as well in this scenario, with the world oil price index rising to 4.5 by 2100. No carbon or green house gas policy is in effect in the base year nor takes effect in the future. Biofuels do not play a significant role in electricity production, with coal and nuclear being the dominant fuel sources in the base year and 2100, respectively. Regarding total energy production, however, biofuels, specifically bio-oil, account for 12 % of global energy production by 2100, with bio-oil trading occuring among regions.

3.2 Results

3.2.1 Land Use

Figure 3-2 illustrates the changes in global land use through 2100. The percentages to the right of the legend show the share of land in total land cover in the base year (percentage on the left) and in 2100 (percentage on the right). Cropland devoted to bio-oil accounts for 11 % of total land use by 2100. The share of cropland used in agriculture increases from 12 % of total land in the base year to 19 % of total land in 2100.

Most of this growth in cropland, however, is in non-irrigated cropland. Global irrigated cropland area expands by 32 % in 2100 with respect to the base year while

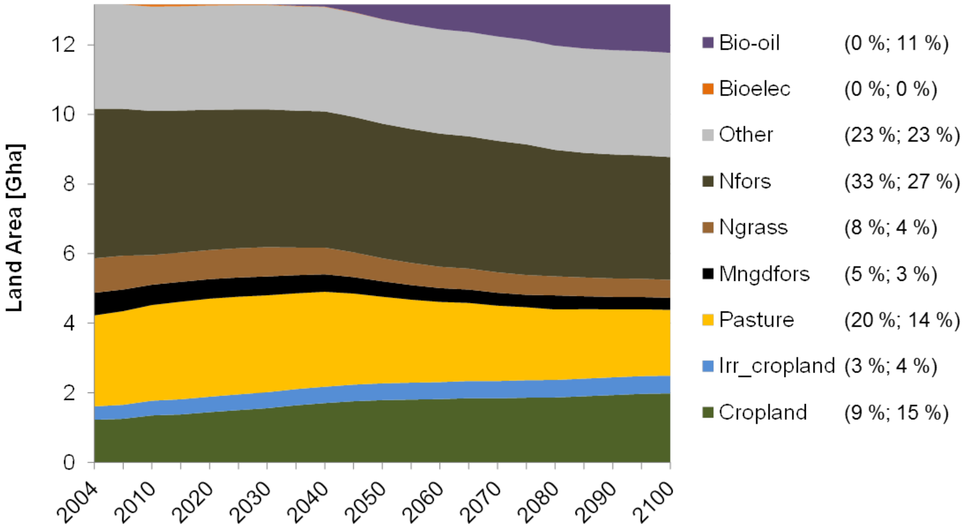

Figure 3-2: Global land cover by land type [Gha].

non-irrigated cropland area used in agriculture expands by 62 % in 2100. On the global level, therefore, non-irrigated cropland is expanding faster relative to irrigated cropland.

Figure 3-3 illustrates regional growth in irrigated cropland, non-irrigated cropland and total cropland used in agriculture from the base year to 2100. Most regions experience growth in irrigated cropland which leads to the overall expansion of irrigated cropland noted above. Africa (188 %), Mexico (78 %), rest of Europe and Central Asia (70 %) and dynamic Asia (68 %) experience the largest growth rates in irrigated cropland.

Figure 3-3 also illustrates that the majority of regions that experience positive total cropland growth show higher expansion rates in non-irrigated cropland compared to irrigated land, following the trend observed at the global level. Two notable exceptions are Brazil and the rest of Europe and Central Asia. In these two regions, growth in irrigated cropland is positive, while growth in non-irrigated cropland used in agriculture is slightly negative. In both regions, bio-oil is a significant competitor for non-irrigated cropland. In Brazil, bio-oil uses 78 % of all non-irrigated cropland

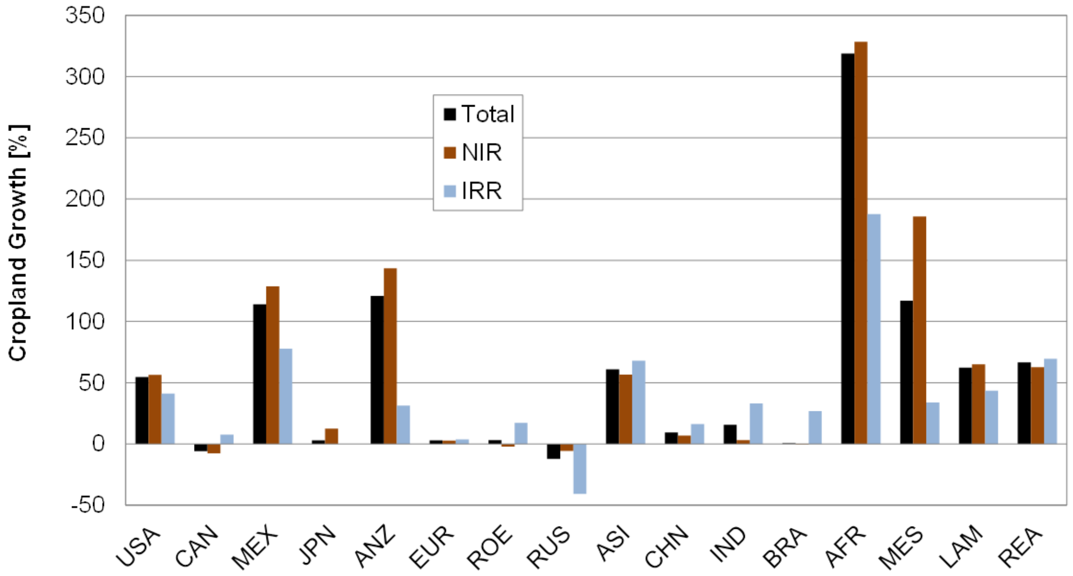

Figure 3-3: Expansion of cropland area; irrigated, non-irrigated and total cropland used in agriculture.

by 2100, and in the rest of Europe and Central Asia region, bio-oil uses 64 % of all non-irrigated cropland. These results suggest that the competition placed on non-irrigated cropland from the bio-oil sector puts pressure on the expansion of irrigated cropland.

Figure 3-4 presents the development of irrigated cropland in each EPPA region through 2100 and illustrates where the majority of irrigated cropland is concentrated. Each region's share of the global irrigated cropland total is presented to the right of the legend for the base year (percentage on the left) and 2100 (percentage on the right). Most regions' share of the global irrigated cropland total does not change appreciably between the base year and 2100. The results indicate that irrigated cropland will continue to be concentrated in India, the rest of East Asia and China, which together account for 45 % of all irrigated cropland in the base year, and 47 % of all irrigated cropland in 2100.

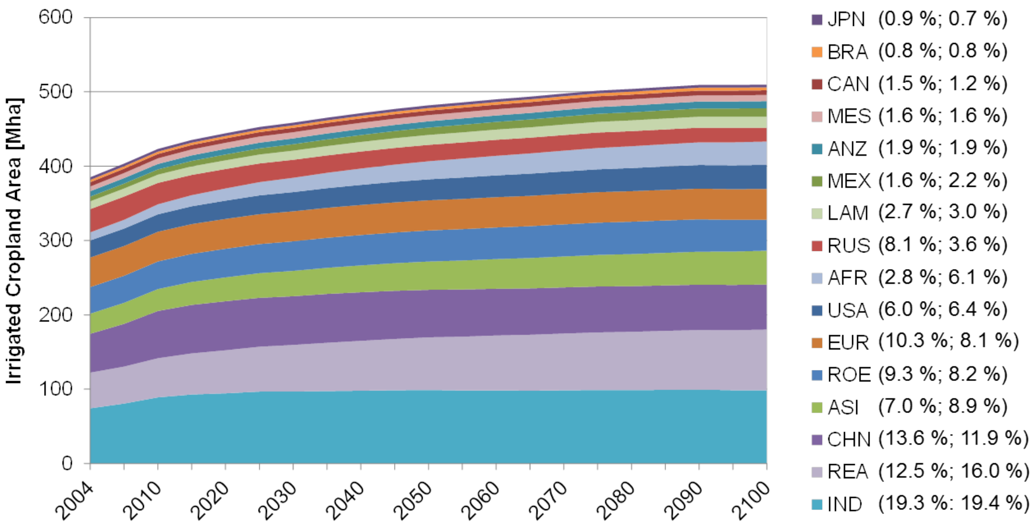

Figure 3-4: Irrigated land cover by region [Mha].

3.2.2 Water Demand

The dynamics of irrigated cropland land drive water demand for irrigation. Water use per hectare is calculated using base year irrigated cropland area and base year agricultural water withdrawals (see Table 2.8). Water withdrawals in future time periods are calculated by the product of the current water withdrawal rate and the time indexed irrigated cropland area[1].

$$WW_{ag,t} = \frac{WW_{ag,2004}}{area^{irr}_{2004}} * area^{irr}_{t} \tag{3.1}$$

Table 2.8 reports the total available renewable water resources in each region after accounting for total regional water withdrawals in the base year. The analysis assumes that all available water can be allocated to agriculture. The amount of water demanded as a share of available water resources due to the growth of irrigated

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[1] One implicit assumption behind this formulation is that irrigation efficiency, defined as the ratio of water beneficially used by the crop to the actual water applied (Burt et al., 1997), remains constant throughout the simulation. Constant efficiency is tantamount to assuming no new adoption of irrigation technology. This analysis, therefore, provides an upper bound on how much water may be demanded in the future.

cropland is presented in Figure 3-5. Most regions are withdrawing less than 30 % of

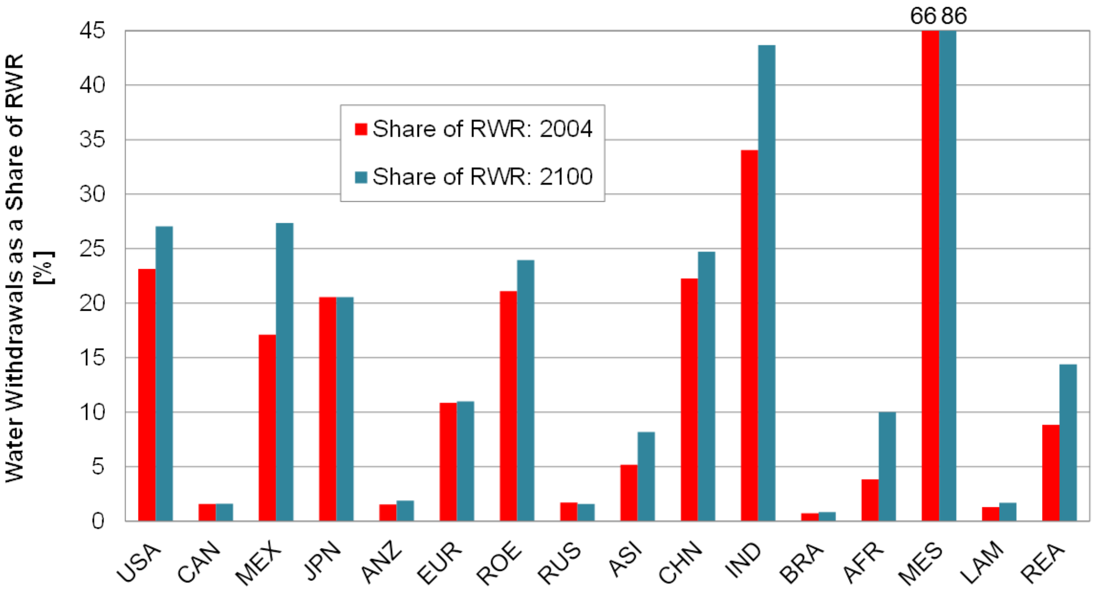

Figure 3-5: Water withdrawals in irrigated cropland as a share of renewable water resources.

their renewable water supplies. Canada, Australia and Oceania, Russia, Brazil and the rest of Americas all use less than 2 % of their total renewable water resources in 2100. And despite the large percentage increase in water withdrawals by Africa, Africa is still withdrawing only 10 % (up from 4 % in the base year) of its renewable water resource in 2100. The most notable exception to the overall trend is the Middle East (India is also withdrawing more than 30 % of its renewable water resource, but is still withdrawing less than 50 % of its renewable water resource). The Middle East is withdrawing 66 % of its total available renewable water resources in the base year. In 2100, due to the increase in irrigation and assuming no increase in other withdrawals, the Middle East is projected to be withdrawing 86 % of its total renewable water resources. Population in the Middle East, however, will continue to grow, thus placing higher demands on water used for purposes other than agriculture. Thus the percentage of renewable water resources withdrawn in the Middle East may be much higher in the future if competing uses drive up water demand in other sectors.

