



***The World's Largest Open Access Agricultural & Applied Economics Digital Library***

**This document is discoverable and free to researchers across the globe due to the work of AgEcon Search.**

**Help ensure our sustainability.**

Give to AgEcon Search

AgEcon Search  
<http://ageconsearch.umn.edu>  
[aesearch@umn.edu](mailto:aesearch@umn.edu)

*Papers downloaded from AgEcon Search may be used for non-commercial purposes and personal study only. No other use, including posting to another Internet site, is permitted without permission from the copyright owner (not AgEcon Search), or as allowed under the provisions of Fair Use, U.S. Copyright Act, Title 17 U.S.C.*

*No endorsement of AgEcon Search or its fundraising activities by the author(s) of the following work or their employer(s) is intended or implied.*



**Global Trade Analysis Project**  
<https://www.gtap.agecon.purdue.edu/>

This paper is from the  
GTAP Annual Conference on Global Economic Analysis  
<https://www.gtap.agecon.purdue.edu/events/conferences/default.asp>

# The Impact of Water Scarcity on Food, Bioenergy and Deforestation

Niven Winchester,<sup>\*,†</sup> Kirby Ledvina\*, Kenneth Strzepek\* and John M. Reilly\*

## Abstract

*We evaluate the impact of explicitly representing irrigated land and water scarcity in an economy-wide model on food prices, bioenergy production and deforestation both with and without a global carbon policy. The analysis develops supply functions of irrigable land from a water resource model resolved at 282 river basins and applies them within a global economy-wide model of energy and food production, land-use change and greenhouse gas emissions. The irrigable land supply curves are built on basin-level estimates of water availability, and the costs of improving irrigation efficiency and increasing water storage, and include other water requirements within each basin. The analysis reveals two key findings. First, explicitly representing irrigated land has a small impact on food, bioenergy and deforestation outcomes. This is because this modification allows more flexibility in the expansion of crop land (i.e., irrigated and rainfed land can expand in different proportions) relative to when a single type of crop land is represented, which counters the effect of rising marginal costs for the expansion of irrigated land. Second, due to endogenous irrigation and storage responses, changes in water availability have small impacts on food prices, bioenergy production, land-use change and the overall economy, even with large scale (~150 exajoules) bioenergy production.*

## Contents

1. INTRODUCTION.....	ERROR! BOOKMARK NOT DEFINED.
2. A GLOBAL MODEL OF THE ECONOMY, ENERGY, AND AGRICULTURE .....	3
2.1 The Economic Projection and Policy Analysis Model .....	3
2.2 Representing irrigated land in the EPPA model .....	6
2.2.1 Irrigated and rainfed crop land and production .....	6
2.2.2 Irrigated land supply curves .....	8
2.2.3 Representing irrigated and rainfed crop production in the EPPA model .....	12
3. SCENARIOS.....	14
4. RESULTS .....	16
4.1 Economic, environment, land use, and bioenergy implications of irrigation .....	16
4.2 Energy, bioenergy, and land use results .....	19
5. CONCLUSIONS.....	22
6. REFERENCES.....	24
APPENDIX.....	27

## 1. INTRODUCTION

In forthcoming decades, increasing populations and economic growth will drive increased food demand. At the same time, energy and climate policies may promote the production of bioenergy creating a new large competitor for land resources. Given basic demand growth for conventional agricultural products, and exogenous trends in productivity of agricultural production, there are three basic margins of adjustment that will determine if there is “room” for biomass energy expansion: (1) yields on existing crop land can increase in response to land price

---

\* Joint Program on the Science and Policy of Global Change, Massachusetts Institute of Technology, Cambridge, MA, USA.

† Corresponding author (email: [niven@mit.edu](mailto:niven@mit.edu)).

increases (intensification), (2) crop land area can expand (extensification), and (3) less food can be used in response to higher food prices. In general, with a new demand for land we would expect movement on all three margins, but how much on each depends how fast costs rise on each margin as expansion advances. A key intensification option is to irrigate more land already in agricultural production, as yields on irrigated land are in general far above that of rainfed land. The feasibility of expanding irrigated production will depend on the costs of improving irrigation efficiency and the cost of increasing water storage. Here, a significant concern is that water is severely limited in many water basins, restricting the potential expansion. Expanding the extensive margin raises concerns about the destruction of natural habitat and deforestation with implications for, among other things, carbon storage. Policy that restricts conversion of forests and natural lands will limit expansion along this margin, and could actually lead to conversion of more land to forests if there are financial incentives to do so. Hence water resource limits and policies regarding protection of natural lands could put more pressure on the food demand response margin. The unfortunate aspect of food response is that those with low incomes are most likely to be priced out of the food market. This paper seeks to better quantify tradeoffs among these margins and bioenergy potential by greatly improving the representation of irrigation potential in a global economy model that includes details on agricultural and energy markets and natural resources.

In addition to increasing food demand, rising greenhouse gas (GHG) concentrations – which will largely depend on future energy production and land use – and the associated changes in climate will also impact food and water systems. Among other channels, rising temperatures will affect irrigation outcomes through changes in crop water demand and evaporation. Food, energy, water, and land use outcomes, therefore, must be considered as an interconnected system.

We advance analysis of food-energy-water-land interactions by representing irrigable land supply curves, which are estimated from detailed spatial data on water availability and irrigation costs, in the MIT Economic Projection and Policy Analysis (EPPA) model (Paltsev *et al.*, 2005), a global model linking economic activity, natural resources, land-use change, and GHG emissions. A global carbon price is simulated in the model under alternative water availability assumptions to estimate how constraints on the expansion of irrigated land, as represented by irrigable land supply curves, will impact food prices, bioenergy production, and deforestation.

Several previous studies have used economy-wide models to examine water issues – see Johansson (2005), Dudu and Chumi (2008) and Dinar (2014) for reviews of this literature. The most relevant strand of previous research for our analysis examines the impacts of water constraints on food and other outcomes using the GTAP-BIO-W model (Taheripour *et al.*, 2013a).<sup>1</sup> This model represents irrigated and rainfed crop production at the agro-ecological zone (AEZ) level and divides the water system into 126 river basins. Rainfed and irrigated crop production compete for land at the river basin-AEZ level, and there is competition for water resources at the river basin level.

---

<sup>1</sup> The GTAP-BIO-W model builds on models developed by Berrittella (2007) and Calzadilla *et al.* (2010).

Taheripour *et al.* (2013b) examine alternative constraints on the expansion of irrigated land and conclude that studies that fail to distinguish rainfed and irrigated land underestimate global land use change and emissions induced by the expansion of corn ethanol production in the US. Liu *et al.* (2014) use the GTAP-BIO-W model to simulate the impact of changes in water available for irrigation estimated by Rosegrant *et al.* (2012). Due to significant declines in projected water availability in key river basins, the authors estimate significant decreases in agricultural production in China, South Asia and the Middle East. However, global impacts are modest as agricultural trade buffers heterogeneous regional impacts.<sup>2</sup>

While the GTAP-BIO-W model has advanced economy-wide modeling of food, water and bioenergy outcomes, several limitations remain. First, the model assumes that the supply of managed land is fixed, so it does not consider conversion of natural to managed areas and issues surrounding deforestation. Second, land is allocated among managed areas using a constant elasticity of transformation (CET) function in GTAP-BIO-W, so transitions from one land type to another decrease the stock of available land. Third, at given water availability, the model does not allow more land to be irrigated by investing in more efficient irrigation systems and/or increasing water storage.

This paper sets out and applies a framework that addresses these limitations in four further sections. Section 2 provides an overview of our economy-wide model, the estimation of irrigable land supply curves, and how these supply curves are included in the EPPA model. Scenarios considered in our modeling analysis are outlined in Section 3. Section 4 presents and discusses results. Concluding remarks are offered in Section 5.

## 2. A GLOBAL MODEL OF THE ECONOMY, ENERGY, AND AGRICULTURE

Our analysis builds on a version of the EPPA model with land use (Gurgel, et al., 2007; Gurgel, et al., 2011), a global model of economic activity, energy production and GHG emissions. We start with a version of the EPPA model augmented to consider land-use change and bioenergy in detail (Winchester and Reilly, 2015), and extend it to represent rainfed and irrigated land and the costs and limitations of expanding irrigated areas.

### 2.1 The Economic Projection and Policy Analysis Model

The EPPA model is recursive-dynamic, multi-region computable general equilibrium global model and is solved through time in five-year increments from 2005 through 2050. Regions and sectors represented in the model are outlined in **Table 1**. For each of the 16 countries or regions in the model, 14 broad production sectors are defined: five energy-producing sectors (coal, crude oil, refined oil, gas and electricity), three agricultural sectors (crops, livestock and forestry), and

---

<sup>2</sup> In other related literature, using a regional integrated assessment model and a regional Earth system model of the US, Hejaz *et al.* (2015), find that water demand to integrate bioenergy crops under a climate mitigation scenario can increase water stress.

six other non-energy sectors (energy-intensive industry, commercial transportation, private transportation, food products, services and other industries). Several commodities in the model can be produced using different technologies and/or resources, including ‘advanced technologies’. For example, refined oil products can be produced both from crude oil and biofuels. Due to their higher costs, advanced technologies typically do not operate in the base year but may become cost competitive due to changes in relative prices caused by policies or resource depletion. For example, in the base year electricity is produced by traditional coal, gas, nuclear and hydro generation, but in future years it may also be produced from advanced technologies such as biomass with carbon capture and storage. Oil and gas prices are endogenously estimated, a result of demand for fuels in the economy interacting with the specification of resource availability and supply technology. Prices rise through time and reach, in 2010 dollars, \$150 per barrel and \$31 per million British thermal unit, respectively, by 2050. While energy prices are notoriously variable this forecast is in line with other sources such as projections by the EIA (2012).

