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

Niven Winchester, Kirby Ledvina, Kenneth Strzepek and John M. Reilly

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***—Ronald G. Prinn and John M. Reilly,***
*Joint Program Co-Directors*

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GLOBAL CHANGE

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

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**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 at 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.



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# 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 increases (intensification), (2) crop land area can expand (extensification), and (3) food usage can decrease 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 increasing water storage. 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.

Water resource limits and policies regarding protection of natural lands could put more pressure on the food demand response margin, potentially pricing the lowest-income populations out of the food market. Rising greenhouse gas (GHG) concentrations and the associated changes in climate —which will largely depend on future energy production and land use—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.

This paper seeks to better quantify tradeoffs among these margins and bioenergy potential by greatly improving the representation of irrigation potential 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. 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. 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).[1] 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.

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.[2]

While the GTAP-BIO-W model has advanced economy-wide modeling of food, water and bioenergy outcomes, at least two limitations remain. First, the model assumes that the supply of accessible land is fixed, so while there is land conversion among forestry, pasture and cropland, it does not consider deforestation due to the conversion of (currently) inaccessible land to managed uses. Second, the model does not currently allow investment in irrigation systems and/or water storage in response to changes in relative prices, which could be driven by water scarcity or rising food demand.

We apply 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

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

2 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.

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 six other non-energy sectors (energy-intensive industry, commercial transportation, private transportation, food products, services and other industries). Several commodities

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

| Regions & Factors | | | | | | | |
|---|---|---|---|---|---|---|---|
| ***Regions*** | | | | | | | |
| **USA** | United States | **ANZ** | Australia-New Zealand | **CHN** | China | **BRA** | Brazil |
| **CAN** | Canada | **EUR** | European Union | **IND** | India | **LAM** | Other Latin America |
| **MEX** | Mexico | **ROE** | Rest of Europe and Central Asia | **ASI** | Dynamic Asia | **AFR** | Africa |
| **JPN** | Japan | **RUS** | Russia | **REA** | Rest of East Asia | **MES** | Middle East |

| ***Factors*** | |
|---|---|
| Capital | |
| Labor | |
| Land | *Crop land, managed forest land, natural forest land, managed grassland, natural grassland, other land* |
| Resources | *For coal; crude oil; gas; shale oil; shale gas; hydro, nuclear, wind and solar electricity* |

| **Sectors** | |
|---|---|
| ***Energy*** | |
| Coal | |
| Crude oil | *Conventional crude oil; oil from shale, sand* |
| Refined oil | *From crude oil, first and second generation biofuels* |
| Natural gas | *Conventional gas; gas from shale, sandstone, coal* |
| Electricity | *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 & without CCS* |

| ***Non-energy*** | | |
|---|---|---|
| Agriculture | Livestock | |
| | Forestry | |
| | Crops | *Food crops; biofuel crops (corn, wheat, energy beet, soybean, rapeseed, sugarcane, oil palms, represent. energy grass, represent. woody crop)* |
| Other Non-Energy | Energy-intensive industry | |
| | Other industry | |
| | Services | |
| | Commercial transportation | |
| | Household transport | *Conventional, hybrid & plug-in electric vehicles* |

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 (CCS). Fossil fuel prices are endogenously estimated, a result of demand for fuels in the economy interacting with the specification of resource availability and supply technology. The oil price rises through time and reaches, in 2010 dollars, $123.90 per barrel by 2050. While energy prices are notoriously variable this forecast is in line with other sources such as projections by the EIA (2012).

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 thermochechemical process (both of which can operate with and without 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 varied 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 constant elasticity of substitution (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 regions 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." Increased land rents cause small changes in deforestation in developed regions, while deforestation is most sensitive to changes in land rents 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 ($CO_2$), 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 (~10 km2) for 26 crop types. We aggregate the data spatially and across crop types to calculate total rainfed and irrigated areas for each grid cell. **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