3.2.3 Crop Production

The model developed by Gurgel et al. (2008), EPPA-LUC, implicitly includes irrigated and non-irrigated production, but does not describe any constraints on water resources. Therefore, the model developed by Gurgel et al. (2008) assumes that any implicit increase in irrigated crop productuion is not constrained by water resources. The model developed here, EPPA-IRC, does include such constraints and allows for an investigation into the extent to which, if any, crop production is impacted by water constraints.

At the global scale, water constraints do not have a large impact on crop production. Compared to the projection of EPPA-LUC, (the water unconstrained model), global crop production in 2100 projected by EPPA-IRC (the water constrained model developed in this research) falls by 1.7 %. This suggests that on the global scale, crop production is reduced on account of water resources, but not significantly.

Water constraints, however, have a large impact on crop production in the Middle East. Crop production in 2100 projected by EPPA-IRC is nearly 37 % lower than crop production in 2100 projected by EPPA-LUC. This is due to the combined factors of a highly constrained expansion in irrigated cropland and a high irrigated share of total crop production in the Middle East. EPPA-IRC projects total cropland used in agriculture (irrigated and non-irrigated) to expand by 117%, while EPPA-LUC, the water unconstrained model, projects cropland used in agriculture to expand by 436 %. 80 % of the crop production in the Middle East is from irrigated land in the base year, and so it can be inferred that much of the expansion in cropland area projected by EPPA-LUC (the water unconstrained model) is implicitly in irrigated cropland. In EPPA-IRC, however, the limited water resources constrain the expansion of irrigated cropland to 34 %[2]. Since much of the crop production occurs on irrigated lands, the

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[2] Table 2.8 indicates that the water resources of the Middle East constrain the expansion of irrigated area by 57 %, not 34 %. This arises from the need to avoid very small numbers less than 1E-7 in the model construction. By 2070, the fixed factor supply for the Middle East reaches this level and thus the conversion to irrigated land in the Middle East is turned off in the model.

highly constrained irrigated cropland in the Middle East causes a significant reduction in crop production compared to crop production projections by EPPA-LUC.

Globally, EPPA-IRC projects that the irrigated share of total crop production remains essentially constant throughout the simulation at 36 %[3]. Figure 3-6 illustrates each region's share of irrigated, non-irrigated and total crop production in global crop production in the base year and 2100.

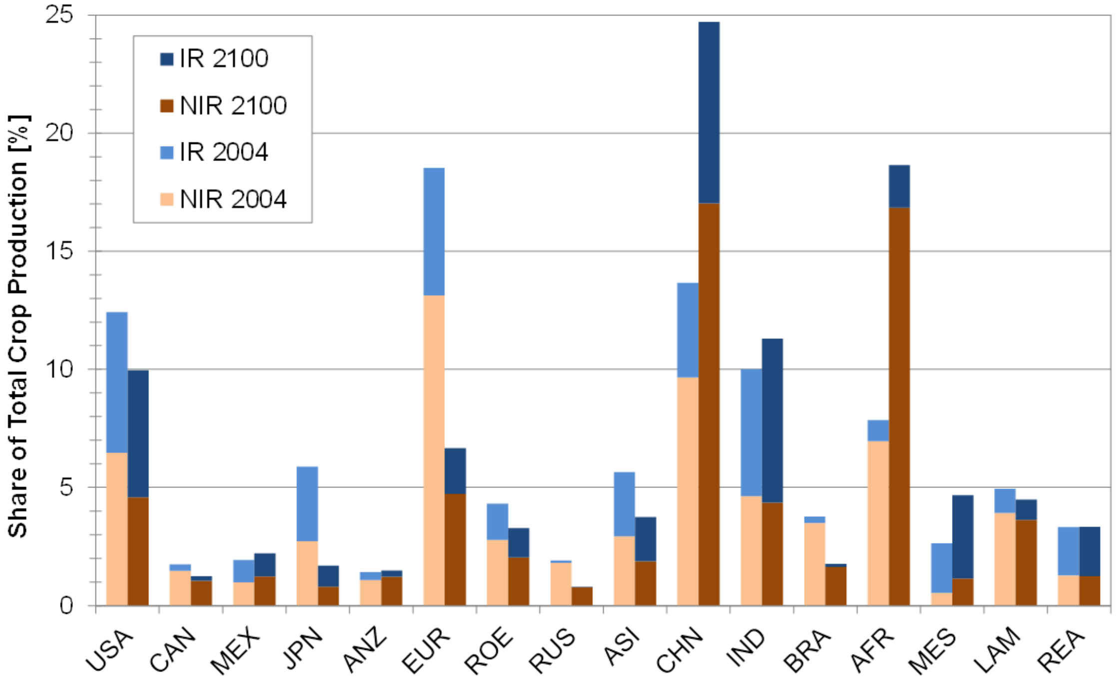

Figure 3-6: Regional irrigated, non-irrigated and total crop production shares in global crop production.

In the base year, crop production is concentrated in the USA, Europe, China and India. In 2100, crop production is concentrated in the USA, China, India and Africa. In 2100, Europe is producing a significantly smaller share of global crop production (the ratio of irrigated to non-irrigated production, however, remains ap-

---

[3] Crop production in EPPA is vintaged. In this analysis, vintaged production of crops has not been disaggregated between irrigated and non-irrigated vintaged production. Total vintaged crop production is separated by the irrigated / non-irrigated share of non-vintaged total production. Explicitly modelling irrigated and non-irrigated vintaged crop production is left to future work.

proximately constant) while Africa significantly increases its share of global crop production. These changes are, at least in part, driven by population which effects demand. Africa experiences a 215 % growth in population while Europe exerpiences a 26 % decline in population by 2100. The USA, China and India remain significant producers of crops in 2100.

Figure 3-6 also illustrates which regions are the major sources of irrigated crops. Defining major sources of irrigated crops as those regions which produce more than 5 % of the total global crop production on irrigated lands, the USA (6 %), Europe (5.4 %) and India (5.4 %) are major sources of irrigated crops in the base year. In 2100, China (7.7 %) displaces Europe as a major source of irrigated crops, while the USA (5.4 %) and India (6.9 %) remain major sources of irrigated crops. The concentration of irrigated crop production is in some constrast to the concentration of irrigated cropland coverage. For example, the rest of East Asia region contains 16 % of all irrigated cropland in 2100 (see Figure 3-4), yet the irrigated crop output only accounts for 2 % of the global crop total. India, on the other hand, contains 19 % of all irrigated cropland in 2100 and the associated irrigated crop ouput is nearly 7 % of the global total. The USA contains only 6 % of all irrigated cropland in 2100 yet the associated crop output is over 5 % of the global total. These results reflect the differences in irrigated cropland productivity accross regions.

3.2.4 Land Rents

The global price index for crops increases more or less steadily to approximately 1.5. Regarding land rents, in most regions, the difference between irrigated and non-irrigated land rents follows the diverging trend observed at the global level, shown in Figure 3-7[4].

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[4] The two exceptions to this trend are observed in Japan and Russia. In these two regions, rents on non-irrigated land grow faster than rents on irrigated land. This is explained by the fact that non-irrigated rents are higher than irrigated rents in the base year, Table 2.6.

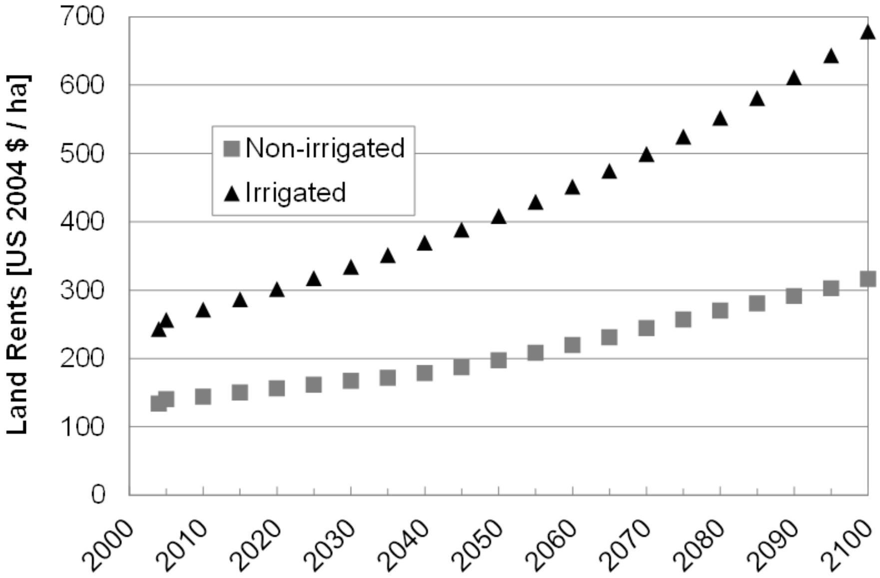

Figure 3-7: Global irrigated and non-irrigated land rents [US 2004 $/ha].

3.3 Impact of Lower Yield Growth

EPPA incorporates an exogenous land productivity growth factor of 1 % per year. On account of the uncertainty surrounding future yield growth (Gitiaux et al., 2011), this section investigates the impact of reducing this exogenous factor to 0.5 % per year. Increasing crop demand is met either through increases in land productivity or cultivated area. Reducing the productivity growth factor will therefore drive further expansion of cropland used in agriculture. The question investigated here is whether the expansion in land will occur primarily in irrigated or non-irrigated cropland. It is also of interest to consider any shift in crop production, that is, whether production shifts towards or away from irrigated production. Finally, I draw implications for water use.