**Table 1.** Aggregation in the EPPA model extended to represent bioenergy in detail.

Regions & Factors	Sectors
<b>Regions</b>	<b>Energy sectors</b>
United States (USA)	Coal
Canada (CAN)	Crude oil <i>Conventional crude oil; oil from shale, sand</i>
Mexico (MEX)	
Japan (JPN)	Refined oil <i>From crude oil, first and second generation biofuels</i>
Australia-New Zealand (ANZ)	
European Union (EUR)	Natural gas <i>Conventional gas; gas from shale, sandstone, coal</i>
Rest of Europe and Central Asia (ROE)	
Russia (RUS)	Electricity <i>Coal, gas, refined oil, hydro, nuclear, wind, solar, biomass with and without CCS, natural gas combined cycle, integrated gasification combined cycle, advanced coal and gas with &amp; without CCS</i>
China (CHN)	
India (IND)	
Dynamic Asia (ASI)	
Rest of East Asia (REA)	<b>Agriculture</b>
Brazil (BRA)	Crops <i>Food crops; biofuel crops (corn, wheat, energy beet, soybean, rapeseed, sugarcane, oil palms, represent. energy grass, represent. woody crop)</i>
Other Latin America (LAM)	
Africa (AFR)	Livestock
Middle East (MES)	Forestry
<b>Factors</b>	<b>Non-energy sectors</b>
Capital	Crops
Labor	Livestock
Land	Forestry
<i>Crop land, managed forest land, natural forest land, managed grassland, natural grassland, other land</i>	Energy-intensive industry
Resources	Other industry
<i>For coal; crude oil; gas; shale oil; shale gas; hydro, nuclear, wind and solar electricity</i>	Services
	Commercial transportation
	Household transport <i>Conventional, hybrid and plug-in electric vehicles</i>

Following Winchester and Reilly (2015), the model used for this analysis includes (1) seven first generation biofuel crops and conversion technologies; (2) a representative energy grass and

a representative woody crop; (3) agricultural and forestry residues; (4) lignocellulosic (LC) ethanol via a biochemical process and LC drop-in fuel using a thermochemical process, both of which can operate with and without carbon capture and storage (CCS); (5) an ethanol-to-diesel upgrading process; (6) electricity from biomass, with and without CCS; and (7) heat from biomass for use in industrial sectors. The model also explicitly represents bioenergy co-products (e.g. distillers' dry grains and surplus electricity), international trade in biofuels, and limits on the blending of ethanol with gasoline. Whether some, all, or none of these technologies will operate in the future depends on the basic input requirements specified for each technology, the prices of these inputs as endogenously determined and vary over time, and the output price when compared against the reference fuel with which it competes. For this analysis, we update the LC ethanol costs in Winchester and Reilly (2015) to reflect estimates by BP (2015). Under these projections, the cost of LC ethanol, in 2010 dollars per gasoline equivalent gallon, falls through time and from \$7.10 in 2015 to \$2.63 in 2050.

Production sectors are represented by nested CES production functions. Inputs for each sector include primary factors (labor, capital, land, and energy resources) and intermediate inputs. For energy and climate policy analysis, important substitution possibilities include the ability for producers to substitute among primary energy commodities, and between aggregate energy and other inputs. Goods are traded internationally and differentiated by region of origin following the Armington assumption (Armington, 1969), except for crude oil and biofuels, which are considered to be homogenous goods.

Factors of production include capital, labor, resources specific to energy extraction and production, and six land types (crop land, managed forest land, natural forest land, managed grassland, natural grassland, and other land). In the version of the model used in this paper, land-use change is represented following Gurgel et al. (2007) and Melillo et al. (2009). The approach explicitly represents conversion costs by requiring inputs of capital, labor and intermediate inputs in the transformation process, and consistency in land accounting is maintained by combining land and other inputs in a Leontief nest (i.e., one hectare of one land type is required to produce one hectare of another land type). If land is being converted from natural forests, in addition to one ha of another land type, there is a one-time output of timber associated with clearing the land.

The responsiveness of land conversion of natural forestland or natural grassland to a managed land type in each region is parameterized as an elasticity of land supply estimated to represent historical relationships between changes in land use and land rents. As noted by Gurgel et al. (2007, p.15), “underlying this response may be increasing costs associated with specializing inputs, timing issues in terms of creating access to ever more remote areas, and possible resistance to conversion for environmental and conservation reasons that may be reflected in institutional requirements and permitting before conservation.” Deforestation in response to an increase in land rents is smallest in developed regions, while increases in land rents induce the largest changes in deforestation in Africa, and Other Latin America.

There is a single representative utility-maximizing agent in each region that own all factor endowments (capital, labor, and natural resources) in the region, derives income from factor payments and allocates expenditure across goods and investment. A government sector collects revenue from taxes and (if applicable) emissions permits, and purchases goods and services. Government deficits and surpluses are passed to consumers as lump-sum transfers. Final demand separately identifies household transportation and other commodities purchased by households. Household transportation is comprised of private transportation (purchases of vehicles and associated goods and services needed to run and maintain them) and purchases of commercial transportation (e.g., transport by buses, taxis and airplanes). The model projects emissions of GHGs (carbon dioxide (CO<sub>2</sub>), methane, nitrous oxide, perfluorocarbons, hydrofluorocarbons and sulfur hexafluoride) and conventional pollutants that also impact climate (sulfur dioxide, carbon monoxide, nitrogen oxide, non-methane volatile organic compounds, ammonia, black carbon and organic carbon).

The model is calibrated using economic data from Version 7 of the Global Trade Analysis Project (GTAP) database (Narayanan & Walmsley, 2008; Aguiar et al., 2016), population forecasts from the United Nations Population Division (UN, 2011), and energy data from the International Energy Agency (IEA, 2006 & 2012). Regional economic growth through 2015 is calibrated to International Monetary Fund (IMF) data (IMF, 2013). The model is coded using the General Algebraic Modeling System (GAMS) and the Mathematical Programming System for General Equilibrium analysis (MPSGE) modeling language (Rutherford, 1995).

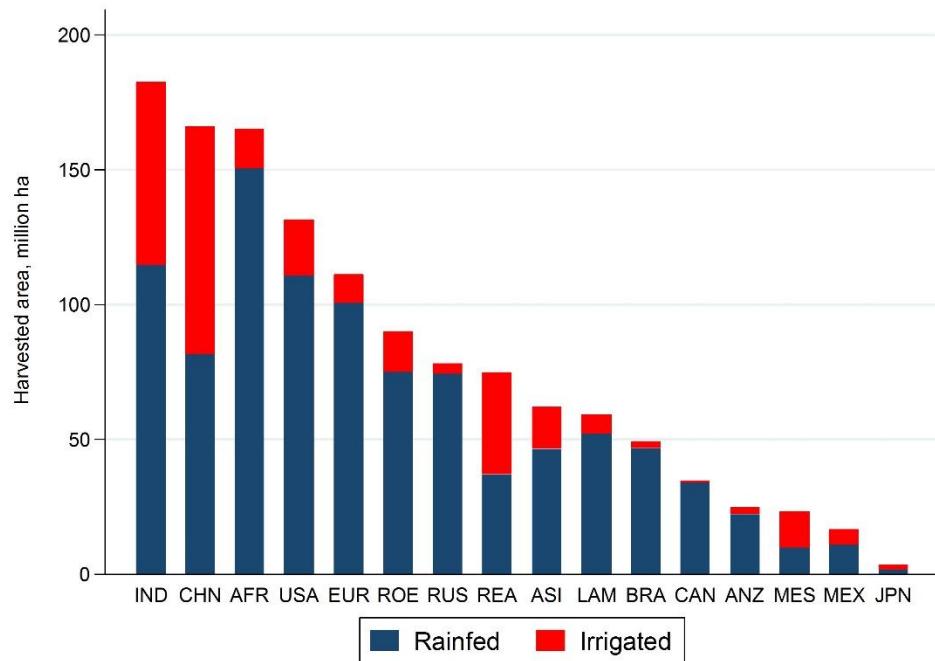
## 2.2 Representing irrigated land in the EPPA model

As noted in Section 2.1, the EPPA model includes a single, aggregated crop land type. We extend the model by explicitly representing rainfed and irrigated areas, and the scope for expanding irrigated land. There are three necessary steps: (1) we disaggregate crop land and production into irrigated and rainfed components; (2) we estimate multiple irrigable land supply curves for each EPPA region that describe how the marginal cost irrigated land increases with expansion to capture the within region variability in crop yields and water availability; and (3) We augment the EPPA model to represent irrigated and rainfed crop production and, irrigable land supply curves. In the extended EPPA model, we assume bioenergy crops are only grown on rainfed land, which is consistent with assumptions used to estimate yields for bioenergy feedstocks and prevailing practices, however, the indirect effect of using more rainfed land for energy crops may be to increase other crop yields by irrigating.

### 2.2.1 Irrigated and rainfed crop land and production

We first identify current rainfed and irrigated areas and the value of production on those land types. To disaggregate crop land in the EPPA model, we use data on harvested area for rainfed and irrigated areas from the Monthly Irrigated and Rainfed Crop Areas (MIRCA2000) data set (Portmann et al., 2010). This data is available at a spatial resolution of 5 arc-minutes by 5 arc-minutes ( $\sim 10 \text{ km}^2$ ) for 26 crop types. We aggregate the data spatially and across crop types to calculate total rainfed and irrigated areas for each grid cell. For presentation purposes, **Figure 1**

presents irrigated and rainfed land for each EPPA region. At the global level, 76.1% of crop land is rainfed and 23.9% is irrigated. The portion of irrigated land in total harvested area is largest in the Middle East, China, Japan, the Rest of East Asia and India. Conversely, the fraction of crop land that is irrigated is relatively low in Australia-New Zealand, Europe, Africa, Brazil, Russia and Canada.

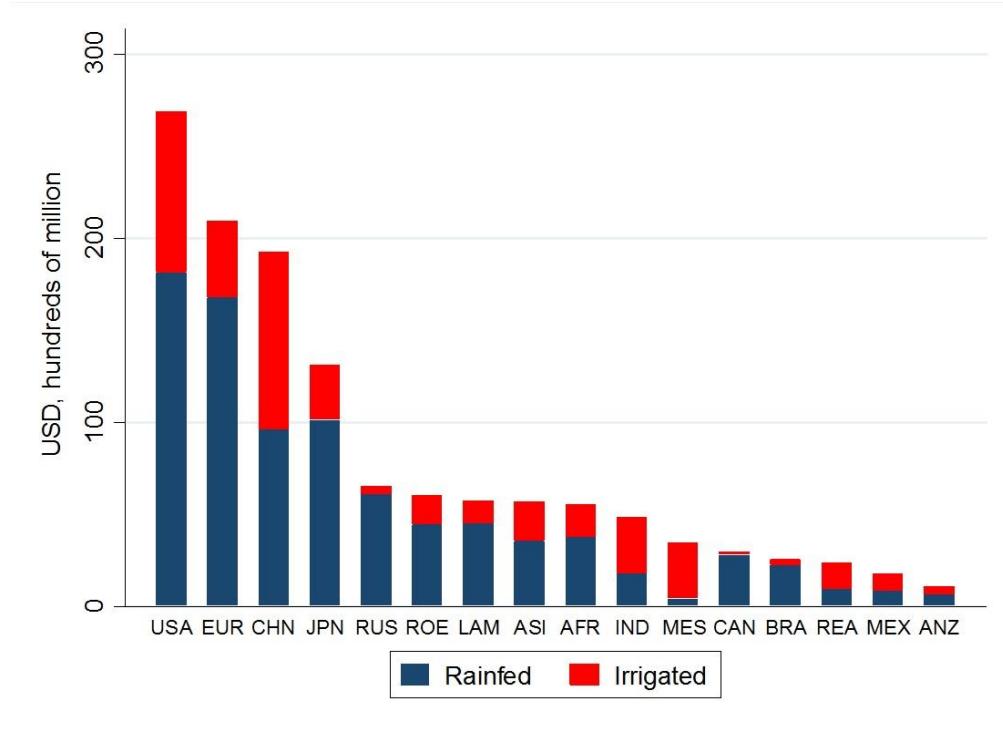


**Figure 1.** Rainfed and irrigated harvested area by EPPA region.

Source: Authors' aggregation of data from the MIRCA2000 data set (Portmann et al., 2010).