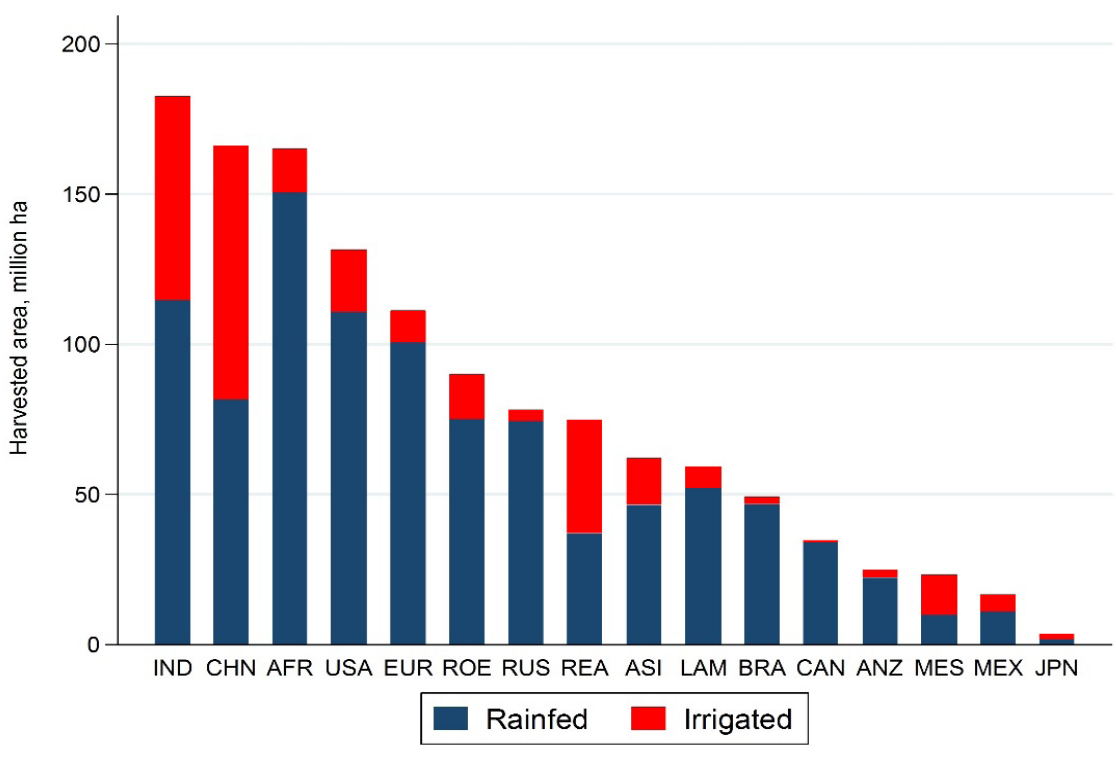



**Figure 1.** Rainfed and irrigated harvested area by EPPA region.

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

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.

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 rainfed and irrigated land hectares and production value, this implies that on average globally irrigated land is 55% more productive than rainfed land in terms of value of crop produced.

### 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 globally—named Assessment Sub-Regions (ASRs) by the U.S. Water Resources Council or Food Producing Units (FPUs) by the International Food Policy Research Institute. 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