3.3.1 Cropland Expansion and Changes in Production

Table 3.3 shows the expansion in 2100 of irrigated and non-irrigated cropland and production[5].

Table 3.3: Expansion of irrigated and non-irrigated crop production and cropland area in 2100 based on a 0.5 % annual exogenous land productivity growth factor.

	Production		Area	
	Δ_{nir}	Δ_{irr}	Δ_{nir}	Δ_{irr}
USA	-12.4	2.1	-1,345	3,447
CAN	-1.8	-0.3	-1,973	-182
MEX	3.0	-1.8	26,061	1,010
JPN	2.3	-0.1	662	0
ANZ	8.9	1.0	63,481	989
EUR	-7.8	-2.9	-3,287	-732
ROE	5.0	0.3	40,808	4,645
RUS	-1.7	-0.1	2,888	-838
ASI	-9.7	-6.2	-6,601	2,259
CHN	-70.7	-31.3	-2,715	-1,024
IND	-19.6	-29.9	-817	1,863
BRA	11.1	1.0	34,906	1,884
AFR	70.0	3.1	191,811	5,528
MES	1.0	-1.5	2,468	119
LAM	8.8	-1.9	57,431	1,278
REA	-5.5	-7.2	-2,880	2,383
GLOBAL	-19.0	-75.8	400,899	22,629

Regarding cropland expansion, globally, the expansion of non-irrigated cropland area is greater than the expansion of irrigated cropland area by a ratio of nearly 18:1. This suggests that at lower levels of yield, cultivating irrigated land becomes relatively less economical than cultivating non-irrigated land. This result also has significant implications for the land area allocated to biofuels. In response to the reduction in the yield and subsequent expansion in non-irrigated land used in agriculture, non-irrigated land allocated to biofuels decreases globally by nearly 70 %.

The global trend of higher non-irrigated area expansion compared to irrigated area expansion is observed in a majority of regions. In the Canada, Europe and

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[5] Expansion is defined as the value (area or production) projected by the model with the 0.5 % annual productivity growth factor assumption minus the value projected by the model with the 1 % annual productivity growth factor assumption.

China, however, both irrigated and non-irrigated area contracts, though non-irrigated area contracts more. These three regions experience an increase in pasture land and China and Canada also experience an increase in managed forest. This suggests that under decreased yield, it becomes more economical in these regions to shift towards livestock or forestry production. Finally, in the USA, dynamic Asia, India and the rest of East Asia, non-irrigated land area contracts and irrigated land area increases. This suggests that in these four regions, it is relatively more economical to continue to irrigate under decreased yield.

Another result shown by Table 3.3 is that while a contraction in area is always accompanied by a reduction in production, an expansion in area is not always accompanied by an increase in production. This is most clearly observed at the global scale, where expansion in both irrigated and non-irrigated area lead to reduction in production levels. However, irrigated production is reduced by significantly more than non-irrigated production. This leads to a situation where the share of irrigated production at the global level no longer remains at a constant 36 % as occured under the assumption of a 1 % annual productivity growth factor. With the assumption of a 0.5 % annual productivity growth factor, the share of irrigated production decreases to 33 % by 2100. Thus, under a situation of reduced productivity, at the global scale there is a shift towards more non-irrigated crop production. But the expansion in area is not sufficient to overcome the reduction in yield.

3.3.2 Implications for Water Demand

Water demand is not significantly affected by the reduction in land productivity. On the global scale, the percent of total renewable water resources withdrawn increases from 9 % to 10 %. Regional increases in water withdrawals follow the increases in irrigated land area. Regional water withdrawals for the base year, 2100 under the 1 % annual productivity growth factor assumption and 2100 under the 0.5 % annual productivity growth factor assumption are shown in Figure 3-8. The regional results follow the global trend in that increases in the share of total renewable water resources withdrawn are not very significant. For example, the largest difference between the shares of renewable water resources withdrawan under the different annual productivity growth factors is just over 2 % in the rest of Europe and Central Asia region.

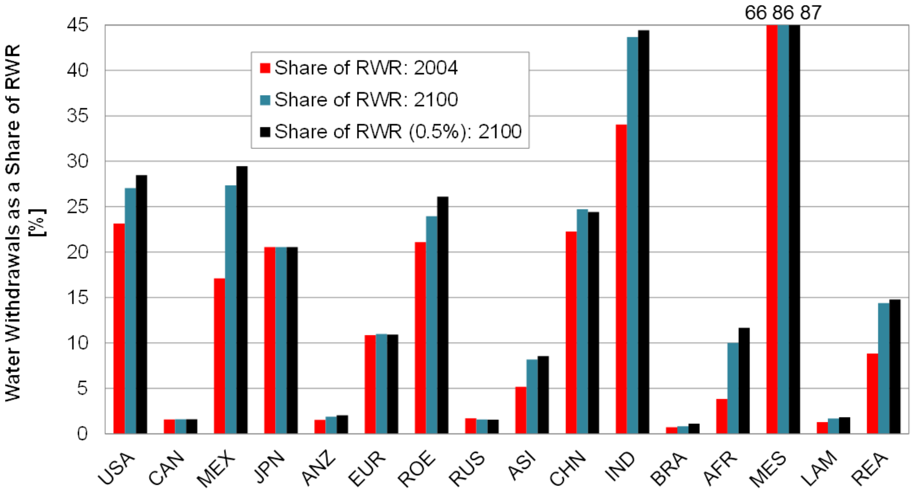

Figure 3-8: Water withdrawals in irrigated cropland as a share of renewable water resources under reduced yield growth.

Chapter 4

Conclusion

4.1 Discussion

This research has demonstrated an approach to include water constraints and irrigated cropland within the context of a global CGE land use change model. A single crop production structure is described as the aggregate production of crops grown on irrigated and non-irrigated land, with irrigated and non-irrigated land specficially introduced as factors of production. Water constraints enter the model in the production of irrigated land. Each region operates on a specific irrigable land supply curve that is paramterized to reflect the water resources of that particular region. There are signficant data limitations for parameterizing this structure but I was able to use existing literature to estimate key parameters that are of first-order importance.

Observing growth rates in irrigated and non-irrigated cropland used in agriculture suggest that, overall, non-irrigated cropland is growing faster than irrigated cropland. However, competition for non-irrigated cropland from the biofuels and agricultural sectors may in some regions drive further expansion of irrigated cropland.

Regarding crop production, the results show that water resources place a constraint on crop production by limiting the supply of irrigated land. This is most evident in the Middle East, where crop production falls by nearly 37 % in 2100 compared to crop production projected under no water constraints. This fact highlights the importance of considering water constraints for highly water scarce regions. Ignoring water constraints for such regions will overstate the maximum irrigable land coverage and consequent crop production levels.

Regarding water resources, the results suggest that most regions are withdrawing well below their maximum renewable water supplies, with the exception of the Middle East. The Middle East is projected to withdraw 86 % of it renewable water supplies by 2100, increasing from 66 % in the base year of the model. This analysis, however, has assumed that all remaining available renewable water resources in the base year could be devoted to agriculture. Competing uses for water, however, can be sigificant. For example, in the United States, water withdrawn for thermo-electric cooling accounts for nearly 50 % of national water withdrawals (Kenny et al., 2009). If increases in water withdrawals from the domestic and industrial sectors were to be included in this analysis, the percentage of total renewable water resources withdrawn in the Middle East would be even higher than 86 %, and the land that could be devoted to irrigation would be even more constrained. The amount of land that can be coverted to irrigated land in the Middle East reported in this analysis, therefore, is something of an upper bound, or optimistic projection of the actual amount of irrigable land in the Middle East region.

Finally, the model is used to investigate the impact of a decreased annual productivity growth factor, perhaps on account of climate change. Regarding cropland area, as anticipated, both irrigated and non-irrigated areas increase globally, but the dominant increase is from non-irrigated land. On the production side, both irrigated and non-irrigated production decrease, with greater decrease observed in irrigated production. On the whole, there is a shift towards non-irrigated crop production with the decreasing yield which will consequentially reduce the amount of non-irrigated cropland available for biofuel production. Despite the increases in irrigated land cover under the reduced yield assumption, water demand does not rise markedly.

4.2 Future Work

Though the parameters that are of first order importance have been estimated, there are several areas for future work. One area is developing a more detailed representation of irrigated and non-irrigated input shares in irrigated and non-irrigated crop production. This will allow differences in irrigated and non-irrigated land productivity to be more acurately described as well as describe any differences in the shares of capital, labor, energy and intermediates used in irrigated versus non-irrigated crop production.

Another avenue of future work related to crop production is the development of a dissaggregated crops sector. This will allow for a more accurate parameterization of the elasticity of subsitution between irrigated and non-irrigated crop production, σ_{crop}. As a first step towards finer crop resolution, paddy rice could be separated from irrigated crop production as it is sufficiently different from other irrigated crop production to merit a seperate treatement.

Perhaps the most critical area of future work is the construction of the land supply curves through the parameterization of the supply elasticity of irrigated land, the water resource share in irrigated land production, and the maximum amount of irrigable land. These requirements suggest the linkage of EPPA with a model that describes the physical water resource and its allocation among sectors such as the Water Resource Systems (WRS) model (Strzepek et al., 2010). WRS is refined at the river basin level and describes available water resources and how these resources are allocated among industrial and residential users; agriculture retains the remainder of available run-off (Strzepek et al., 2010). WRS could be used to parameterize the irrigated land supply curves and, as EPPA projects increased irrigated land coverage, WRS could be used to update the land supply parameters as necessary. Among the advantages of this approach is that the maximum supply of irrigable land would take into consideration competing uses for water.