The value of production on each land type in each region is estimated by combining the MIRCA2000 harvested area data with price and yield data. Crop prices in 2000 by country are sourced from the Food and Agricultural Organization (FAO) and yield data are taken from Siebert and Döll (2010). These data, like the harvested area data, are available at a spatial resolution of 5 arc-minutes by 5 arc-minutes for 26 crop types. Consequently, we calculate production by crop and land type at this level of aggregation using appropriate country-level prices for each grid cell. To match the 26 (aggregate) crop types, we calculate production-weighted average prices. For example, the price for citrus from the MIRCA data set is computed using a combination of the FAO prices for grapefruit, lemons, limes, oranges, and other citrus fruits. For presentation purposes, the value of crop production on each land type is aggregated to EPPA regions, as shown in **Figure 2**. The fraction of regional production value from irrigated land is above 50% in the Middle East, India, Rest of East Asia, Mexico, and China. Conversely, irrigated land is responsible for a relatively low share of production values (less than 15%) in

Brazil, Russia, and Canada. Globally, 67.3% of production value comes from rainfed land and 32.7% comes from irrigated land. Given the fractions of dry- and irrigated land hectares and production value, this implies that on average globally irrigated land is 55% more productive than rainfed land in term of value of crop produced.



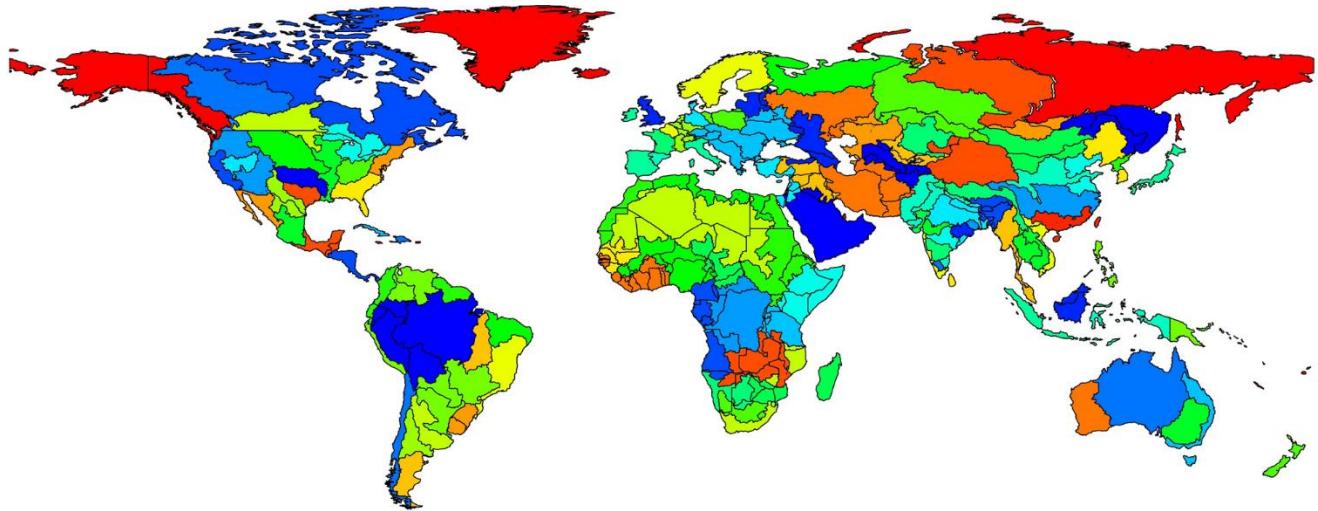
**Figure 2.** The value of crop production on rainfed and irrigated areas by EPPA region.

Source: Authors' own calculation based on area data from the MIRCA2000 data set (Portmann *et al.*, 2010), yield data from Siebert and Döll (2010), and price data from the FAO.

### 2.2.2 Irrigated land supply curves

The scope for irrigating additional areas relative to the base year is modeled by specifying a suite of supply curves for additional irrigable land. These supply curves allow irrigated areas to be expanded by (1) improving conveyance efficiency, (2) improving irrigation efficiency, and (3) increasing water storage. The irrigable land supply curves employ the Integrated Global System Model–Water Resource System (IGSM-WRS) model (Strzepek *et al.*, 2012), which identifies 282 large river basins – named Assessment Sub-Regions (ASRs) by the U.S. Water Resources Council or Food Producing Units (FPUs) by the International Food Policy Research Institute – globally. Since the ASRs/FPUs are delineated such that they do not cross political borders and water resources can have an international dimension, we group the FPUs into 126 transnational water regions. Water regions and their constituent FPUs are shown in **Figure 3**. A list of water regions by EPPA region is displayed in **Table A1**.

We first develop the irrigable land supply curves and at the water region level. In each water region, improving conveyance and/or irrigation efficiency means that the same amount of water can irrigate more land, and an increase in the quantity of water storage increases average water availability. Crop water requirements for each water region from Strzepek *et al.* (2012), which are determined by characteristics such as climate and soil quality, are used to determine how much irrigated land can expand due to improvements in irrigation efficiency and increases in storage.



**Figure 3.** Food producing units (lines) and water regions (colors).

At a regionally-specific cost, each water region can upgrade its conveyance and irrigation efficiencies from their current levels. Defining conveyance efficiency as the ratio of the amount of water that reaches the field to the amount of water supplied, a canal without lining has a conveyance efficiency of 0.75 and a lined canal has an efficiency of 0.95. Irrigation efficiencies – the ratio of the amount of water consumed by the crop to the amount of water supplied through irrigation – for the four irrigation schemes considered are shown in **Table 2**. This table also shows overall scheme efficiencies for alternative conveyance-irrigation systems, which is the product of conveyance and irrigation efficiencies.

**Table 2.** Irrigation and scheme efficiency with and without canal lining.

Irrigation system	Irrigation efficiency	Scheme efficiency*	
		Without canal lining	With canal lining
Flood	0.6	0.45	0.57
Furrow	0.7	0.52	0.67
Low-Efficiency Sprinkler	0.8	0.60	0.76
High-Efficiency Sprinkler	0.9	0.68	0.86

*Note:* \* Scheme efficiency is calculated as the product of conveyance and irrigation efficiencies.

The least expensive upgrade, providing there is existing irrigation, is always the addition of canal lining to improve conveyance efficiency.<sup>3</sup> Irrigation efficiency upgrades progress in the order of no irrigation, flood, furrow, low-efficiency sprinkler, and finally high-efficiency sprinkler.

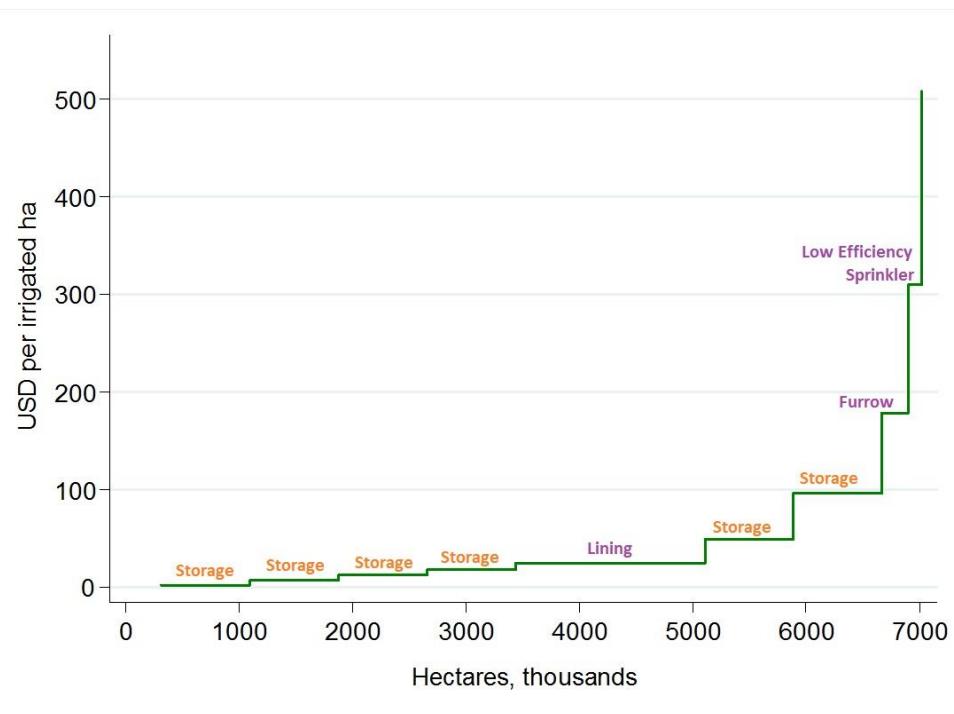
For water storage, curves describing the relationship between water storage and water yield (water that is available for consumption each year after accounting for evaporation) are developed following Wiberg and Strzepek (2005) and using estimates from Strzepek et al. (2013). In each water region, the water storage-yield curve spans all water storage increases available starting from zero storage. For our purposes, we approximate storage-yield curves using a step function with 10 discrete upgrades. Each water region starts at a point of the storage-yield curve consistent with existing storage in that region, so a region typically has less than 10 storage upgrade options to store additional water.

Irrigable land supply curves for each water region are constructed by assembling conveyance and irrigation efficiency and storage options from lowest to highest cost, forming a step function describing supply of additional irrigable land. As the marginal cost of increasing irrigable land by adding additional storage increases, storage upgrades are typically dispersed among conveyance and irrigation efficiency upgrades in each water region. As an example, the supply curve for additional irrigable land in the Mississippi River water region is depicted in **Figure 4**. We also calculate the maximum irrigation potential for each region, which is reached when all irrigation is via high-efficiency sprinklers and average water yield is equal to average runoff (i.e., all available runoff is stored and used).

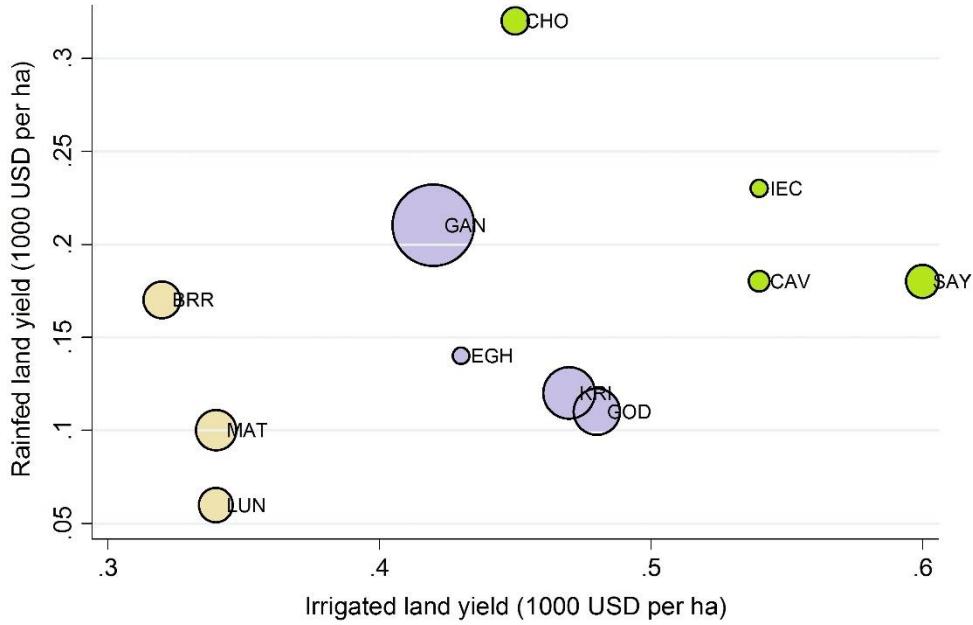
For computational reasons, we aggregate the 126 water region supply curves to a smaller number. As the EPPA model will treat irrigated land within each sub region as homogenous and it is typically more expensive to expand irrigation in high yield regions (which have already implemented low cost irrigation options) than low-yield areas, care must be taken when aggregating water regions. For example, combining irrigable land supply curves for high and low yield regions would result in yields on newly irrigated land equal to the average for that combination, but at the cost of expanding irrigation in the low yield region. To avoid this issue, we use *k*-means clustering to group the water regions within each EPPA region with similar rainfed and irrigated yields. We designed the analysis so that each EPPA region contains between one and four clusters of water regions, which we call irrigation response units (IRUs). **Figure 5** shows irrigated and rainfed yields for water regions in India, and illustrates the grouping of these regions into three IRUs using different colors. A complete list of IRUs and their constituent water regions is provided in **Table A2**.