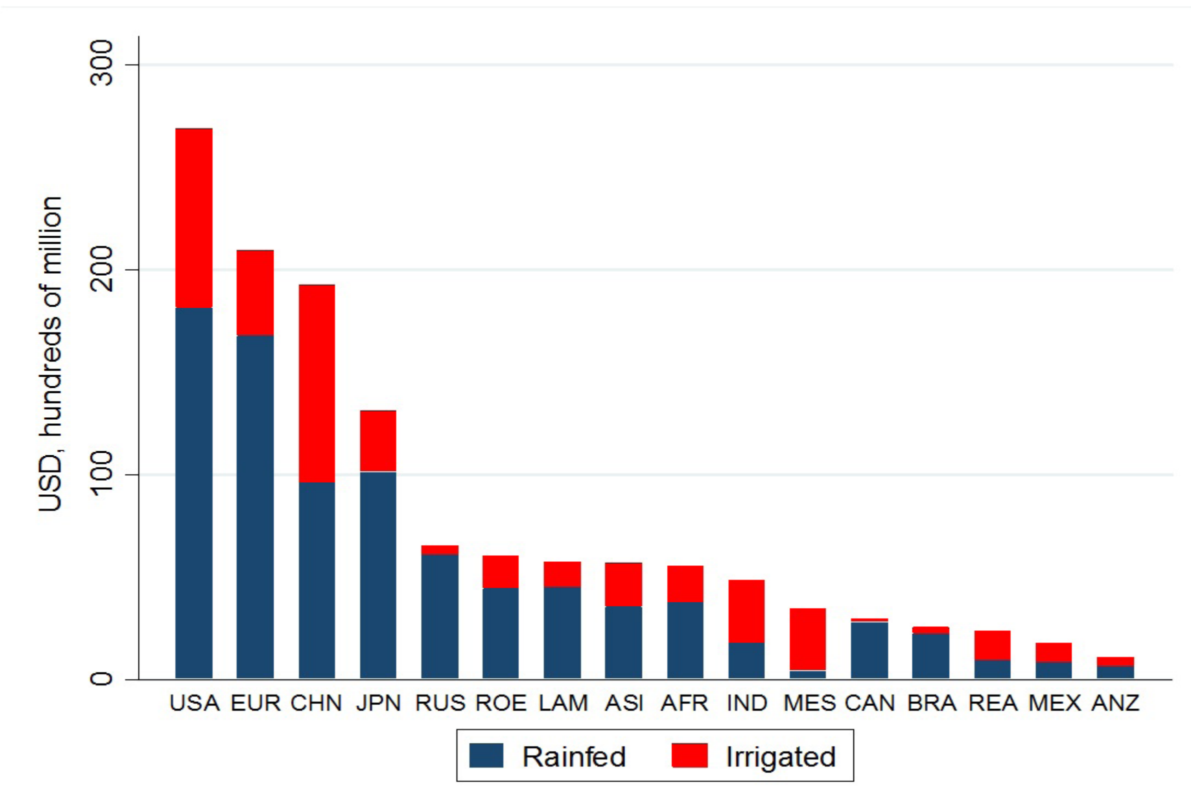



**Figure 2.** The value of crop production on rainfed and irrigated areas by EPPA region.

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

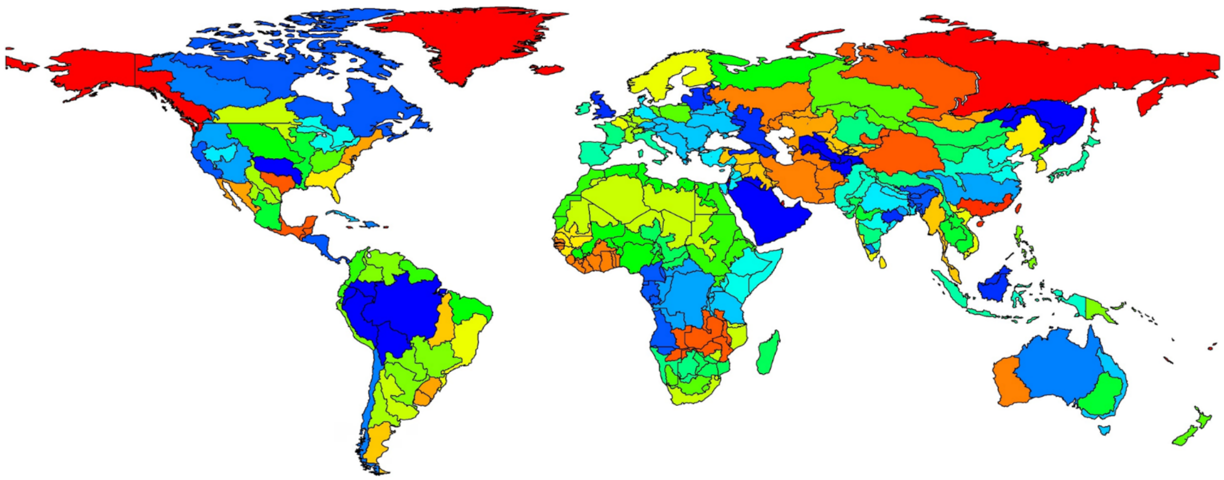


**Figure 3.** Food producing units (lines) and water regions (colors).

**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 |

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

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 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.

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.

Provided that there is existing irrigation, the least expensive upgrade is always the addition of canal lining to improve conveyance efficiency.[3] Irrigation efficiency upgrades progress in the order of no irrigation, flood, furrow, low-efficiency sprinkler, and 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

3 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%.