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Appendix A

Details of Calculating Land and Value Shares for all Regions except USA

A.1 GAMS Code

```
* THIS PROGRAM READS IN THE GDX FILE OF AREA, IRRIGATION YIELD AND THEN AGGREGATES
* THE DATA FROM FPU'S TO EPPA5 REGIONS

* THE PROGRAM OUTPUTS SHARE OF PRODUCTION THAT IS IRRIGATED VS. NON-IRRIGATED BASED ON
* PRICES FROM IMPACT

* THESE PRICES ONLY CONSIDER WHEAT, MAIZE, O-GRAINS, POTATO, SWEET POT/YAMS, CASSAVA AND
*         OTHER R&T, RICE, AND SOYBEANS

* read in the include files that contain the tuples between fpu's and eppa5 regions
$include EPPA_FPU_Tuple.inc
$include IW_Sets_Crops.inc

SET CM / CM8, CM9, CM10, CM11, CM12, CM13, CM14, CM15 /;
SETS     ArYld    area-yield data / YRF, YIR, ARF, AIR /,

         Yield(ArYld)     yield data /
```

```
        YRF              rainfed yield
        YIR              irrigated yield/,

        Area(ArYld)      area data /
        ARF              rainfed area
        AIR              irrigated area /;

* Load in the irrigation data gdx file
parameter ay_gdx(wshd,CM,ArYld);
$gdxin are_yld.gdx
$load ay_gdx=are_yld
$gdxin

parameter P_world(C);
$CALL gdxxrw ”WorldMarketPrices.xlsx” par=P_world rdim=1
$gdxin WorldMarketPrices.gdx
$load P_world
$gdxin

display p_world, ay_gdx;

* Translate from set C to set CM
parameter wmp(CM)        world market price in 2000 dollars per
    metric ton;
wmp(”CM8”)  = p_world(”whea”);
wmp(”CM9”)  = p_world(”maiz”);
wmp(”CM10”) = p_world(”ogrn”);
wmp(”CM11”) = p_world(”pota”);
wmp(”CM12”) = p_world(”swpy”);
wmp(”CM13”) = p_world(”cass”);
wmp(”CM14”) = p_world(”rice”);
wmp(”CM15”) = p_world(”soyb”);

* Crop area by crop type by eppa region
parameter area_eppa5(eppa_5,CM,area);
area_eppa5(eppa_5,CM,area) = sum(eppa5reg(wshd,eppa_5), ay_gdx(
    wshd,CM,area));

* Total crop area (by irrigated and non-irrigated land) by eppa
    region
parameter Atot_eppa5(eppa_5,area), Atotal(eppa_5);
Atot_eppa5(eppa_5,area) = sum(CM, area_eppa5(eppa_5, CM, area));
Atotal(eppa_5) = sum(area, Atot_eppa5(eppa_5,area));

* Ratio of irrigated/non-irrigated to total land by eppa5 region
parameter ratioA(eppa_5,area);
ratioA(eppa_5,area) = Atot_eppa5(eppa_5,area) / Atotal(eppa_5);
```

```
display atot_eppa5;

* Weighted yield calculation = sum(yield * area by fpu) over eppa region / total eppa region area

* Production by croptype and fpu
* production in tons
parameter prodRF(wshd, CM), prodIR(wshd,cm), prodTot(wshd,cm);
prodRF(wshd, CM) = ay_gdx(wshd,cm,”arf”) * ay_gdx(wshd,cm,”yrf”);
prodIR(wshd, CM) = ay_gdx(wshd,cm,”air”) * ay_gdx(wshd,cm,”yir”);
prodTot(wshd,cm) = prodRF(wshd,cm) + prodIR(wshd,cm);
* Production in dollars
parameter prodRF_p(wshd,CM), prodIR_p(wshd,cm), prodTot_p(wshd,cm);
prodRF_p(wshd,CM)  = prodRF(wshd,CM)  * wmp(CM);
prodIR_p(wshd,CM)  = prodIR(wshd,CM)  * wmp(CM);
prodTot_p(wshd,CM) = prodTot(wshd,CM) * wmp(CM);

* Sum production [tons] over eppa5 regions
parameters
prodRF_e5(eppa_5,cm), prodIR_e5(eppa_5,cm), prodTot_e5(eppa_5,cm),
prodRF_e5_p(eppa_5,cm), prodIR_e5_p(eppa_5,cm), prodTot_e5_p(eppa_5,cm);

* total production in tons
prodRF_e5(eppa_5,cm) = sum(eppa5reg(wshd,eppa_5), prodRF(wshd,cm));
prodIR_e5(eppa_5,cm) = sum(eppa5reg(wshd,eppa_5), prodIR(wshd,cm));
prodTot_e5(eppa_5,cm)= sum(eppa5reg(wshd,eppa_5), prodTot(wshd,cm));

* total production in dollars
prodRF_e5_p(eppa_5,cm) = sum(eppa5reg(wshd,eppa_5), prodRF_p(wshd,cm));
prodIR_e5_p(eppa_5,cm) = sum(eppa5reg(wshd,eppa_5), prodIR_p(wshd,cm));
prodTot_e5_p(eppa_5,cm)= sum(eppa5reg(wshd,eppa_5), prodTot_p(wshd,cm));

* CALCULATE SHARE OF PRODUCTION (DOLLARS) FROM RAINFED / IRRIGATED CROPS
PARAMETER ir_shr_p(eppa_5), nir_shr_p(eppa_5);
ir_shr_p(eppa_5) = sum(cm, prodIR_e5_p(eppa_5,cm)) / sum(cm, prodTot_e5_p(eppa_5,cm));
```

```
nir_shr_p(eppa_5) = sum(cm, prodRF_e5_p(eppa_5,cm)) / sum(cm,
    prodTot_e5_p(eppa_5,cm));

* calculate yields by eppa region (tons/area)
parameter yldir_eppa(eppa_5), yldnir_eppa(eppa_5);
yldir_eppa(eppa_5) = sum(cm, prodIR_e5(eppa_5,cm)) / Atot_eppa5(
    eppa_5,”AIR”);
yldnir_eppa(eppa_5) = sum(cm, prodRF_e5(eppa_5,cm)) / Atot_eppa5(
    eppa_5,”ARF”);

* unload shares to excel file
execute_unload ’wrldProdShr_v3.gdx’, ratioA, ir_shr_p, nir_shr_p,
     yldnir_eppa, yldir_eppa;
execute ’gdxxrw.exe wrldProdShr_v3.gdx O=wrldProdShr_v3.xlsx par=
    yldir_eppa rng=yld-IR! rdim=1’;
execute ’gdxxrw.exe wrldProdShr_v3.gdx O=wrldProdShr_v3.xlsx par=
    yldnir_eppa rng=yld-NIR! rdim=1’;
execute ’gdxxrw.exe wrldProdShr_v3.gdx O=wrldProdShr_v3.xlsx par=
    ratioA rng=lndRatio! rdim=1 cdim=1’;
execute ’gdxxrw.exe wrldProdShr_v3.gdx O=wrldProdShr_v3.xlsx par=
    ir_shr_p rng=ir_shrP! rdim=1’;
execute ’gdxxrw.exe wrldProdShr_v3.gdx O=wrldProdShr_v3.xlsx par=
    nir_shr_p rng=nir_shrP! rdim=1’;
```

A.2 Mapping between FPU's and EPPA Regions

I have placed the ROW_ROW fpu into the RUS EPPA region because the portion of Russia in ROW_ROW appears to be the largest of all other countries comprising the ROW_ROW FPU.

Also, Adriatic is placed in EPPA region ROE which means that Greece and Slovenia, which should be in EPPA region EUR, are in EPPA region ROE.

Finally, Moldova, which should be in EPPA region ROE, is in EPPA region EUR because most of the Central European FPU countries are in EPPA region EUR. Half of Belarus is in EPPA region EUR under the Baltic FPU. The rest of Belarus is in EPPA region ROE under the DNI_BAL FPU.

Provided that the data from IMPACT will be used in the future, I recommend a re-delineation for some FPUs. To begin, Russia should be broken out of the ROW_ROW FPU into its own country. Also, Alaska needs to be separated out from the ROW_ROW FPU as does Greenland and Iceland. The Adriatic and Central

European FPUs could also be broken up so to create a better mapping between FPU and EPPA regions. Belarus could be broken out of the Balkans region.

Below is the GAMS SET definitions and mapping between FPUs and EPPA regions.

```
SETS

EPPA_5   Regions in EPPA5
/
USA          United_States
CAN          Canada
MEX          Mexico
BRA          Brazil
RUS          Russia
CHN          China
IND          India
JPN          Japan
LAM          Rest_of_Americas
EUR          Europe
ROE          Rest_of_Europe_and_Central_Asia
ASI          Dynamic_Asia
REA          Rest_of_East_Asia
ANZ          Australia_and_Oceania
MES          Middle_East
AFR          Africa
/

wshd
/
*{FPUs in North America}

CAN_CAN        Canada_Arctic_At Canada
CCA_CAN        Central_Canada_S Canada
COB_CAN        Columbia Canada
GLA_CAN        Great_Lakes Canada
RWI_CAN        Red_Winnipeg Canada
MIM_MEX        Middle_Mexico Mexico
RIG_MEX        Rio_Grande Mexico
UME_MEX        Upper_Mexico Mexico
ROW_ROW        ROW ROW
ARK_UNS        Arkansas United_States
CAL_UNS        California United_States
COL_UNS        Colorado United_States
COB_UNS        Columbia United_States
GBA_UNS        Great_Basin United_States
GLA_UNS        Great_Lakes United_States
```

```
MIS_UNS        Mississippi United_States
MOU_UNS        Missouri United_States
OHI_UNS        Ohio United_States
RWI_UNS        Red_Winnipeg United_States
RIG_UNS        Rio_Grande United_States
SEU_UNS        Southeast_US United_States
USN_UNS        US_Northeast United_States
WGM_UNS        Western_Gulf_Mex United_States

*{FPUs in Central and South America}
PAR_ARG        Parana Argentina
RIC_ARG        Rio_Colorado Argentina
SAL_ARG        Salada_Tierra Argentina
TIE_ARG        Tierra Argentina
AMA_BRA        Amazon Brazil
NEB_BRA        Northeast_Brazil Brazil
PAR_BRA        Parana Brazil
SAN_BRA        San_Francisco Brazil
TOC_BRA        Toc Brazil
URU_BRA        Uruguay Brazil
YUC_CCA        Yucatan Carribean_Central_America
CAM_CCA        Central_America Carribean_Central_America
CUB_CCA        Cuba Carribean_Central_America
CAR_CCA        Carribean Carribean_Central_America
AMA_CSA        Amazon Central_South_America
PAR_CSA        Parana Central_South_America
CHC_CHL        Chile_Coast Chile
NWS_COL        Northwest_South_ Colombia
ORI_COL        Orinoco Colombia
AMA_COL        Amazon Colombia
AMA_ECU        Amazon Ecuador
NWS_ECU        Northwest_South_ Ecuador
YUC_MEX        Yucatan Mexico
NSA_NSA        North_South_America_Coast Northern_South_America
ORI_NSA        Orinoco Northern_South_America
AMA_PER        Amazon Peru
PEC_PER        Peru_Coastal Peru
URU_URU        Uruguay Uruguay

*{FPUs in Australia and Islands}
CAU_AUS        Central_Australi Australia
EAU_AUS        Eastern_Australi Australia
MAU_AUS        Murray_Australia Australia
WAU_AUS        Western_Australi Australia
BOR_INO        Borneo Indonesia
INE_INO        Indonesia_East Indonesia
INW_INO        Indonesia_West Indonesia
```

```
BOR_MLY        Borneo Malaysia
NZE_NZE        New_Zealand New_Zealand
PAO_PNG        Papau_Oceania Papua_New_Guinea
PHI_PHI        Philippines Philippines

*{FPUs in Europe}
DAN_ADR        Danube Adriatic
DAN_AEU        Danube Alpine_Europe
RHI_AEU        Rhine Alpine_Europe
BAL_BAL        Baltic Baltic
DNI_BAL        Dnieper Baltic
RHI_BEL        Rhine Belgium_Luxembourg
IRE_BRI        Ireland British_Isles
BRI_BRI        Britain British_Isles
BLA_CAU        Black_Sea Caucus
DAN_CEU        Danube Central_Europe
EME_CYP        Eastern_Med Cyprus
EME_EGY        Eastern_Med Egypt
LBO_FRA        Loire_Bordeaux France
RHI_FRA        Rhine France
RHO_FRA        Rhone France
SEI_FRA        Seine France
DAN_GER        Danube Germany
ELB_GER        Elbe Germany
ODE_GER        Oder Germany
RHI_GER        Rhine Germany
ARA_GUL        Arabian_Peninsul Gulf
IWA_IBE        Iberia_West_Atla Iberia
IEM_IBE        Iberia_East_Med Iberia
TIG_IRN        Tigris_Euphrates Iran
ARA_IRQ        Arabian_Peninsul Iraq
TIG_IRQ        Tigris_Euphrates Iraq
EME_ISR        Eastern_Med Israel
ITA_ITA        Italy Italy
EME_JOR        Eastern_Med Jordan
EME_LEB        Eastern_Med Lebanon
RHI_NET        Rhine Netherlands
ODE_POL        Oder Poland
BAL_RUS        Baltic Russia
BLA_RUS        Black_Sea Russia
DNI_RUS        Dnieper Russia
ODE_RUS        Oder Russia
SCA_SCA        Scandinavia Scandinavia
ELB_SCA        Elbe Scandinavia
EME_SYR        Eastern_Med Syria
TIG_SYR        Tigris_Euphrates Syria
BLA_TKY        Black_Sea Turkey
```

```
DAN_TKY     Danube Turkey
EME_TKY     Eastern_Med Turkey
TIG_TKY     Tigris_Euphrates Turkey
BLA_UKR     Black_Sea Ukraine
DAN_UKR     Danube Ukraine
DNI_UKR     Dnieper Ukraine

*{FPUs in Africa}
NAC_ALG     North_African_Co Algeria
SAH_ALG     Sahara Algeria
CAF_ANG     Central_African_ Angola
CON_ANG     Congo Angola
ZAM_ANG     Zambezi Angola
NIG_BEN     Niger Benin
VOT_BEN     Volta Benin
KAL_BOT     Kalahari Botswana
LIM_BOT     Limpopo Botswana
ZAM_BOT     Zambezi Botswana
NIG_BUF     Niger Burkina_Faso
VOT_BUF     Volta Burkina_Faso
EAC_BUR     East_African_Coa Burundi
CAF_CAM     Central_African_ Cameroon
LCB_CAM     Lake_Chad_Basin Cameroon
NIG_CAM     Niger Cameroon
CAF_CAR     Central_African_ Central_African_Republic
CON_CAR     Congo Central_African_Republic
LCB_CAR     Lake_Chad_Basin Central_African_Republic
LCB_CHA     Lake_Chad_Basin Chad
NIG_CHA     Niger Chad
SAH_CHA     Sahara Chad
CAF_CON     Central_African_ Congo
CON_CON     Congo Congo
NIL_DJI     Nile Djibouti
CON_DRC     Congo DRC
EAC_DRC     East_African_Coa DRC
ZAM_DRC     Zambezi DRC
NIL_EGY     Nile Egypt
NAC_EGY     North_African_Co Egypt
SAH_EGY     Sahara Egypt
CAF_EQG     Central_African_ Equatorial_Guinea
NIL_ERI     Nile Eritrea
HOA_ETH     Horn_of_Africa Ethiopia
NIL_ETH     Nile Ethiopia
CAF_GAB     Central_African_ Gabon
WAC_GAM     West_African_Coa Gambia
VOT_GHA     Volta Ghana
SEN_GUI     Senegal Guinea
```