---

<sup>3</sup> The initial data in several rice farming areas in China overestimated potential gains in irrigated land. Specifically, in the rice paddies, water that leaks out of irrigation pipes prior to its intended destination fell into the rice field, so it was not wasted. Therefore, the benefit of adding lining to the irrigation system pipes was overestimated. We identified those problem regions and decreased irrigable land gains from the lining by 90%.



**Figure 4.** Annual irrigable land supply curve for the Mississippi River water region.



**Figure 5.** Irrigation response units for India (colors) built on clustered water regions.

*Note:* Bubble sizes are related to the number of hectares of crop land in each water region.

The supply step functions for the water regions within each cluster are aggregated across water regions to form an IRU supply step function. As illustrated in **Figure 6**, we approximate each IRU step function by estimating a constant elasticity supply function of the form  $q = \beta p^\lambda$ , where  $q$  is the quantity of additional irrigable land,  $p$  is the price/cost of irrigating additional hectares, and  $\beta$  and  $\lambda$  are parameters to be estimated. For each IRU we also calculate its maximum irrigation potential, which is defined as the area that can be irrigated when annual average water yield is equal to annual average runoff (i.e., all available runoff is stored and used), all irrigation canals are lined, and high efficiency sprinklers are used for all irrigation.

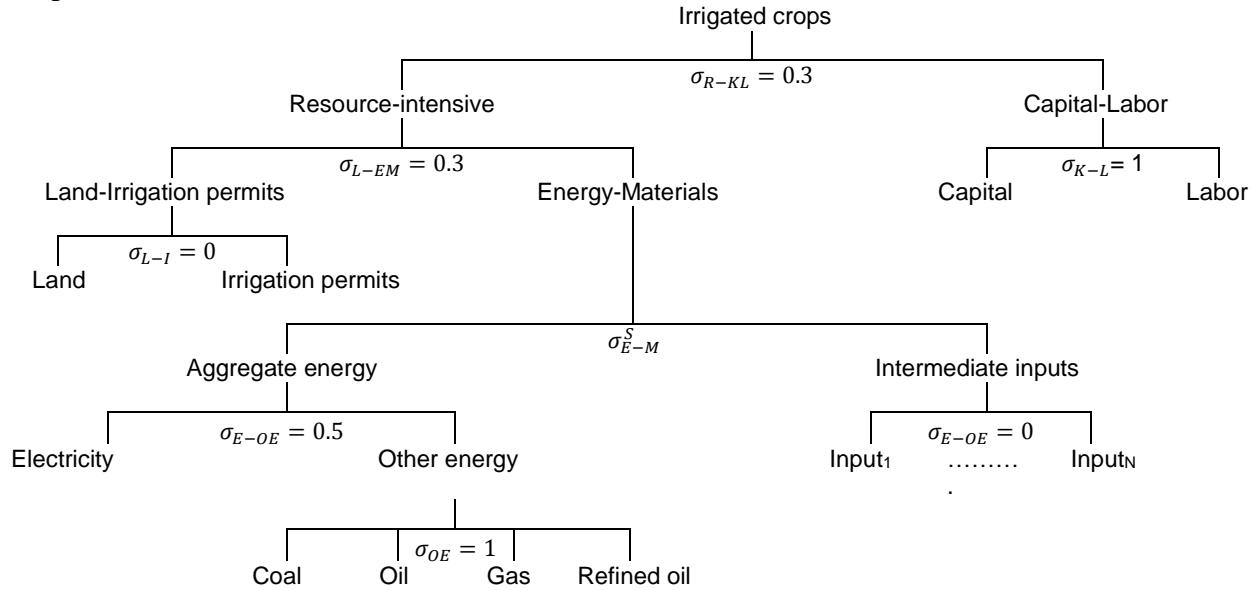
### 2.2.3 Representing irrigated and rainfed crop production in the EPPA model

As the GTAP database used to calibrate sectoral production functions in the EPPA model does not differentiate irrigated and rainfed production, irrigation costs are included in payments to factors of production and intermediate inputs in (aggregate) crop production. Our disaggregation approach follows Taheripour et al. (2013b) and is applied to each IRU. First, we divide land rental payments net of irrigation costs (innate land payments) between irrigated and rainfed production according area shares. Second, we allocate the value of aggregate crop production to the two crop production types using production value shares for each IRU. Third, for each production type, we calculate residual production costs as total costs minus land costs and allocate residual costs to other inputs according to each input's cost share in total crop production costs. As irrigated yields are higher than rainfed yields, the value of innate land payments per dollar of irrigated crop production is lower and the value of other inputs higher than that for rainfed production. As a result, irrigation costs in the base year are captured by additional capital and other costs relative to those for rainfed production.

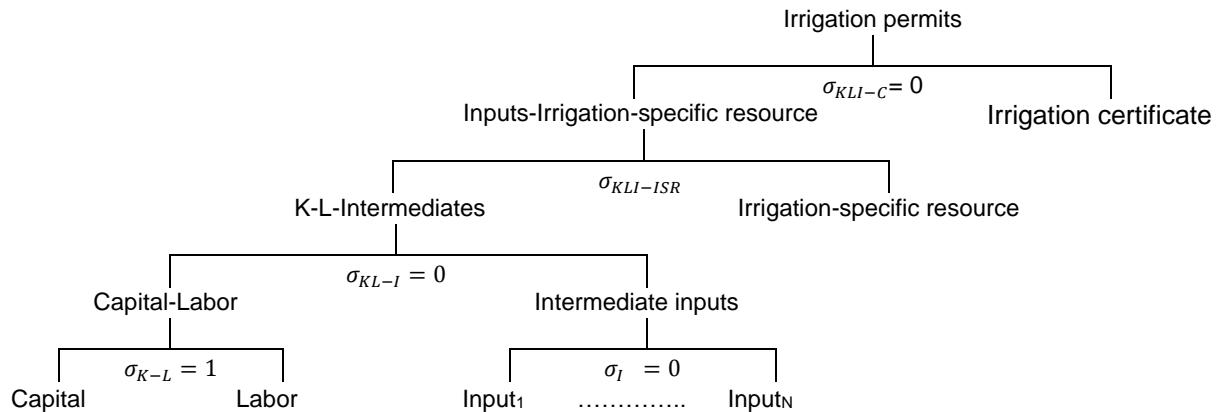
The nested constant elasticity of substitution production structures for crops produced on irrigated land in each IRU in the EPPA model is sketched in Figure 6. As irrigation production uses innate land, we include an irrigation permit system to ensure that the amount of irrigated land used in each IRU is equal to the amount of available irrigated land in that IRU. Specifically, each hectare of land used in the production of irrigated crops requires an IRU-specific irrigation permit. This is shown in Figure 6 in the Land-irrigation permit nest, where  $\sigma_{L-I}=0$ . Initially, each region is endowed with a quantity of irrigation permits equal to the quantity of land currently irrigated in each IRU. Thus, in each IRU, the model allows the current quantity of irrigated land to be maintained by replicating existing costs for irrigated crop production and, as discussed below, it can be expanded at additional costs and subject to water resource constraints. This specification also mandates that adding an additional hectare of irrigated land requires taking one hectare of land away from rainfed crop production.

The production structure for rainfed crops is identical to that for irrigated crops except that inputs of irrigation permits are not required. Key substitution possibilities in the production functions for both irrigated and rainfed crop production include those between land and the energy materials composite ( $\sigma_{L-EM}$ ), and between the resource-intensive bundle and the capital-labor aggregate ( $\sigma_{R-KL}$ ). Both of these elasticities allow endogenous yield improvements due to

increases in land prices.<sup>4</sup> Guided by Baker (2013), crops produced in each IRU are imperfect substitutes for each other, and composite irrigated crops are imperfect substitutes for rainfed crops.



**Figure 6.** Irrigated crop production in for an IRU in the EPPA model.



**Figure 7.** Production of irrigated land permits for each IRU in the EPPA model.

Additional irrigation permits can be produced by using water resources and other inputs, as shown in **Figure 7**, which are added to the original endowment of permits, allowing expansion of irrigation beyond that in the base year data. A key element in this specification is substitution between the capital-labor-intermediates composite and an irrigation specific resource. For each IRU, following the calibration routine outlined by Rutherford (2002), the value of irrigation

<sup>4</sup> As previous versions of the EPPA model have implicitly considered the expansion of irrigated areas through substitution between resource-intensive and capital-labor bundles and this option is now explicitly modeled, we decrease the value of set  $\sigma_{R-KL}$  from 0.7 used in previous versions to 0.55.

specific resources and  $\sigma_{KLI-ISR}$  is chosen to replicate the elasticities of supply for additional irrigated land estimated in Section 2.2.3. Under this framework, irrigating additional hectares requires not only installing irrigation infrastructure on newly irrigable land, but also upgrading existing infrastructure to free up additional water and/or increasing water storage. The capital, labor, and intermediate inputs used in the production of irrigation permits reflects the inputs used to expand irrigable land, thus connecting the expansion with a draw on actual inputs.

As noted above, the supply of irrigable land has a hard upper limit in each IRU, however, the estimated irrigable land supply curve could allow expansion beyond this limit. To ensure the maximum limits are not exceeded, we introduce another allowance mechanism, ‘irrigation certificates’. Each region is endowed with a quantity of IRU-specific irrigation certificates equal to the maximum number of additional hectares that can be irrigated. One certificate is required for each permit that is produced, as shown in the top nest in Figure 7. In our analysis,  $\sigma_{KLI-C} = 0$ , ensuring that once the endowed number of certificates are exhausted no more irrigation permits can be produced. As long as the limit has not been reached the shadow value of certificates are zero, once it is reached there is a positive shadow price on certificates with rents going to the representative household in the region.