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**.

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 aver-

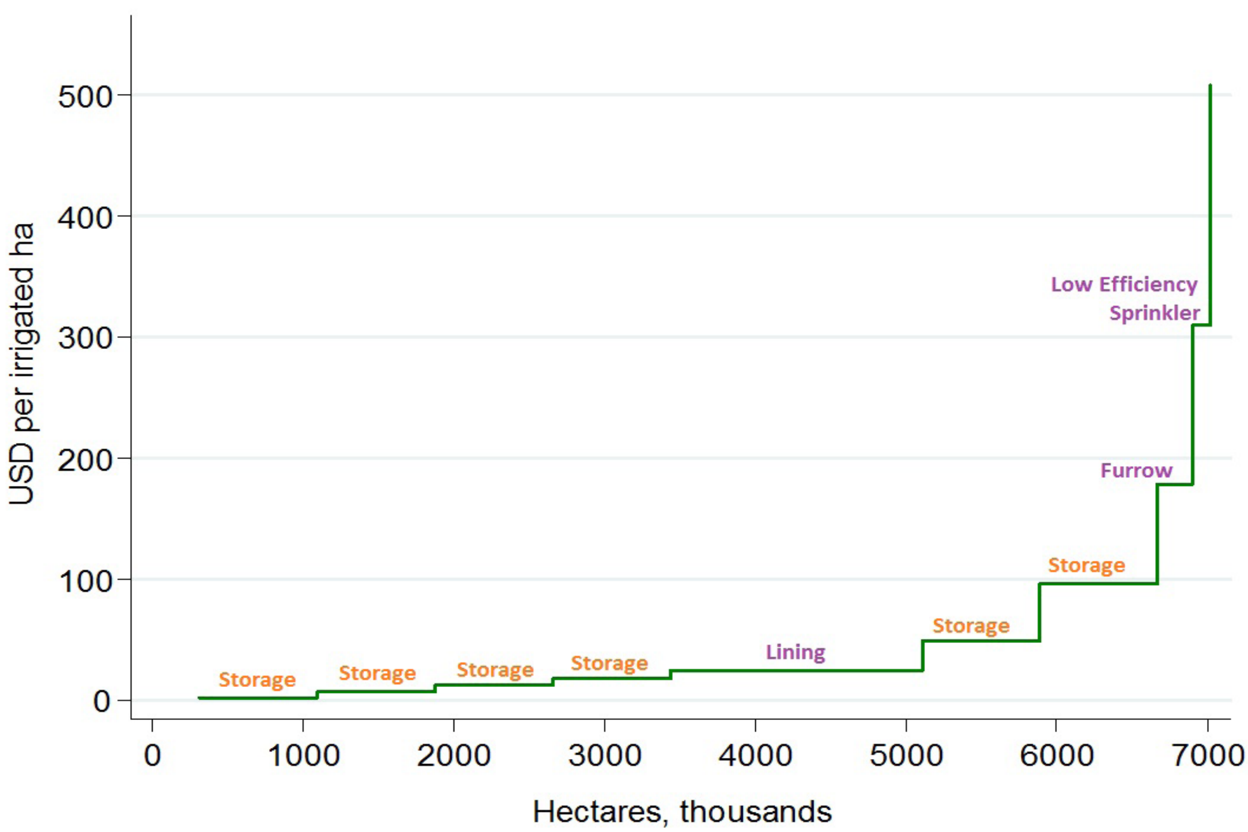



**Figure 4.** Annual irrigable land supply curve for the Mississippi River water region.

age 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 differentiated 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 CES 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 $s_{L-I} = 0$. 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.