	NIG_GUI	Niger Guinea
184	WAC_GUI	West_African_Coa Guinea
	WAC_GUB	West_African_Coa Guinea_Bissau
186	VOT_IVC	Volta Ivory_Coast
	WAC_IVC	West_African_Coa Ivory_Coast
188	NIG_IVC	Niger Ivory_Coast
	HOA_KEN	Horn_of_Africa Kenya
190	ORA_LES	Orange Lesotho
	WAC_LIB	West_African_Coa Liberia
192	NAC_LBY	North_African_Co Libya
	SAH_LBY	Sahara Libya
194	MAD_MAD	Madagascar Madagascar
	ZAM_MLW	Zambezi Malawi
196	NIG_MAL	Niger Mali
	SAH_MAL	Sahara Mali
198	SEN_MAL	Senegal Mali
	VOT_MAL	Volta Mali
200	NWA_MAU	Northwest_Africa Mauritania
	SAH_MAU	Sahara Mauritania
202	SEN_MAU	Senegal Mauritania
	NWA_MOR	Northwest_Africa Morocco
204	SAH_MOR	Sahara Morocco
	LIM_MOZ	Limpopo Mozambique
206	SAF_MOZ	Southeast_Africa Mozambique
	ZAM_MOZ	Zambezi Mozambique
208	CAF_NAM	Central_African_ Namibia
	KAL_NAM	Kalahari Namibia
210	ORA_NAM	Orange Namibia
	ZAM_NAM	Zambezi Namibia
212	LCB_NIG	Lake_Chad_Basin Niger
	NIG_NIG	Niger Niger
214	SAH_NIG	Sahara Niger
	LCB_NIA	Lake_Chad_Basin Nigeria
216	NIG_NIA	Niger Nigeria
	EAC_RWA	East_African_Coa Rwanda
218	SEN_SEN	Senegal Senegal
	WAC_SEN	West_African_Coa Senegal
220	WAC_SLE	West_African_Coa Sierra_Leone
	HOA_SOM	Horn_of_Africa Somalia
222	KAL_SAF	Kalahari South_Africa
	LIM_SAF	Limpopo South_Africa
224	ORA_SAF	Orange South_Africa
	SAC_SAF	South_African_Co South_Africa
226	NIL_SUD	Nile Sudan
	SAH_SUD	Sahara Sudan
228	SAC_SWA	South_African_Co Swaziland
	EAC_TAN	East_African_Coa Tanzania

```
SAF_TAN       Southeast_Africa Tanzania
ZAM_TAN       Zambezi Tanzania
VOT_TOG       Volta Togo
NAC_TUN       North_African_Co Tunisia
EAC_UGA       East_African_Coa Uganda
HOA_UGA       Horn_of_Africa Uganda
NIL_UGA       Nile Uganda
NWA_WSA       Northwest_Africa Western_Sahara
ZAM_ZAM       Zambezi Zambia
LIM_ZIM       Limpopo Zimbabwe
SAF_ZIM       Southeast_Africa Zimbabwe
ZAM_ZIM       Zambezi Zimbabwe

*{FPUs in Asia}
AMD_AFG       Amudarja Afghanistan
WAI_AFG       Western_Asia_Ira Afghanistan
BRT_BAN       Brahmaputra Bangladesh
GAN_BAN       Ganges Bangladesh
TMM_BAN       Thai_Myan_Malay Bangladesh
BRT_BHU       Brahmaputra Bhutan
AMR_CHN       Amur China
BRT_CHN       Brahmaputra China
CHJ_CHN       Chang_Jiang China
GAN_CHN       Ganges China
HAI_CHN       Hail_He China
HUL_CHN       Hual_He China
HUN_CHN       Huang_He China
IND_CHN       Indus China
LAJ_CHN       Langcang_Jiang China
LMO_CHN       Lower_Mongolia China
OB_CHN        Ob China
SEA_CHN       SE_Asia_Coast China
SON_CHN       Songhua China
YHE_CHN       Yili_He China
ZHJ_CHN       Zhu_Jiang China
BRT_IND       Brahmaputra India
BRR_IND       Brahmari India
CAV_IND       Cauvery India
CHO_IND       Chotanagpui India
EGH_IND       Easten_Ghats India
GAN_IND       Ganges India
GOD_IND       Godavari India
IEC_IND       India_East_Coast India
IND_IND       Indus India
KRI_IND       Krishna India
LAJ_IND       Langcang_Jiang India
LUN_IND       Luni India
```

```
MAT_IND         Mahi_Tapti India
SAY_IND         Sahyada India
WAI_IRN         Western_Asia_Ira Iran
JAP_JAP         Japan Japan
AMD_KAZ         Amudarja Kazakhstan
LBA_KAZ         Lake_Balkhash Kazakhstan
OB_KAZ          Ob Kazakhstan
SYD_KAZ         Syrdarja Kazakhstan
URA_KAZ         Ural Kazakhstan
YHE_KAZ         Yili_He Kazakhstan
LBA_KYR         Lake_Balkhash Kyrgyzstan
SYD_KYR         Syrdarja Kyrgyzstan
TMM_MLY         Thai_Myan_Malay Malaysia
LMO_MON         Lower_Mongolia Mongolia
UMO_MON         Upper_Mongolia Mongolia
MEK_MYN         Mekong Myanmar
TMM_MYN         Thai_Myan_Malay Myanmar
GAN_NEP         Ganges Nepal
NKP_NOK         North_Korea_Peni North_Korea
IND_PAK         Indus Pakistan
WAI_PAK         Western_Asia_Ira Pakistan
AMR_RUS         Amur Russia
NER_RUS         North_Euro_Russi Russia
OB_RUS          Ob Russia
UMO_RUS         Upper_Mongolia Russia
URA_RUS         Ural Russia
VOG_RUS         Volga Russia
YEN_RUS         Yenisey Russia
SKP_SKO         South_Korea_Peni South_Korea
MEK_SEA         Mekong Southeast_Asia
SRL_SRL         Sri_Lanka Sri_Lanka
AMD_TAJ         Amudarja Tajikistan
MEK_THA         Mekong Thailand
TMM_THA         Thai_Myan_Malay Thailand
AMD_TKM         Amudarja Turkmenistan
URA_TKM         Ural Turkmenistan
WAI_TKM         Western_Asia_Ira Turkmenistan
AMD_UZB         Amudarja Uzbekistan
SYD_UZB         Syrdarja Uzbekistan
SEA_VIE         SE_Asia_Coast Vietnam
VOG_KAZ         Volga Kazakhstan
TMM_SIN         Thai_Myan_Malay Singapore
/

eppa5reg(wshd, eppa_5) creating EPPA5 regions out of FPUs
/
(ARK_UNS, CAL_UNS, COL_UNS, COB_UNS, GBA_UNS, GLA_UNS, MIS_UNS,
```

```
    MOU_UNS,
OHI_UNS, RWI_UNS, RIG_UNS, SEU_UNS, USN_UNS, WGM_UNS).USA

(CAN_CAN, CCA_CAN, COB_CAN, GLA_CAN, RWI_CAN).CAN

(MIM_MEX, RIG_MEX, UME_MEX, YUC_MEX).MEX

(AMA_BRA, NEB_BRA, PAR_BRA, SAN_BRA, TOC_BRA, URU_BRA).BRA

(AMR_RUS, BAL_RUS, BLA_RUS, DNI_RUS, NER_RUS, OB_RUS, ODE_RUS,
    UMO_RUS,
URA_RUS, VOG_RUS, YEN_RUS, ROW_ROW).RUS

(AMR_CHN, BRT_CHN, CHJ_CHN, GAN_CHN, HAI_CHN, HUL_CHN, HUN_CHN,
    IND_CHN,
LAJ_CHN, LMO_CHN, OB_CHN, SEA_CHN, SON_CHN, YHE_CHN, ZHJ_CHN).CHN

(BRT_IND, BRR_IND, CAV_IND, CHO_IND, EGH_IND, GAN_IND, GOD_IND,
    IEC_IND,
IND_IND, KRI_IND, LAJ_IND, LUN_IND, MAT_IND, SAY_IND).IND

(JAP_JAP).JPN

(PAR_ARG, RIC_ARG, SAL_ARG, TIE_ARG,
CAM_CCA, CAR_CCA, CUB_CCA, YUC_CCA,
AMA_CSA, PAR_CSA,
CHC_CHL,
NWS_COL, ORI_COL, AMA_COL,
AMA_ECU, NWS_ECU,
NSA_NSA, ORI_NSA,
AMA_PER, PEC_PER,
URU_URU).LAM

(DAN_AEU, RHI_AEU,
BAL_BAL,
RHI_BEL,
DAN_CEU,
EME_CYP,
SCA_SCA, ELB_SCA,
LBO_FRA, RHI_FRA, RHO_FRA, SEI_FRA,
DAN_GER, ELB_GER, ODE_GER, RHI_GER,
BRI_BRI, IRE_BRI,
ITA_ITA,
RHI_NET,
ODE_POL,
IEM_IBE, IWA_IBE).EUR