### 3. SCENARIOS

To address the question posed in the introduction, we consider eight scenarios that differ with respect to (1) policies, (2) whether or not irrigated land is explicitly represented, and (3) the amount of water available for irrigation. Following Winchester and Reilly (2015), we consider two policy cases. The reference case imposes ‘business as usual’ assumptions about economic, population and productivity growth. It includes renewable fuel mandates in the EU and the US, extended through the 2050 horizon of our study, but it does not include any other policies that would create incentives to expand bioenergy production. In the policy case, we add to the reference a global price on all GHG emissions except those from land-use change of \$25 per metric ton of CO<sub>2</sub> equivalent (tCO<sub>2</sub>e) in 2015 and rising by 4% per year to \$99/tCO<sub>2</sub>e in 2050. This was chosen because it creates greater incentives for bioenergy production, and an interest of our research with whether, under expanded demand for land resources from bioenergy, water constraints pose a more serious concern, and ultimately limit bioenergy expansion.

Three alternatives water availability cases are considered: constant, increasing, and decreasing. Water available for irrigation is fixed at its 2010 level in all regions in the constant case. In the decreasing case, beginning in 2015, water available for irrigation in each region decreases by 2.5% relative to the 2010 level every five years, so water available for irrigation in 2050 is 20% lower than in 2010. Equivalent increases are simulated in the increasing case every five years and water available for irrigation is 20% higher in each region in 2050 relative to 2010. These changes in water availability are illustrative and designed to highlight sensitivities of the model to changes in water availability. Actual changes could come from greater demand for water uses and/or from changes in climate. While the former would most likely reduce water availability for irrigation, the latter could increase or decrease availability, and in cases these

changes would not be uniform across all regions (see e.g., Fant et al., 2016). Irrigation is responsible for about 80% of current water consumption worldwide (MIT Joint Program, 2014), and so a 20% reduction, assuming no change in supply would allow a doubling of all other uses. Overall, climate change is expected to speed up the hydrological cycle and increase precipitation but water availability in rivers and lakes is the result of uncertain patterns of climate change and complex interactions with temperature, land cover, and evapotranspiration. While beyond the scope of this paper, the model developments reported here are designed to allow consideration of shifts in the irrigable water supply function that can be derived from the IGSM-WRS. The WRS can use IGSM (Sokolov et al, 2005) projections of changing climate or that of other climate models.

To understand the impact of implicitly representing irrigated land, it is important to realize that in EPPA with aggregated crop land, crop production costs and yields are production-weighted averages of those on rain fed and irrigated crop land. Irrigated crops, and production from them, are included in the base data and model, but are not explicitly differentiated. The implication in that formulation is that as aggregate crop land production expands, the proportion of rainfed and irrigable land expand proportionally, and non-land costs of adding additional irrigable capacity are constant. In contrast, in our new formulation marginal costs of expanding irrigation capacity are increasing, and the proportions of rainfed and irrigable crop land can vary over time depending on the ease of expanding and the value/yields from additional production on each land type.

We expect the costs of expanding crop production to differ in the revised formulation of the model which we can measure as macroeconomic welfare difference, and seen in terms of areas devoted to crops, food prices, and other metrics. The revision has two opposing effects. On the one hand, rising marginal irrigation costs means that expansion of irrigable areas is more expensive than when aggregate crop land is considered. On the other hand, freeing the model from the constraint that the proportion of irrigated crop land in total crop land is constant may result in lower costs of expanding crop production, especially in regions where land is relatively scarce. In these regions, it may be cheaper to improve irrigation systems than to use more crop land. On balance, we expect rising marginal irrigation costs to result in more costly crop production when irrigated land is represented, but note that the offsetting effect of relaxing the fixed proportion constraint will reduce overall impacts and can lead to reduced crop production costs in regions with low incremental irrigation costs and/or high crop land rents.

The scenarios are designed to address four broad questions. First, comparing results for the *Reference* policy setting with *No* water resources explicitly represented (*Ref-N*) with the *Reference* policy setting and *100%* of water for irrigation available (*Ref-100%*) allows us to quantify the impact of explicitly representing irrigable crop land at current water availability. A key question is the extent and direction of bias, if any, of models that only identify aggregated crop land. A second broad question is whether results are sensitive to changes in the amount of available water, which we test in the *Reference* scenario by decreasing water availability to *80%* (*Ref-80%*) or increase it to *120%* (*Ref-120%*) of currently available water. Then we are interested

in the effect of explicit water constraints on bioenergy expansion, which we can determine by comparing a *Policy* with *No* water constraints (*Pol-N*) scenario, with a *Policy* scenario with water availability at 100% of our of the current level (*Pol-100%*). Here the key question is: Does explicit representation of water resources change our estimate of commercial biomass energy supply potential (or price impacts on food) substantially compared with the same policy stimulus for bioenergy but no explicit water constraint. Finally we are interested in whether less (*Pol-80%*) or more (*Pol-120%*) water availability affects our conclusions on bioenergy expansion. The details of the eight scenarios are summarized in **Table 3**.

**Table 3.** Scenarios considered.

Scenario	Carbon price?	Irrigated land?	Water resources
<i>Ref-N</i>	No	No	Not explicitly represented
<i>Ref-80%</i>	No	Yes	Beginning in 2015, water available for irrigation in each region decreases by 2.5% relative to the 2010 level every five years, so water availability in 2050 are 20% lower than in 2010
<i>Ref-100%</i>	No	Yes	Water available for irrigation is fixed at its 2010 level in all regions
<i>Ref-120%</i>	No	Yes	Beginning in 2015, water available for irrigation in each region increases by 2.5% relative to the 2010 level every five years, so water availability in 2050 are 20% higher than in 2010
<i>Pol-N</i>	Yes	No	Not explicitly represented
<i>Pol-80%</i>	Yes	Yes	Beginning in 2015, water available for irrigation in each region decreases by 2.5% relative to the 2010 level every five years, so water availability in 2050 are 20% lower than in 2010
<i>Pol-100%</i>	Yes	Yes	Water available for irrigation is fixed at its 2010 level in all regions
<i>Pol-120%</i>	Yes	Yes	Beginning in 2015, water available for irrigation in each region increases by 2.5% relative to the 2010 level every five years, so water availability in 2050 are 20% higher than in 2010

## 4. RESULTS

We organize results in two sections, first answering our four main questions, focusing on results in 2050. We then present some of the broad energy, bioenergy, and land use results.

### 4.1. Economic, environment, land use, and bioenergy implications of irrigation

**Table 4** reports a summary of global results in 2050 with additional results in Figures 8–10. From this table we can address the four questions we set out to answer. First, what is the extent and direction of bias, if any, of models that only identify aggregated crop land? Overall, comparing *Ref-100%* to *Ref-N* we find that including water constraints reduces global welfare by 0.19%, food use declines by 0.2% and food prices rise by 0.14%. Overall, these are relatively

minor effects. One reason for the relatively small impact is that irrigated area expands less than proportional to expansion of rainfed land when that flexibility is allowed. Hence, food production expansion uses more of the less-costly rainfed land. In *Ref-N*, 1,765 Mha of land is used globally for food crops and this increases to 1,774 Mha in *Ref-100%*. Relative to the *Ref-N* scenario, global irrigated crop land decreases by 43 (346 – 389) Mha and rainfed crop land increases by 53 (1,428 – 1,375) Mha resulting in total land used for food crops increasing by 9 Mha (0.5%). However, rainfed land is less productive explaining the decline in food use (and food production) and increase in food prices.

**Table 4.** Summary of global results in 2050.

	Ref-N	Ref-80%	Ref-100%	Ref-120%	Pol-N	Pol-80%	Pol-100%	Pol-120%
Welfare change (%) <sup>*</sup>	-	-0.21	-0.19	-0.18	-3.15	-3.42	-3.41	-3.05
CO <sub>2</sub> emissions (MMt)	74,145	73,803	73,814	73,771	42,741	41,307	41,136	41,455
Primary energy (EJ)	700	703	703	703	517	518	518	520
Primary bioenergy (EJ)	28.5	29.4	29.5	29.7	140.9	142.5	142.7	143.5
Final bioenergy (EJ)	14.5	15.1	15.2	15.5	67.3	68.3	68.5	69.4
Bioenergy land (Mha)	13.5	12.9	13.1	13.3	152.2	150.1	150.5	158.1
Food crop land (Mha)	1,765	1,769	1,774	1,778	1,646	1,649	1,653	1,646
Rainfed land (Mha)	1,375	1,444	1,428	1,427	1,271	1,335	1,320	1,310
Irrigated land (Mha)	389	325	346	351	375	315	333	336
Natural Forest land (Mha)	3,993	3,997	3,997	3,996	3,818	3,827	3,826	3,826
Managed grassland (Mha)	3,064	3,064	3,060	3,057	3,196	3,193	3,191	3,189
Change in food use (%) <sup>*</sup>	-	-0.26	-0.20	-0.18	-4.10	-4.48	-4.47	-4.26
Change in food price (%) <sup>*</sup>	-	0.23	0.14	0.12	3.73	4.10	4.05	3.94

*Note:* \* Change relative to the *Ref-N* scenario.

Interestingly, more bioenergy is produced when irrigated land is explicitly represented than when there is one type of crop land (i.e., primary bioenergy is 29.5 EJ in the *Ref-100%* scenario and 28.5 EJ in the *Ref-N* scenario). This change is driven by bioenergy production in India. In this region, less land is needed for food crops in the *Ref-100%* scenario than the *Ref-N* case. This occurs because the implicit constraint that rainfed and irrigated land must be added in fixed proportions in the *Ref-N* scenario results in higher land prices relative to the *Ref-100%* scenario, where the proportion of irrigated land can change but the marginal cost of expanding irrigation is increasing.

A further curious result is that explicitly representing irrigated land increases natural forest areas relative to when a single crop land type is included. For example, natural forests cover is 3,997 Mha in the *Ref-100%* scenario and 3,993 Mha in the *Ref-N* scenario. While a small difference, it is in the reverse direction one might expect. It is due to a shift in livestock production from regions with more land-intensive livestock production (Africa and China) to regions with less land intensive production (the EU, the US and India), which reduce global managed grass land and provides scope for less deforestation (and more natural forest) in Africa

and China. More natural forest land when irrigated land is explicitly represented also results in less CO<sub>2</sub>e emissions than in the *Ref-100%* scenario relative to *Ref-N* case.

Moving to our second question: Are results sensitive to changes in the amount of available water? Comparing *Ref-80%* and *Ref-120%* to *Ref-100%*, we see results that are generally in the direction one would expect. Less water increases the welfare loss, results in higher food prices, less food consumption, and less irrigated land compared to *Ref-100%*, and *vice versa* when there is more water. Increasing water availability leads to more land devoted to bioenergy and more bioenergy production, but changes are small (e.g., global primary bioenergy increases from 29.4 EJ in the *Ref-80%* to 29.7 EJ *Ref-120%*). Total food crop land is less when there is less water and more when there is more water. While there is a switch toward rainfed from irrigated crop land in all scenarios with irrigated land explicitly modeled, comparing *Ref-80%* to *Ref-100%* land expansion is overall more expensive. The flexibility to use rainfed instead of irrigated land exists in both scenarios, unlike the comparison of *Ref-N* and *Ref-100%* where the new flexibility of expanding irrigated and rainfed land in different proportions had a partially offsetting effect on food prices (and hence land area). Again, while these results are generally in the direction we expect, the magnitudes are small especially looking at the food price effects, which remain well below 1% even with less water.