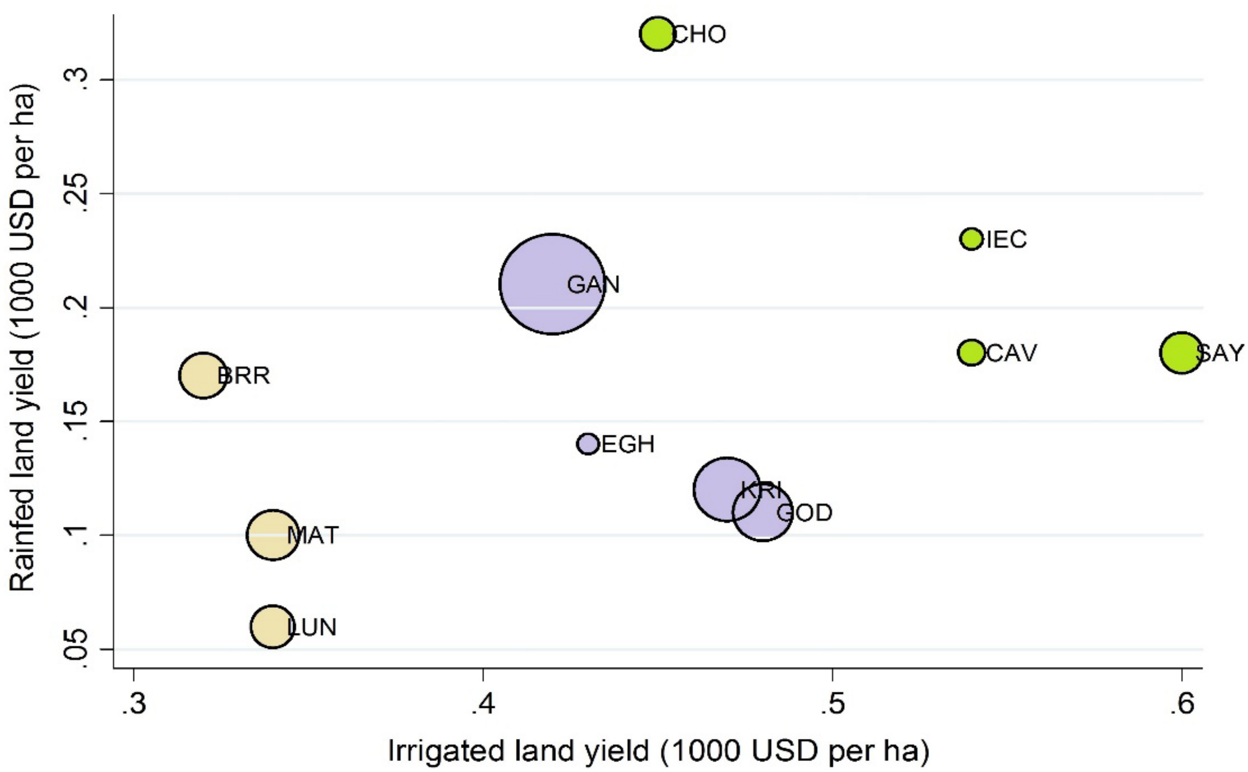



**Figure 5.** Irrigation response units for India (colors) built on clustered water regions.

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

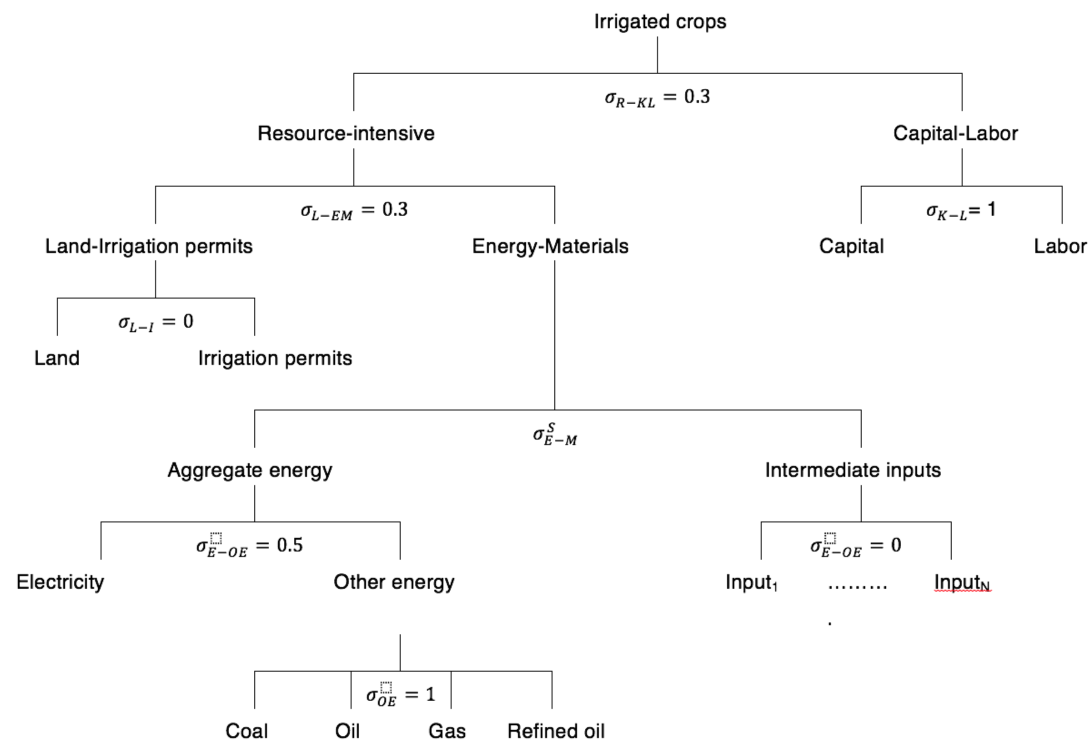



**Figure 6.** Irrigated crop production in for an IRU in the EPPA model.

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 ($\sigma_{L\text{-}EM}$), and between the resource-intensive bundle and the capital-labor aggregate ($\sigma_{R\text{-}KL}$). Both of these elasticities allow endogenous yield improvements due to increases in land prices.[4] 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.

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 specific resources and $\sigma_{KLI\text{-}ISR}$ 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, $\sigma_{KLI\text{-}C} = 0$, 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 certifi-