```

```
(DAN_ADR,
BLA_CAU,
DNI_BAL,
AMD_KAZ, LBA_KAZ, OB_KAZ, SYD_KAZ, URA_KAZ, YHE_KAZ, VOG_KAZ,
LBA_KYR, SYD_KYR,
AMD_TAJ,
BLA_TKY, DAN_TKY, EME_TKY, TIG_TKY,
AMD_TKM, URA_TKM, WAI_TKM,
BLA_UKR, DAN_UKR, DNI_UKR,
AMD_UZB, SYD_UZB).ROE

(BOR_INO, INE_INO, INW_INO,
SKP_SKO,
BOR_MLY, TMM_MLY,
PHI_PHI,
TMM_SIN,
MEK_THA, TMM_THA).ASI

(AMD_AFG, WAI_AFG,
BRT_BAN, GAN_BAN, TMM_BAN,
BRT_BHU,
MEK_SEA,
LMO_MON, UMO_MON,
MEK_MYN, TMM_MYN,
GAN_NEP,
NKP_NOK,
IND_PAK, WAI_PAK,
SRL_SRL,
SEA_VIE).REA

(CAU_AUS, EAU_AUS, MAU_AUS, WAU_AUS,
NZE_NZE,
PAO_PNG).ANZ

(TIG_IRN, WAI_IRN,
ARA_IRQ, TIG_IRQ,
EME_ISR,
EME_JOR,
ARA_GUL,
EME_LEB,
EME_SYR, TIG_SYR).MES

(NAC_ALG,SAH_ALG,
CAF_ANG,CON_ANG,ZAM_ANG,
NIG_BEN,VOT_BEN,
KAL_BOT,LIM_BOT,ZAM_BOT,
NIG_BUF,VOT_BUF,
```

```
EAC_BUR,
CAF_CAM,LCB_CAM,NIG_CAM,
CAF_CAR,CON_CAR,LCB_CAR,
LCB_CHA,NIG_CHA,SAH_CHA,
VOT_IVC,WAC_IVC,NIG_IVC,
CAF_CON,CON_CON,
CON_DRC,EAC_DRC,ZAM_DRC,
NIL_DJI,
EME_EGY,NIL_EGY,NAC_EGY,SAH_EGY,
CAF_EQG,
NIL_ERI,
HOA_ETH,NIL_ETH,
CAF_GAB,
WAC_GAM,
VOT_GHA,
SEN_GUI,NIG_GUI,WAC_GUI,
WAC_GUB,
HOA_KEN,
ORA_LES,
WAC_LIB,
NAC_LBY,SAH_LBY,
MAD_MAD,
ZAM_MLW,
NIG_MAL,SAH_MAL,SEN_MAL,VOT_MAL,
NWA_MAU,SAH_MAU,SEN_MAU,
NWA_MOR,SAH_MOR,
LIM_MOZ,SAF_MOZ,ZAM_MOZ,
CAF_NAM,KAL_NAM,ORA_NAM,ZAM_NAM,
LCB_NIG,NIG_NIG,SAH_NIG,
LCB_NIA,NIG_NIA,
EAC_RWA,
SEN_SEN,WAC_SEN,
WAC_SLE,
HOA_SOM,
KAL_SAF,LIM_SAF,ORA_SAF,SAC_SAF,
NIL_SUD,SAH_SUD,
SAC_SWA,
EAC_TAN,SAF_TAN,ZAM_TAN,
VOT_TOG,
NAC_TUN,
EAC_UGA,HOA_UGA,NIL_UGA,
*NWA_WSA,
ZAM_ZAM,
LIM_ZIM,SAF_ZIM,ZAM_ZIM).AFR
/;
```

Appendix B

Calculating the Irrigated Land and Value Shares for the USA region

B.1 ε_{supply} Calculation Details

ε_{supply} is calcualted for the US as a whole, as well as subregions of the US defined by the USDA (such as "Lake States", "Appalachia" and "Southeast"). The mapping between states and subnational regions is described in the GAMS code below. Repeating Eq. (2.21), the elasticity for each year is calculated as follows:

$$\varepsilon_{supply} = \frac{\%\Delta land^{irrigated}}{\%\Delta rent^{irrigated}} \tag{B.1}$$

$\%\Delta land^{irrigated}$ in Eq. (B.1) is the percentage change in the quantity of harvested irrigated land in the US and US subregions for which rent data exists for the specified range of years; 1997 to 2007, 1997 to 2002, and 2002 to 2007. Rent data is not reported in all states, so including land coverage from states where no rent data exists would bias ε_{supply}.

Harvested irrigated land as well as total irrigated land is reported by NASS. Harvested irrigated land is used versus total irrigated land because harvested land is sure to be cropland, and I want to avoid including some irrigated land that may not in fact be cropland[1].

$\%\Delta rent^{irrigated}$ in Eq. (B.1) is the percentage change in irrigated rents per acre for the specified range of years for the US and all US subregions. Recall, however, that rents are not reported for every state where there exists irrigated land coverage; some states report no rents, and some states report an aggregate rent that does not distinguish between irrigated and non-irrigated rents. To avoid losing an excessive amount of data, the rules presented in Chapter 2, Section 2.3.2 are applied to those states that report aggregate land rent.

To calculate $\%\Delta rent^{irrigated}$ in Eq. (B.1), for each year, the total irrigated rents for the US and US subregions, $rent_{yr}^{irrigated}$ must be calculated, then divided by the appropriate land area:

$$rent_{yr}^{irrigated} = \frac{\sum_{st}\left(rent_{yr,st}^{irrigated} * land_{yr,st}^{irrigated}\right)}{\sum_{st} land_{yr,st}^{irrigated}} \tag{B.2}$$

where $land_{yr,st}^{irrigated}$ is the total harvested cropland in the US or US subregions for which rent data exists. The GAMS script that calculates the elasticities described in Eq. (B.1) as well as the data from NASS are presented below. The elasticities are presented in Table B.1. The elasticity used for the USA in this analysis is taken to be the average of the three elasticities for the USA, or $\varepsilon_{supply} = 0.23$.

Note that some of the values in Table B.1 do not make much economic sense. Consider the elasticity from 1997 to 2002 for the Mountain region. The negative elasticity indicates that as rents increase, the quantity of land decreases. But if the value of irrigated cropland increases, a rational economic actor would irrigate more, not less. In these regions, (the Southern Plains, Mountain and Pacific) water resources are more constrained than in the other regions. Perhaps the negative elasticity is indicative of factors, such as water scarcity, that act upon a farmer's decision to irrigate independent of irrigated cropland value. In the Delta states and Southeast, where farmers would be less constrained by water resources, they are able to respond

---

[1] Harvested irrigated land is a value slightly less then the reported total irrigated land.

Table B.1: Elasticities of supply for irrigated cropland transformation.

	97-02	**97-07**	**02-07**
USA	0.59	0.23	-0.15
Northeast	–	–	–
Southeast	0.27	0.48	1.32
Appalachia	–	–	–
Delta States	0.78	0.66	0.59
Lake States	–	–	–
Cornbelt	–	–	–
Northern Plains	1.21	0.74	0.61
Southern Plains	-2.39	-0.46	0.03
Mountain	-9.72	2.46	-0.74
Pacific	-0.05	-0.17	-0.58

to increasing land value in the way one would expect; that is, by increasing irrigated land.

B.2 Data

NASS Quickstats online tool can be found at: http://quickstats.nass.usda.gov/. To access total cropland coverage and irrigated cropland coverage used in this research, select the following items:

- Under *Program*, select CENSUS
- Under *Sector*, select ECONOMICS
- Under *Group*, select FARMS, LAND & ASSETS
- Under *Commodity*, select AG LAND
- Under *Catagory*, select AREA
- Under *Data Item*, select AG LAND, CROPLAND - ACRES and AG LAND, IRRIGATED - ACRES
- Under *Domain*, select HARVESTED CROPLAND and TOTAL

- Under *Geographic Level*, select STATE
- Under *Year* and *State*, make no selections; this selects all years and states

This data is downloaded in to a *.csv file, then copied in to a *.xlsx file. Empty columns as well as columns *Period*, *Geo Level* and *State Fips* are removed to facilitate reading in by the code below.