Regarding our third question: Does explicit representation of water resources change our estimate of commercial biomass energy supply potential and its effects on the economy and environment? The comparison of *Pol-N* and *Ref-N* was the basis of an earlier paper (Winchester and Reilly, 2015) and the policy impacts shown here are similar, with the differences resulting from the revised cost estimates for LC ethanol used in this study. In that paper, the food price impacts were decomposed into those due to expansion of bioenergy and those due to higher energy prices and other impacts of the overall GHG-pricing policy. The paper found that about 60% of the increase in food prices were due to the carbon price increasing costs throughout the economy, and around 40% were due to the production of bioenergy.<sup>5</sup> The relatively small impacts of a significant (~150 EJ) commercial bioenergy industry on food prices led to the question of whether a lack of water constraints in that version of the model led to a serious underestimate of the impacts and/or the ability to expand bioenergy. Comparing *Pol-100%* and *Pol-N* quantitatively answers that question. As hypothesized water constraints increase the overall cost of the policy by about 8% or 0.26 percentage points (3.41%-3.15%). While the 0.26 percentage point increase is small, that this one additional feature increases the overall climate policy cost by an order of 10% is not insubstantial. Food price increase of 4.05% compared with 3.73% in *Pol-N* are greater but remain relatively small, at least compared with concerns in the 2007-2008 period where some attributed biofuel expansion (at much lower levels) for a significant portion of the spike in crop and food prices at the time (e.g., Mitchell, 2008). Explicitly representing irrigable land increases natural forests (by reducing the rate of

---

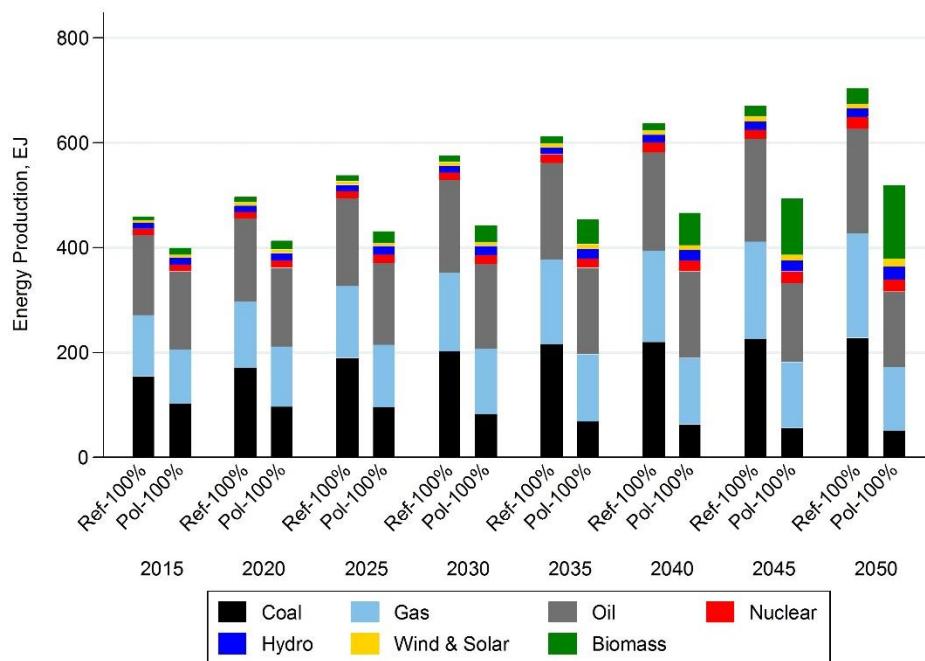
<sup>5</sup> The drivers of the increase in food price are decomposed by simulating each scenario without any bioenergy pathways and comparing the changes in food prices to those in the core scenarios (with bioenergy technologies).

deforestation) and increases slightly bioenergy production through the same indirect routes earlier described for the *Ref* cases.

Moving to our fourth question: Does less or more water availability affect our conclusions on bioenergy expansion and its effects on the economy and environment? Comparing *Pol-100%* and *Pol-80%* reveals results in the expected direction—higher welfare costs, higher food prices, less food used, and less bioenergy—but the differences are quite small. The welfare cost increase is 0.01 percentage points (a 0.003% increase in welfare cost), the food price impact of 0.05 percentage points increases the food price impact by under 1%. Primary bioenergy production is reduced from 142.7 EJ to 142.5 EJ (0.14%). Somewhat surprisingly, the effects of increasing water supply (comparing *Pol-120%* to *Pol-100%*) are somewhat asymmetric to those associated with less water, at least for welfare and food impacts. Increasing water availability by 20% results in a larger magnitude change in welfare costs, food prices and bioenergy production than the magnitude change associated with 20% less water.

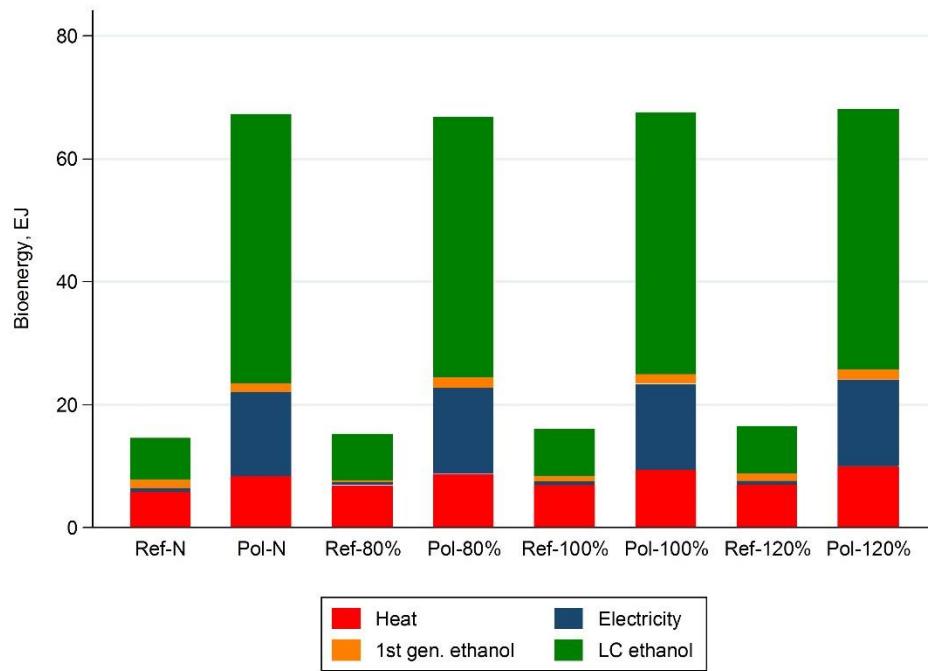
#### 4.2 Energy, bioenergy, and land use results

The GHG pricing policy is implemented gradually, assumed to have started in 2015 at \$25 and rising to \$99/ton CO<sub>2</sub>e by 2050. This policy initially reduces global energy use by about 50 EJ, and the rising CO<sub>2</sub>e price keeps energy use well below the *Ref-100%* scenario (**Figure 8**). As important for climate concerns fossil energy use continues to drift down through 2050 with coal use, in particular, dropping substantially. While other low carbon sources of energy expand, the main reason energy use is able to increase, while fossil energy decreases, is because of the substantial contribution from bioenergy.



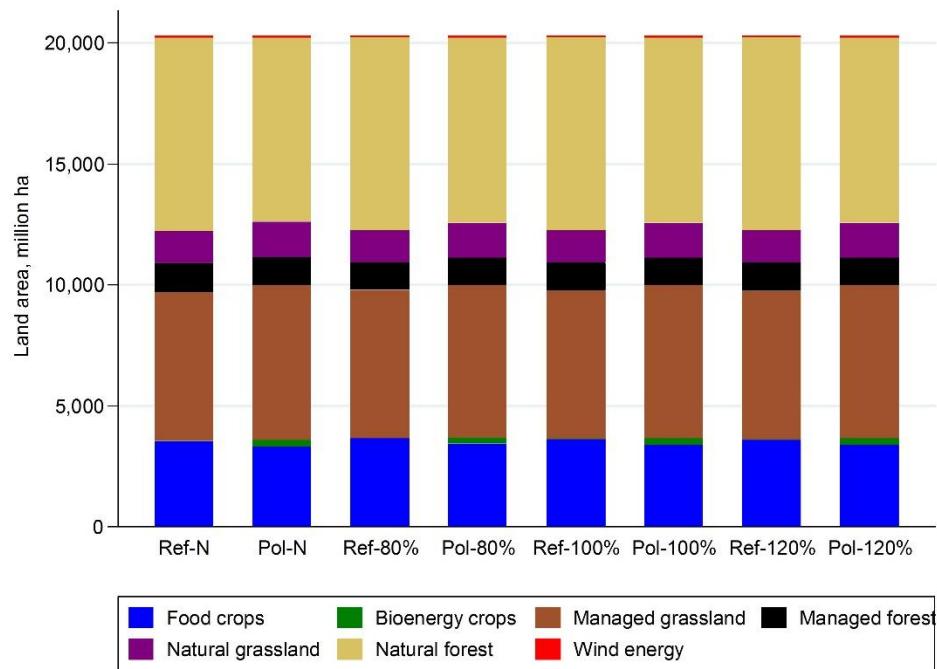
**Figure 8.** Global primary energy through 2050.

The biggest increase in bioenergy by 2050 as a result of the policy is from ethanol produced via a lignocellulosic production pathway (**Figure 9**). Given the assumed cost reductions in LC-ethanol it becomes generally less expensive than corn-based ethanol, especially with the GHG price. There remains some first generation ethanol, primarily sugarcane-based from Brazil. There is also a large increase in bioenergy used for electricity, from almost none in the *Ref* scenarios to about 15 EJ in the policy scenarios. Bioenergy used for heat contributes about 5 EJ in the *Ref* scenarios. It increases but not by much in the *Pol* scenarios. Other bioenergy forms and production pathways are not commercially viable in 2050 given these economic and policy scenarios. As previously noted, the explicit representation of irrigable land and sensitivity to available water (+/- 20%) has very small overall impacts, barely detectable in Figures 8 and 9, and are not reported in this sub-section.