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

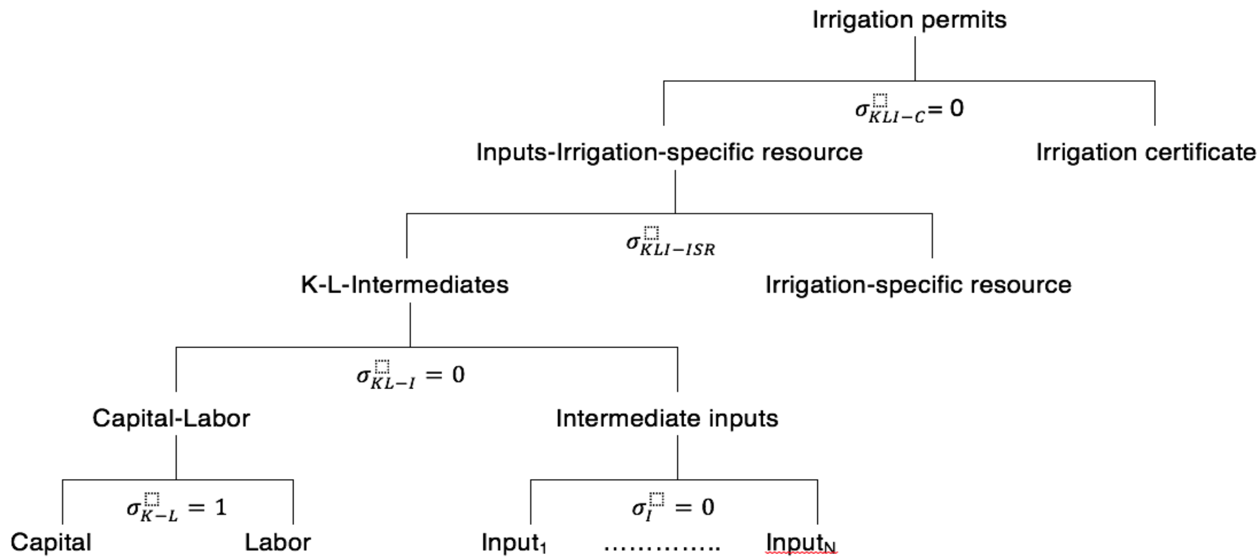



**Figure 7.** Production of irrigated land permits for each IRU in the EPPA model.

cates 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 $CO_2$ equivalent ($tCO_2e$) in 2015 and rising by 4% per year to \$99/$tCO_2e$ 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 for water availability are considered: constant, increasing, and decreasing. In the constant case, water available for irrigation is fixed at its 2010 level in all regions. 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. In the increasing case, equivalent increases are simulated, and water available for irrigation is 20% higher in each region in 2050 relative to 2010.