NASS Quickstats also provides state wide data regarding irrigated and non-irrigated rents. To access the rents used in this research, follow the same online link presented above and select the following itmes:

- Under *Program*, select SURVEY
- Under *Sector*, select ECONOMICS
- Under *Group*, select EXPENSES
- Under *Commodity*, select RENT
- Under *Catagory*, select EXPENSE
- Under *Data Item*, select RENT, CASH, CROPLAND - EXPENSE, MEASURED IN $ / ACRE and RENT, CASH, CROPLAND, IRRIGATED - EXPENSE, MEASURED IN $ / ACRE and RENT, CASH, CROPLAND, NON-IRRIGATED - EXPENSE, MEASURED IN $ / ACRE
- Under *Domain*, select TOTAL
- Under *Geographic Level*, select STATE
- Under *Year* and *State*, make no selections; this selects all years and states

This data is downloaded in to a *.csv file, then copied in to a *.xlsx file. Empty columns as well as columns *Period*, *Geo Level* and *State Fips* are removed to facilitate reading in by the code below. Also, the following label names under the *Data Item* column are shortened:

RENT, CASH, CROPLAND - EXPENSE, MEASURED IN $ / ACRE became **AGGREGATE RENT - $/ACRE**

RENT, CASH, CROPLAND, IRRIGATED - EXPENSE, MEASURED IN $ / ACRE became **IRRIGATED RENT - $/ACRE**

RENT, CASH, CROPLAND, NON-IRRIGATED - EXPENSE, MEASURED IN $ / ACRE became **NON-IRRIGATED RENT - $/ACRE**

B.3 GAMS Code

The following code reads in the *.xlsx file created from the data above and calculates the irrigated land share, the irrigated land value share based on rents, and also calculates the elasticity of conversion to irrigated cropland for three time periods: 1997 to 2007, 1997 to 2002 and 2002 to 2007.

```
* This file reads in 'Rents&Acreage.xlsx' to construct ratios of irrigated cropland to
*    total cropland for 1997, 2002, 2007

SETS
* Type of data
program /CENSUS, SURVEY/

year / 1994 * 2010 /
elasyr / '97-02', '97-07', '02-07' /

* State names
state / ALABAMA, ALASKA, ARIZONA, ARKANSAS, CALIFORNIA, COLORADO, CONNECTICUT,
DELAWARE, FLORIDA, GEORGIA, HAWAII, IDAHO, ILLINOIS, INDIANA, IOWA, KANSAS, KENTUCKY,
LOUISIANA, MAINE, MARYLAND, MASSACHUSETTS, MICHIGAN, MINNESOTA, MISSISSIPPI, MISSOURI,
```

```
MONTANA, NEBRASKA, NEVADA, 'NEW HAMPSHIRE', 'NEW JERSEY', 'NEW MEXICO', 'NEW YORK',
'NORTH CAROLINA', 'NORTH DAKOTA', OHIO, OKLAHOMA, OREGON, PENNSYLVANIA, 'RHODE ISLAND',
'SOUTH CAROLINA', 'SOUTH DAKOTA', TENNESSEE, TEXAS, UTAH, VERMONT, VIRGINIA, WASHINGTON,
'WEST VIRGINIA', WISCONSIN, WYOMING /

* Regions: USA, northeast (NE), southeast (SE), appalachia (APP), delta states (DL)
*     lake states (LK), cornbelt (CB), northern plains (NP), southern plains (SP)
*     mountain (MT), pacific (PF)
regs / USA, NE, SE, APP, DL, LK, CB, NP, SP, MT, PF /

regmap(state,regs) /
(ALABAMA, ALASKA, ARIZONA, ARKANSAS, CALIFORNIA, COLORADO, CONNECTICUT,
DELAWARE, FLORIDA, GEORGIA, HAWAII, IDAHO, ILLINOIS, INDIANA, IOWA, KANSAS, KENTUCKY,
LOUISIANA, MAINE, MARYLAND, MASSACHUSETTS, MICHIGAN, MINNESOTA, MISSISSIPPI, MISSOURI,
MONTANA, NEBRASKA, NEVADA, 'NEW HAMPSHIRE', 'NEW JERSEY', 'NEW MEXICO', 'NEW YORK',
'NORTH CAROLINA', 'NORTH DAKOTA', OHIO, OKLAHOMA, OREGON, PENNSYLVANIA, 'RHODE ISLAND',
'SOUTH CAROLINA', 'SOUTH DAKOTA', TENNESSEE, TEXAS, UTAH, VERMONT, VIRGINIA, WASHINGTON,
'WEST VIRGINIA', WISCONSIN, WYOMING).USA

(MAINE, 'NEW HAMPSHIRE', VERMONT, MASSACHUSETTS, 'RHODE ISLAND',
```

```
CONNECTICUT, 'NEW YORK', 'NEW JERSEY', PENNSYLVANIA, DELAWARE,
    MARYLAND).NE

('SOUTH CAROLINA', GEORGIA, FLORIDA, ALABAMA).SE

(VIRGINIA, 'WEST VIRGINIA', 'NORTH CAROLINA', KENTUCKY, TENNESSEE
    ).APP

(MISSISSIPPI, ARKANSAS, LOUISIANA).DL

(MICHIGAN, WISCONSIN, MINNESOTA).LK

(OHIO, INDIANA, ILLINOIS, IOWA, MISSOURI).CB

('NORTH DAKOTA', 'SOUTH DAKOTA', NEBRASKA, KANSAS).NP

(OKLAHOMA, TEXAS).SP

(MONTANA, IDAHO, WYOMING, COLORADO, 'NEW MEXICO', ARIZONA, UTAH,
    NEVADA).MT

(WASHINGTON, OREGON, CALIFORNIA).PF
/

* Description of data
dataitem /
'AG LAND, CROPLAND - ACRES',
'AG LAND, IRRIGATED - ACRES',
'AGGREGATE RENT - $/ACRE',
'IRRIGATED RENT - $/ACRE',
'NON-IRRIGATED RENT - $/ACRE'/
```

```
* Further description of data
domain / TOTAL, ’HARVESTED CROPLAND’ /

* Still further description of data
domaincategory / ANY, ’NOT SPECIFIED’ /

* Set containing the header for the data values
data / value /
;

* Hectares in 1 acre = [(4840 sq yrds)*(3^2 sq ft)*(12^2 sq in)
    *(2.54^2 sq cm)]/[(100^2 sq m)*(10000 Ha)]
SCALAR cnvrt / 0.40468564224 /;

PARAMETERS
coverage(program,year,state,dataitem,domain,domaincategory,data)
      total land in acres
rents(program,year,state,dataitem,domain,domaincategory,data)
    rents

tot_lnd(year,state)        total cropland by state in acres

ir_lnd(year,state)         irrigated land by state in acres
ir_lndh(year,state)        irrigated harvested cropland by state
    in acres
ir_lndhr(year,state)         irrigated harvested for which rent
    data exists

nir_lnd(year,state)        non-irrigated land by state in acres
nir_lndh(year,state)         alternate non-irrigated land by state
     in acres
```

```
nir_lndhr(year,state)        non-irrigated harvested for which rent data exists

sum_ir_lndh(year,regs)         total harvested irrigated cropland in acres
sum_ir_lndhr(year,regs)        total harvested irrigated cropland in acres for which rent data exists
sum_nir_lndh(year,regs)        total non-irrigated cropland in acres
sum_nir_lndhr(year,regs)       total non-irrigated cropland in acres for which rent data exists
sum_tot_lnd(year,regs)         total cropland in acres
sum_tot_lndhr(year,regs)       total cropland in acres for which rent data exists
land_ratio
ir_land_ratio
nir_land_ratio

ir_rnt(year,state)          explicit and assumed irrigated land rents - price per acre
ir_rntA(year,state)
nir_rnt(year,state)         explicit and assumed non-irrigated land rents - price per acre
nir_rntA(year,state)
agg_rnt(year,state)         aggregate rents - price per acre

sum_ir_lndhr_NE(year), sum_ir_lndhr_SE(year), sum_ir_lndhr_APP(year), sum_ir_lndhr_DLT(year), sum_ir_lndhr_LK(year),
sum_ir_lndhr_CB(year), sum_ir_lndhr_NP(year), sum_ir_lndhr_SP(year), sum_ir_lndhr_MTN(year), sum_ir_lndhr_PAC(year)
;