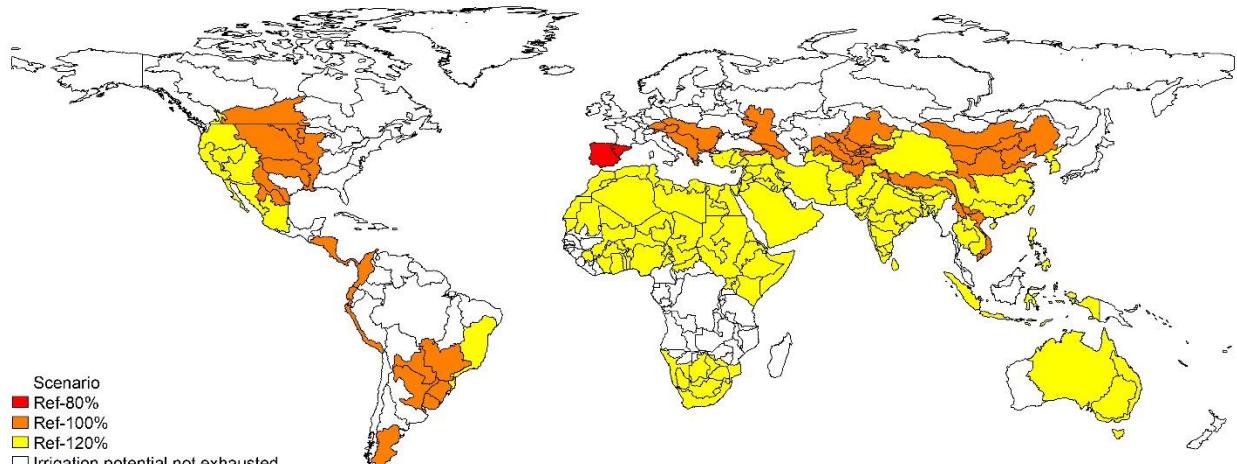
**Figure 9.** Global final bioenergy in 2050.

There are slight differences in land area in different land use types, mostly in comparing *Ref* and *Pol* scenarios (**Figure 10**). The differences between scenarios with or without irrigated land explicitly modeled are, again, so small as to be barely detectable in a figure plotting total land areas. A striking result, similar to Winchester and Reilly (2015) is the land needed for bioenergy is quite small compared with other land uses. There are a number reasons: the energy yield of woody and grassy crops per hectare is fairly high, agricultural and forest waste provides some of the biomass feedstock, and we include a gradual improvement in yields over time. With the small land impacts, it is not surprising that the food price impacts are also small.

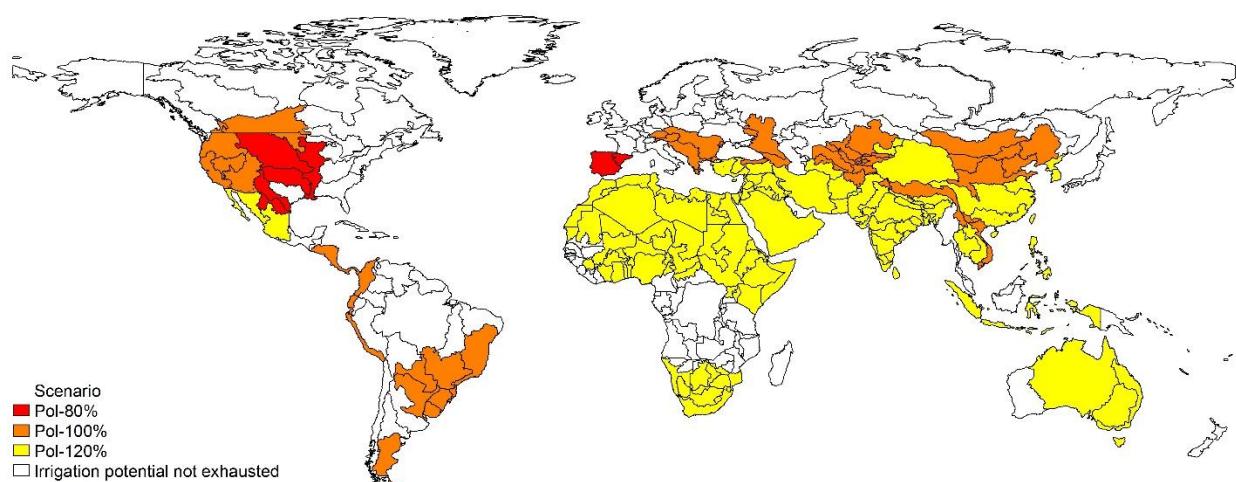


**Figure 10.** Global land use in 2050.

While water constraints are not a problem globally, some water regions are using all of the irrigable land we estimated to be available to them (**Figure 11**). Those colored yellow are at their maximum irrigation potential (i.e., when conveyance and irrigation systems operate at maximum efficiency and storage is such that annual water yield is equal to average runoff) even with water availability at 120% of what we estimate is currently available. Those colored orange are also at their maximum at 100% of currently available water, and those colored red hit the maximum potential if water availability drops to 80% of that currently available. Maximum irrigation capacity is predicted to be exhausted in many regions with rapidly growing populations and/or arid climates. Comparing Figures 11a and 11b indicates that bioenergy production has a small impact on the number of FPUs operating at maximum irrigating potential, which is consistent with bioenergy accounting for a small proportion of total crop land. The implication is that water shortage and stress is a significant concern in many regions, there is likely to be considerable pressure (and value) to improve efficiency of water use and conveyance, and to add additional storage wherever possible in many parts of the world. If those adaptations in the water system are made, and trade in agricultural products (and biomass crops) is an option then these regional water shortfalls need not impinge on the ability to produce bioenergy with relatively small effects on the overall economy.



(a)



(b)

**Figure 11.** FPUs operating at maximum irrigation potential in the (a) reference and (b) policy cases in 2050.

## 5. CONCLUSIONS

Feeding a growing global population and promoting bioenergy to mitigate climate change will put pressure on food prices and land markets. Land use responses to the increased demand for biomass will depend on constraints on the expansion of irrigated land. If expanding irrigation is expensive or limited, deforestation may be needed to bring more rainfed land into crop production to meet food demand, and bioenergy production will be more costly and may be curtailed.

This paper advanced the understanding of food, bioenergy, water and land outcomes by representing irrigated land supply curve in the MIT EPPA model. The irrigable land supply curves were based on spatial-level estimates of the costs of improving irrigation efficiency and increasing water storage, and facilitates parameterization of endogenous changes in irrigation

infrastructure. The model was simulated under a global carbon price with the objective of determining how food, bioenergy and deforestation are affected (1) when irrigated land is explicitly represented, relative to when only a single type of crop land is considered, and (2) by changes in water availability.

We found that explicitly representing irrigated land had small impacts on modeling outcomes relative to when only a single type of crop land is included. This is primarily because representing a single crop land type implicitly assumes that irrigated and rainfed land must expand in equal proportions. When irrigated and rainfed land are separately identified, although rising marginal costs for expanding irrigable land make increasing the quantity of irrigated land more expensive, allowing greater flexibility by relaxing the equal-proportion assumption can decrease the cost of expanding crop production. In contrast, the common approach in economy-wide models of using a CET function to allocate land between irrigated and rainfed uses and assuming substitutability between land and water in production imposes unnecessary restrictions on how crop production can expand. Specifically, under the CET approach any transition from irrigated to rainfed land are costly, which reduces the benefit of changing the ratio of irrigated to rainfed land. Furthermore, including land and water as imperfect substitutes in production prevents water resources from being used more efficiently by using more capital and other inputs.

We also found that changing water availability for agriculture by plus or minus 20% had small impacts on food prices, bioenergy production and deforestation. This is because unlike in the traditional CET approach to including irrigated land in economy-wide models, one hectare of land released from irrigated production can be used in rainfed production. The impacts of changes in water availability on food, bioenergy and land use were also mitigated in our modeling framework by endogenous improvements in irrigation efficiency and water storage, which allowed additional water to be ‘produced’ using capital, labor and other inputs.

Another interesting result was that heterogeneity in irrigation production and expansion possibilities can drive shifts in the global composition of livestock production. In our simulations, livestock production relocated from regions with more land-intensive production to regions with less land-intensive production. As global pasture land is three times the size of global crop land, these land-saving changes increased natural forest areas, even when there was increased demand for crop land.

We close with a cautionary note on the interpretation of our results. Our analysis examined a specific shock that changed the quantity of water available for irrigation (due to a change in demand for other uses) under constant climate conditions. As such, there were no direct impacts on crop yields on either rainfed or irrigated lands. In the future, temperature and precipitation changes will not only directly impact yields, but also water availability through runoff and evaporation. Addressing outcomes under climate change requires an integrated analysis. While such an assessment is beyond the scope of this study, the EPPA model forms part of the MIT IGSM, and the extended model developed in the paper could be included in an integrated analysis in future work.

## Acknowledgements

The authors wish to thank Rosemary Albinson, Bo Chen, Andrew Cockerill, Jo Howes, Fabio Montemurro, James Primrose, and Cameron Rennie for helpful comments and suggestions. Valuable research assistance for this research was provided by Kirby Ledvina. Primary funding for this research was through a sponsored research agreement with BP. The authors also acknowledge support in the basic development of the Economic Projection and Policy Analysis model from the Joint Program on the Science and Policy of Global Change, which is funded by a consortium of industrial sponsors and Federal grants including core funding in support of basic research under U.S. Environmental Protection Agency (EPA-XA-83600001) and U.S. Department of Energy, Office of Science (DE-FG02-94ER61937). For a complete list of sponsors see for complete list see <http://globalchange.mit.edu/sponsors/current.html>). The findings in this study are solely the opinions of the authors.

## 6. REFERENCES

Aguiar, A., B. Narayanan, and R. McDougall, 2016: An Overview of the GTAP 9 Data Base. *Journal of Global Economic Analysis*, 1(1): 181-208.

Baker, J., 2011: The impact of including water constraints on food production within a CGE framework, Master of Science Thesis, Massachusetts Institute of Technology. ([http://globalchange.mit.edu/files/document/Baker\\_MS\\_2011.pdf](http://globalchange.mit.edu/files/document/Baker_MS_2011.pdf))

Berrittella M., A. Hoekstra, K. Rehdanz, R. Roson, and R. Tol, 2007: The economic impact of restricted water supply: A computable general equilibrium analysis, *Water Research*, 41(8): 1799-1813.

BP, 2015: BP Technology Outlook, London, United Kingdom, November 2015. (<http://www.bp.com/content/dam/bp/pdf/technology/bp-technology-outlook.pdf>)

Calzadilla A., K. Rehdanz, and R. Tol, 2010: The economic impact of more sustainable water use in agriculture: A computable general equilibrium analysis, *Journal of Hydrology*, 384(3-4); 292–305.

Gurgel, A., J.M. Reilly and S. Paltsev, 2007: Potential land use implications of a global biofuels industry, *Journal of Agricultural & Food Industrial Organization*, 5(2): 1–34.

Gurgel, A., T. Cronin, J.M. Reilly, S. Paltsev, D. Kicklighter, and J. Melillo, 2011: Food, Fuel, Forests and the Pricing of Ecosystem Services, *American Journal of Agricultural Economics*, 93(2): 342-348.

Dinar, A. 2014: Water and economy-wide policy interventions, *Foundations and Trends in Microeconomics*, 10(2): 85-163.

Dudu, H. and S. Chumi, 2008: Economics of irrigation water management: A literature survey with focus on partial and general equilibrium models, World Bank Policy Research Working Paper 4556, March, 65p. (<http://documents.worldbank.org/curated/en/2008/03/9075869/economics-irrigation-water-management-literature-survey-focus-partial-general-equilibrium-models>)

Hejazi, M.I., N. Voisin, L. Liu, L.M. Bramer, D.C. Fortin, J.E. Hathaway, M. Huang, P. Kyle, L.R. Leung, H-Y. Li, Y. Liu, P.L. Patel, T.C. Pulsipher, J.S. Rice, T.K. Tesfa, C.R. Vernon, and Y. Zhou, 2015: 21st century United States emissions mitigation could increase water stress more than the climate change it is mitigating, *Proceedings of the National Academy of Sciences*, 112(34): 10,635-10,640.