These changes in water availability are illustrative and are 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 like 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 of a constant proportion of irrigated crop land in total crop land 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 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 *Ref*erence policy setting with *N*o water resources explicitly represented (*Ref-N*) with the *Ref*erence 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 *Ref*erence scenario by decreasing water availability to *80%* (*Ref-80%*) or increasing 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 *Pol*icy with *N*o water constraints (*Pol-N*) scenario, with a *Pol*icy 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 when 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**.

## 4. RESULTS

We organize results in two sections, first answering our four main questions, focusing on results in 2050. We

**Table 3.** Scenarios considered.

| Scenario | Carbon price? | Irrigated land? | Water resources |
|---|---|---|---|
| Ref-N | ✖ | ✖ | Not explicitly represented |
| Ref-80% | ✖ | ✔ | 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 |
| Ref-100% | ✖ | ✔ | Water available for irrigation is fixed at its 2010 level in all regions |
| Ref-120% | ✖ | ✔ | 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 |
| Pol-N | ✔ | ✖ | Not explicitly represented |
| Pol-80% | ✔ | ✔ | 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 |
| Pol-100% | ✔ | ✔ | Water available for irrigation is fixed at its 2010 level in all regions |
| Pol-120% | ✔ | ✔ | 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 |

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 in proportion to 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.

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, where 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 forest 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 $CO_2$e emissions the in the *Ref-100%* scenario relative to the *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 *Ref-80%* to 29.7 EJ in *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-*

**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 (%)* | - | -0.21 | -0.19 | -0.18 | -3.15 | -3.42 | -3.41 | -3.05 |
| $CO_2$e 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 (%)* | - | -0.26 | -0.20 | -0.18 | -4.10 | -4.48 | -4.47 | -4.26 |
| Change in food price (%)* | - | 0.23 | 0.14 | 0.12 | 3.73 | 4.10 | 4.05 | 3.94 |

* Change relative to the *Ref-N* scenario.

*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.[5] 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 on 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 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), and 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 $CO_2$e by 2050. This policy initially reduces global energy use by about 50 EJ, and the rising $CO_2$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.

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 that 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.

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

5 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).