```

```
$CALL GDXXRW "Rents&Acreage.xlsx" Par=coverage rng=
    NASS_CrplndCoverage!A1 rdim=6 cdim=1 SQ=N
$gdxin Rents&Acreage.gdx
$load coverage
$gdxin

$CALL GDXXRW "Rents&Acreage.xlsx" Par=rents rng=Irr_NonIrr_Rents!
    A1 rdim=6 cdim=1 SQ=N
$gdxin Rents&Acreage.gdx
$load rents
$gdxin

* Irrigated / non-irrigated / total cropland by state
* non-irrigated cropland calculated by take the difference of
    total cropland and irrigated farm land
tot_lnd(year,state) = coverage("CENSUS",year,state,"AG LAND,
    CROPLAND - ACRES","TOTAL","NOT SPECIFIED","value");
ir_lnd(year,state) = coverage("CENSUS",year,state,"AG LAND,
    IRRIGATED - ACRES","TOTAL","NOT SPECIFIED","value");
ir_lndh(year,state) = coverage("CENSUS",year,state,"AG LAND,
    IRRIGATED - ACRES","HARVESTED CROPLAND","ANY","value");
nir_lnd(year,state) = tot_lnd(year,state) - ir_lnd(year,state);
nir_lndh(year,state) = tot_lnd(year,state) - ir_lndh(year,state);

* Irrigated / non-irrigated / total cropland - national aggregate
sum_ir_lndh(year,regs) = sum(regmap(state,regs), ir_lndh(year,
    state));
sum_nir_lndh(year,regs) = sum(regmap(state,regs), nir_lndh(year,
    state));
sum_tot_lnd(year,regs) = sum(regmap(state,regs), tot_lnd(year,
    state));
```

```
* Share of irrigated land (absolute value)

*  This calculation was also done in summarytables.xls which came from the major land use study done by USDA
*  Irrigated land total: assumed to be irrigated land that is harvested (this underestimates what is reported in summarytables.xls)
*  Total land: assumed to be total cropland as calculated by sum_tot_lnd(year,regs). Wierdly, the national aggregate 2002 value does
*    not agree exactly with summarytables.xls.

* NB: This calculation does NOT depend upon the whether or not irrigated rents exist.
parameter irr_lnd_shr(year,regs);
irr_lnd_shr(year,regs)$sum_tot_lnd(year,regs) = sum_ir_lndh(year,regs) / sum_tot_lnd(year,regs);

* Aggregate land rents (sometimes, this is the only data reported for a state)
agg_rnt(year,state) = rents("SURVEY",year,state,"AGGREGATE RENT - $/ACRE","TOTAL","NOT SPECIFIED","value");

* Irrigated rents: if there is an explicit data point, assign irrigated land rents - otherwise, assign aggregate rents
*    to irrigated lands in a state if the irrigated cropland in that state accounts for >= 90% of the total
ir_rnt(year,state)$(rents("SURVEY",year,state,"IRRIGATED RENT - $/ACRE","TOTAL","NOT SPECIFIED","value"))
  = rents("SURVEY",year,state,"IRRIGATED RENT - $/ACRE","TOTAL","NOT SPECIFIED","value");
```

```
ir_rnt(year,state)$((NOT rents("SURVEY",year,state,"IRRIGATED RENT - $/ACRE","TOTAL","NOT SPECIFIED","value"))
  AND (tot_lnd(year,state) > 0) AND ((ir_lndh(year,state) / tot_lnd(year,state)) >= 0.9)) = agg_rnt(year,state);

* Non-irrigated rents: if there is an explicit data point, assign non-irrigated land rents - otherwise, assign aggregate
*     rents to non-irrigated lands in a state if the non-irrigated cropland in that state accounts for >= 90% of the total
nir_rnt(year,state)$(rents("SURVEY",year,state,"NON-IRRIGATED RENT - $/ACRE","TOTAL","NOT SPECIFIED","value"))
  = rents("SURVEY",year,state,"NON-IRRIGATED RENT - $/ACRE","TOTAL","NOT SPECIFIED","value");
nir_rnt(year,state)$((NOT rents("SURVEY",year,state,"NON-IRRIGATED RENT - $/ACRE","TOTAL","NOT SPECIFIED","value"))
  AND (tot_lnd(year,state) > 0) AND ((nir_lndh(year,state) / tot_lnd(year,state)) >= 0.9)) = agg_rnt(year,state);

* Recalculate land totals based on where we have rent data
*     For example: florida reports irrigated and non-irrigated land, but florida only
* reports non-irrigated rents. For that reason, no irrigated rents are reported
* for florida - therefore, the irrigated land associated with florida should not
* be reported when calculating the elasticity. Also, this means the irrigated land
* reported for florida is "lost"
ir_lndhr(year,state)$ir_rnt(year,state) = ir_lndh(year,state);
nir_lndhr(year,state)$nir_rnt(year,state) = nir_lndh(year,state);

* Sum land coverage for all regions
```

```
sum_ir_lndhr(year,regs) = sum(regmap(state,regs), ir_lndhr(year,state));
sum_nir_lndhr(year,regs) = sum(regmap(state,regs), nir_lndhr(year,state));
sum_tot_lndhr(year,regs) = sum_ir_lndhr(year,regs) + sum_nir_lndhr(year,regs);

* Calculate how much cropland is not considered by virtue of the existence of rent data for that state and land type
land_ratio(year,regs)$sum_tot_lnd(year,regs) = sum_tot_lndhr(year,regs) / sum_tot_lnd(year,regs);
ir_land_ratio(year,regs)$sum_ir_lndh(year,regs) = sum_ir_lndhr(year,regs) / sum_ir_lndh(year,regs);
nir_land_ratio(year,regs)$sum_nir_lndh(year,regs) = sum_nir_lndhr(year,regs) / sum_nir_lndh(year,regs);

* CALCULATE THE ELASTICITY %DELTA QUANTITY / %DELTA PRICE

PARAMETERS
totR_ir(year,regs)  total irrigated rents summed over all states
totR_nir(year,regs) total non-irrigated rents summed over all states
totR(year,regs)    total rents (irrigated plus non-irrigated)
irrR(year,regs)    irrigated rents per acre - national average
irlnd_shr(year,regs)  value share of irrigated land
ir_elas(elasyr,regs)  price elasticity of irrigated land - prcnt change in acres over prcnt change in price per acre
irrR_delta(elasyr,regs) percent change in irrigated land rents
;

* Rent calculation - National aggregate
```

```
totR_ir(year,regs) = sum(regmap(state,regs), (ir_lndhr(year,state) * ir_rnt(year,state)));
totR_nir(year,regs) = sum(regmap(state,regs), (nir_lndhr(year,state) * nir_rnt(year,state)));
totR(year,regs) = totR_ir(year,regs) + totR_nir(year,regs);
irlnd_shr(year,regs)$totR(year,regs) = totR_ir(year,regs) / totR(year,regs);
irrR(year,regs)$sum_ir_lndhr(year,regs) = totR_ir(year,regs) / sum_ir_lndhr(year,regs);


* Calculation of elasticity - national aggregates and regions
* National aggregate
ir_elas("97-02",regs) = ((sum_ir_lndhr("2002",regs) - sum_ir_lndhr("1997",regs)) / (sum_ir_lndhr("1997",regs))) /
          ((irrR("2002",regs) - irrR("1997",regs))/(irrR("1997",regs)));
ir_elas("97-07",regs) = ((sum_ir_lndhr("2007",regs) - sum_ir_lndhr("1997",regs)) / (sum_ir_lndhr("1997",regs))) /
          ((irrR("2007",regs) - irrR("1997",regs))/(irrR("1997",regs)));
ir_elas("02-07",regs) = ((sum_ir_lndhr("2007",regs) - sum_ir_lndhr("2002",regs)) / (sum_ir_lndhr("2002",regs))) /
          ((irrR("2007",regs) - irrR("2002",regs))/(irrR("2002",regs)));

* Percent change in irrigated land rents
irrR_delta("97-02",regs) = ((irrR("2002",regs) - irrR("1997",regs))/(irrR("1997",regs)))*100;
irrR_delta("97-07",regs) = ((irrR("2007",regs) - irrR("1997",regs))/(irrR("1997",regs)))*100;
```

```
irrR_delta(”02−07”,regs) = ((irrR(”2007”,regs) − irrR(”2002”,regs))/(irrR(”2002”,regs)))*100;

* Display parameters
display ir_elas, irrR, irrR_delta;
display sum_ir_lndh, sum_nir_lndh, sum_tot_lnd;
display sum_ir_lndhr, sum_nir_lndhr, sum_tot_lndhr;
display ir_land_ratio, nir_land_ratio, land_ratio;
display ir_lnd, nir_lnd, tot_lnd, ir_rnt, nir_rnt, agg_rnt;
display totR_ir, totR_nir, totR;

execute_unload ”C:\Research\EPPA_development\IrNIr\USA_cropData\ir_elas.gdx”,
ir_elas, irrR_delta, irr_lnd_shr, irlnd_shr, ir_land_ratio, nir_land_ratio, land_ratio;
execute ’GDXXRW.EXE ir_elas.gdx o=elasticityCalc_OUT.xlsx par=ir_land_ratio rng=ir_lost!     rdim=1 cdim=1’;
execute ’GDXXRW.EXE ir_elas.gdx o=elasticityCalc_OUT.xlsx par=nir_land_ratio  rng=nir_lost!    rdim=1 cdim=1’;
execute ’GDXXRW.EXE ir_elas.gdx o=elasticityCalc_OUT.xlsx par=land_ratio   rng=tot_lost!    rdim=1 cdim=1’;
execute ’GDXXRW.EXE ir_elas.gdx o=elasticityCalc_OUT.xlsx par=irlnd_shr    rng=valShr_irlnd! rdim=1 cdim=1’;
execute ’GDXXRW.EXE ir_elas.gdx o=elasticityCalc_OUT.xlsx par=irr_lnd_shr rng=irLndshr!    rdim=1 cdim=1’;
execute ’GDXXRW.EXE ir_elas.gdx o=elasticityCalc_OUT.xlsx par=irrR_delta   rng=pctChgRnt!     rdim=1 cdim=1’;
execute ’GDXXRW.EXE ir_elas.gdx o=elasticityCalc_OUT.xlsx par=ir_elas    rng=elasticity!    rdim=1 cdim=1’;

* Sanity check: make sure the cropland totals I calculate are those reported by the census report
```

```
*      Checked - values are the same
parameter sc02, sc07;
sc02 = sum(state, tot_lnd("2002",state));
sc07 = sum(state, tot_lnd("2007",state));
display sc02, sc07;
```

Appendix C

Distance Function Methodology for Calculating the Elasticity of Irrigable Land Supply

This appendix describes an alternative approach to calculating the elasticity of irrigable land supply introduced in Chapter 2 Section 2.4.3. This method is based on the the increase in the cost/benefit ratio of irrigation as a function of the distance from an irrigation source. Distance from the irrigation source therefore acts as a proxy to water scarcity.

The FAO AEZ project estimates potential percentage increase in yield due to irrigation for the globe in 5 minute by 5 minute grid cell resolution for six different irrigation impact classes (Fischer et al., 2002). The increase in yield due to irrigation at each grid point is thus associated with a benefit. Additionally, each grid cell is located at some distance from respective irrigation sources. As sources become inreasingly distant from the grid cell, the cost of supplying water for irrigation increases. The increase in the cost / benefit ratio associated with each grid cell can then be plotted as a function of the distance from an irrigation source. Thus a plot such as shown below in Figure C-1 would be developed for each grid point. The elasticity of irrigated land supply could then be parameterized based on this curve. To calculate the elasticity for a given region, the average value of all individual grid cell elasticities would be taken.

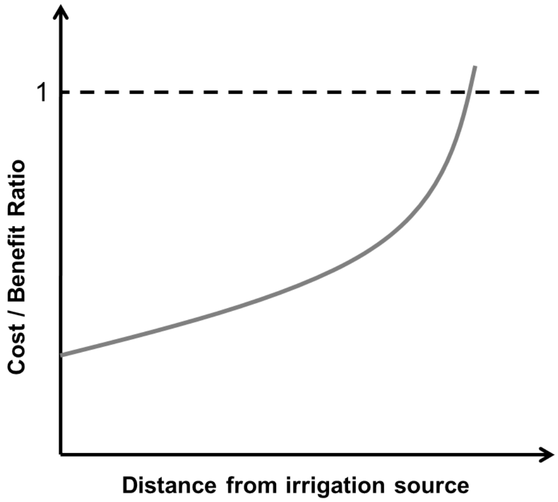

Figure C-1: Illustration of the distance function concept.

Developing an estimate of costs is straightforward. As a place to start, a "cost of conveyance" approach is proposed. In other words, the cost of irrigation is simply the cost of transporting the water from the reservoir to the area to be irrigated. The primary cost of conveyance is the cost of constructing an irrigation canal. Of course, the cost of an irrigation canal will depend on the type of construction and geographic location. If an unlined canal is built in sandy soil, construction will be cheap. If a lined canal is to be built in New England (which tends to have very rocky soil), construction will be expensive. Costs will also depend upon the EPPA region. The result is a regional average canal cost per unit length.

The second component to costs will be calculating the distance of an irrigation source from each grid cell so that total costs associated with drawing water from each irrigation source can be determined for each grid cell. This method proposes to calculate the distance to reservoirs used for irrigation within a 200km radius using the point distance function in ArcGIS.[1]

---

[1] A 200km radius is used to place some limit on the computation time and so as not to produce

Benefits are modeled as the product of the potential increase in production on account of irrigation and price of cereals. Fischer et al. (2002) note that “the potential contribution from irrigation is particularly great in impact classes 4 and 5” which represent, respectively, a 50 % - 100 %, and greater than 100 % potential increases in yield above rainfed conditions. Plate 47 of the supporting data associated with Fischer et al. (2002), describes the potential increase in yield due to irrigation for the six impact classes defined by Fischer et al. (2002).

The original raster image from FAO can be converted into a point file in ArcGIS. An important note to this data is that only cereal production is considered. Therefore, low consumption but potentially high valued crops such as fruits and vegetables are ignored. Developing a distance function approach without such crops will potentially overstate the cost/benefit ratio.

For each grid cell turned point feature, current production and yield must be calculated so that the increase in yield can be associated with an increase in production. Benefits are then taken as the product of production and the world market price for the particular crop. Knowledge of the current benefits and potential percentage increase in yield allows for a calculation of future potential benefits simply by adding the current benefits to the percentage yield increase of these benefits.

---

more data than needed. Clearly, at some distance from the irrigation source, the cost/benefit ratio will be greater than unity, indicating that irrigation is no longer economical. This method assumes that sensical cost/benefit ratios likely fall somewhere within the 200km radius. Another reason for the choice of 200km radius is that, at least in the US, the longest irrigation canal (The All-American Canal) is only 80 miles, or approximately 129 km, in length. 200km allows for a longer canal, but within some reason.