IEA [International Energy Agency], 2006: World Energy Outlook: 2007. OECD/IEA: Paris. (<https://www.iea.org/publications/freepublications/publication/weo2006.pdf>)

IEA [International Energy Agency], 2012: World Energy Outlook: 2007. OECD/IEA: Paris. (<http://www.worldenergyoutlook.org/publications/weo-2012>)

IMF [International Monetary Fund], 2013. *World Economic Outlook*. International Monetary Fund. (<http://www.imf.org/external/pubs/ft/weo/2013/01/weodata/download.aspx>)

Johansson, R.C, 2005: Micro and macro-level approaches for assessing the value of irrigation water, World Bank Policy Research Working Paper 3778, December, 68 p. (<https://openknowledge.worldbank.org/bitstream/handle/10986/8471/wps3778.pdf;sequence=1>)

Liu, J. T.W. Hertel, F. Taheripour, T. Zhu, and C. Ringler, 2014: International trade buffers the impact of future irrigation shortfalls, *Global Environmental Change*, 29: 22-31.

Melillo, J.M., J.M. Reilly, D.W. Kicklighter, A.C. Gurgel, T.W. Cronin, S. Paltsev, B.S. Felzer, X. Wand, A.P. Sololov, and C.A. Schlosser, 2009: Indirect Emissions from Biofuels: How Important? *Science*, 326(5958): 1397–1399.

MIT Joint Program, 2014. 2014 Climate and Energy Outlook, MIT Joint Program on the Science and Policy of Global Change, Cambridge, MA. (<http://globalchange.mit.edu/files/2014%20Energy%20%26%20Climate%20Outlook.pdf>)

Mitchell, D., 2008: A note on rising food prices, The World Bank, Development Prospects Group, Policy Research Working Paper No. 4682, July, 21 p. ([http://www-wds.worldbank.org/servlet/WDSContentServer/WDSP/IB/2008/07/28/000020439\\_20080728\\_103002/Rendered/PDF/WP4682.pdf](http://www-wds.worldbank.org/servlet/WDSContentServer/WDSP/IB/2008/07/28/000020439_20080728_103002/Rendered/PDF/WP4682.pdf))

Narayanan, B.G. and T.L. Walmsley (Eds.), 2008: *Global Trade, Assistance, and Production: The GTAP 7 Data Base*. Center for Global Trade Analysis.

Portmann, F.T., S. Siebert, and P. Döll, 2010: MIRCA2000 Global monthly irrigated and rainfed crop areas around the year 2000: A new high-resolution data set for agricultural and hydrological modeling. *Global Biogeochemical Cycles*, 24(1) GB1011.

Rosegrant, M.W., C. Ringler, S. Msangi, T.B. Sulser, T. Zhu, and S.A. Cline, 2012: International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) Model Description. International Food Policy Research Institute. (<http://www.ifpri.org/sites/default/files/publications/impactwater2012.pdf>)

Rutherford, T.F., 2002: Lecture notes on constant elasticity functions, University of Colorado. (<http://www.gamsworld.org/mpsge/debreu/ces.pdf>)

Rutherford, T.F., 1995: Extension of GAMS for complementary problems arising in applied economic analysis. *Journal of Economics Dynamics and Control*, 19(8): 1299–1324.

Siebert, S. and P. Döll, 2010: Quantifying blue and green virtual water contents in global crop production as well as potential production losses without irrigation. *Journal of Hydrology*, 384(3-4): 199–217.

Sokolov, A.P., C.A. Schlosser, S. Dutkiewicz, S. Paltsev, D.W. Kicklighter, H.D. Jacoby, R.G. Prinn, C.E. Forest, J.M. Reilly, C. Wang, B. Felzer, M.C. Sarofim, J. Scott, P.H. Stone, J.M. Melillo and J. Cohen, 2005: The MIT Integrated Global System Model (IGSM) Version 2: Model Description and Baseline Evaluation, MIT JPSPGC *Report 124*, July 40 p. ([http://globalchange.mit.edu/files/document/MITJPSPGC\\_Rpt124.pdf](http://globalchange.mit.edu/files/document/MITJPSPGC_Rpt124.pdf))

Strzepek, K., C.A. Schlosser, A. Gueneau, X. Gao, E. Blanc, C. Fant, B. Rasheed and H.D. Jacoby, 2013: Modeling water resource systems within the framework of the MIT Integrated Global System Model: IGSM-WRS, *Journal of Advances in Modeling Earth Systems*, 5(3): 638–653.

Strzepek, K., C.A. Schlosser, A. Gueneau, X. Gao, E. Blanc, C. Fant, B. Rasheed and H.D. Jacoby, 2012: *Modeling Water Resource Systems under Climate Change: IGSM-WRS*. MIT JPSPGC *Report 236*, August, 54 p. ([http://globalchange.mit.edu/files/document/MITJPSPGC\\_Rpt236.pdf](http://globalchange.mit.edu/files/document/MITJPSPGC_Rpt236.pdf))

Taheripour, F., T.W. Heretl, and J. Liu, 2013a: Introducing water by river basin into the GTAP-BIO model: GTAP-BIO-W, GTAP Working paper No. 77. (<https://www.gtap.agecon.purdue.edu/resources/download/6648.pdf>)

Taheripour, F., T.W. Heretl, and J. Liu, 2013b: The role of irrigation in determining the global land use impacts of biofuels, *Energy Sustainability and Society*, 3(4): 1- 18.

UN [United Nations], 2011: World Population Prospects: The 2010 Revision, Population Division, United Nations Department of Economic and Social Affairs.

Wiberg, D.A. and Strzepek, K., 2005: Development of regional economic supply curves for surface water resources and climate change assessment: A case study of China, The International Institute for Applied Systems Analysis, Research Report 05-001, Vienna, Austria.

Winchester, N. and J.M. Reilly 2015: The feasibility, costs, and environmental implications of large-scale biomass energy, *Energy Economics*, 51, 188-203.

## APPENDIX

**Table A1.** Water regions included in each EPPA region.

Water Regions								
AFR	CAF	CentralAfrican	LCB	LakeChad	NLE	Nile	SAH	Sahara
	CON	Congo	LIM	Limpopo	NWA	NorthwestAfrica	SEN	Senegal
	EAC	EastAfrCoast	MAD	Madagascar	ORA	Orange	VOT	Volta
	HOA	HornofAfrica	NAC	NorthAfricanCoast	SAC	SouthAfricaCoast	WAC	WestAfricanCoast
	KAL	Kalahari	NIG	Niger	SAF	SoutheastAfrica	ZAM	Zambezi
ANZ	CAU	CentralAust	MAU	Murray	PAO	Papau		
	EAU	EasternAustr	NZE	New	WAU	WesternAust		
ASI	BOR	Borneo	INW	IndonesiaWest	PHI	Philippines	TMM	ThaiMyan
	INE	IndonesiaEast	MEK	Mekong	SKP	SouthKoreaPeninsula		
BRA	AMA	Amazon	NEB	NortheastBrazil	SAN	SanFrancisco	TOC	Toc
CAN	CAN	Canada	CCA	CentralCanada	GLA	GreatLakes	RWI	RedWinnipeg
	CHJ	ChangJiang	HUN	HuangHe	SEA	SEAsiaCoast	ZHJ	ZhuJiang
	HAI	HailHe	LAJ	LangcangJiang	SON	Songhua		
	HUL	HualHe	LMO	LowerMongolia	YHE	YiliHe		
EUR	BRI	Britain	IRE	Ireland	LBO	LoireBordeaux	SCA	Scandinavia
	ELB	Elbe	ITA	Italy	RHI	Rhine	SEI	Seine
	IEM	IberiaEastMed	IWA	IberiaWestAtl	RHO	Rhone		
IND	BRR	Brahmari	EGH	EasternGhats	IEC	IndiaEastCoast	MAT	MahiTapti
	CAV	Cauvery	GAN	Ganges	KRI	Krishna	SAY	Sahyada
	CHO	Chotanagpui	GOD	Godavari	LUN	Luni		
JPN	JAP	Japan						
LAM	CAM	CentralAmer	NSA	NorthSouthAmerica	PEC	Peru	TIE	Tierra
	CAR	Carribean	NWS	NorthwestSouthAmerica	RIC	RioColorado	URU	Uruguay
	CHC	ChileCoast	ORI	Orinoco	TIG	Tigris		
	CUB	Cuba	PAR	Parana	SAL	SaladaTierra		
MES	ARA	Arabian	EME	EasternMed	WAI	WesternAsia		
MEX	MIM	MiddleMexico	UME	UpperMexico	YUC	Yucatan		
REA	BRT	Brahmaputra	NKP	NorthKoreaPeninsula	SRL	SriLanka		
	IND	Indus	ROW	ROW				
ROE	AMD	Amudarja	BLA	Black	DNI	Dnieper	ODE	Oder
	BAL	Baltic	DAN	Danube	LBA	LakeBalkhash	SYD	Syrdarja
RUS	AMR	Amur	OB	Ob	URA	Ural	YEN	Yenisey
	NER	NorthEurope	UMO	UpperMongolia	VOG	Volga		
	ARK	Arkansas	COL	Colorado	MOU	Missouri	SEU	SoutheastUS
USA	CAL	California	GBA	GreatBasin	OHI	Ohio	USN	USNortheast
	COB	Columbia	MIS	Mississippi	RIG	RioGrande	WGM	WesternGulfMexico

**Table A2.** The mapping of water regions to irrigation response units (IRUs).

EPPA Region	River region 1	River region 2	River region 3	River region 4
AFR	CON	CAF, EAC, MAD, SAF, SEN, WAC, ZAM	HOA, KAL, LCB, LIM, NIG, NWA, VOT	NAC, NLE, ORA, SAC, SAH
ANZ	CAU, EAU, MAU	NZE, WAU	PAO	
ASI	BOR, TMM	INE, INW, MEK, PHI	SKP	
BRA	AMA, TOC	NEB	SAN	
CAN	CAN, CCA, GLA	RWI		
CHN	CHJ, HUL, YHE, ZHZ	HAI, HUN, LAJ, SON	LMO, SEA	
EUR	BRI, IRE, RHI	ELB, SCA	IEM, IWA	ITA, LBO, RHO, SEI
IND	BRR, LUN, MAT	CAV, CHO, IEC, SAY	EGH, GAN, GOD, KRI	
JPN	JAP			
LAM	CAM, NWS, PAR, PEC, TIE, URU	CAR, CHC, CUB, NSA, ORI, RIC, SAL		
MES	ARA, TIG	EME, WAI		
MEX	MIM, UME	YUC		
REA	BRT, IND, SRL	NKP, ROW		
ROE	AMD, BLA, DAN, LBA, SYD	BAL, DNI, ODE		
RUS	AMR, OB, URA	NER, UMO, VOG, YEN		
USA	OHI, SEU, USN, WGM	CAL, COB, COL, GBA	ARK, MIS, MOU, RIG	