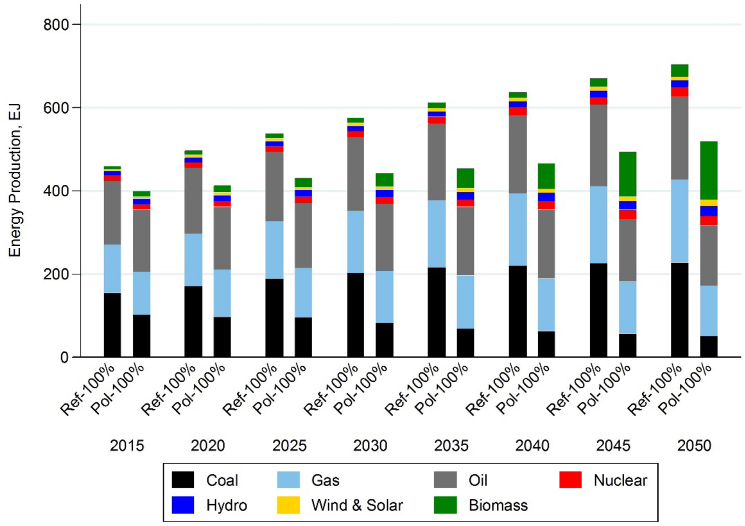



**Figure 8.** Global primary energy through 2050.

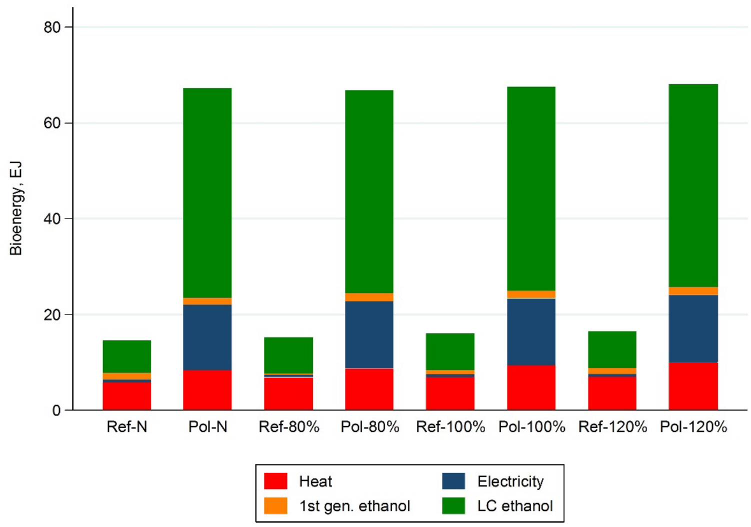



**Figure 9.** Global final bioenergy in 2050.

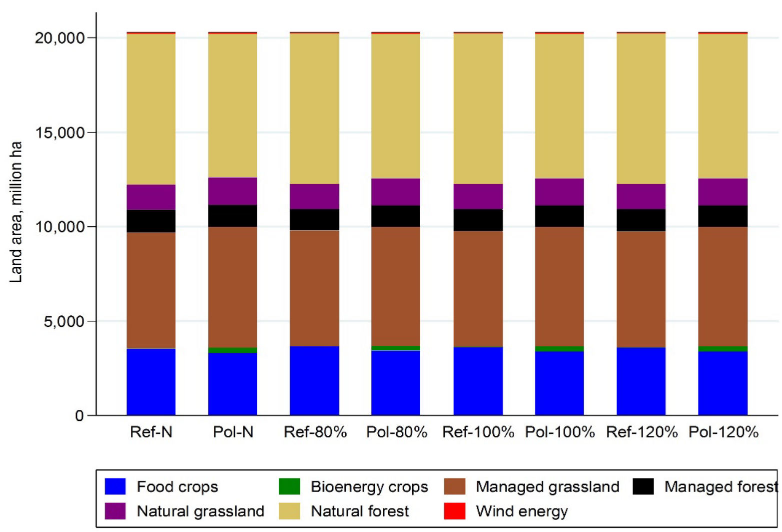
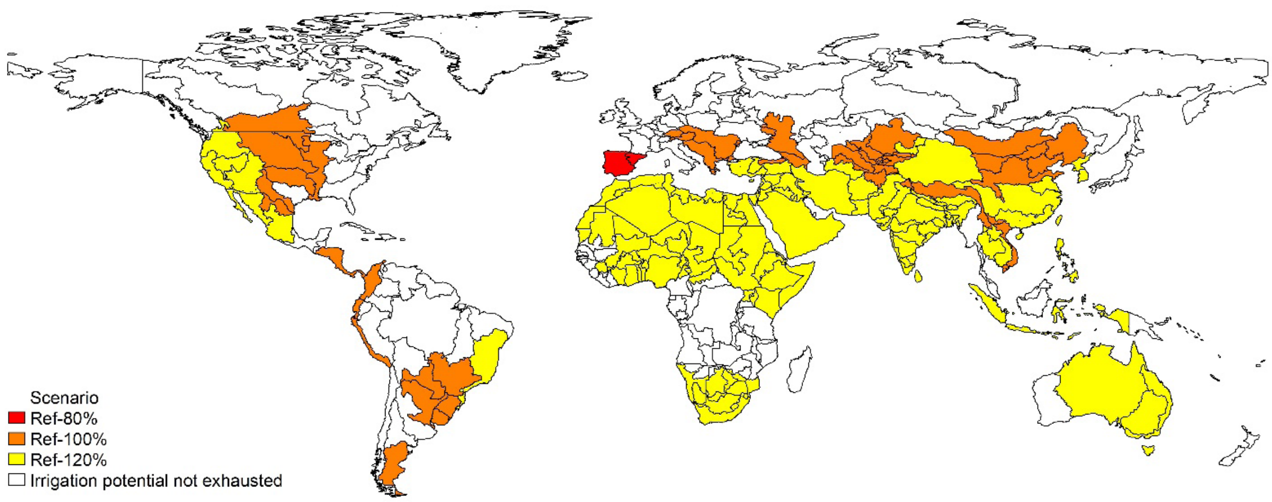


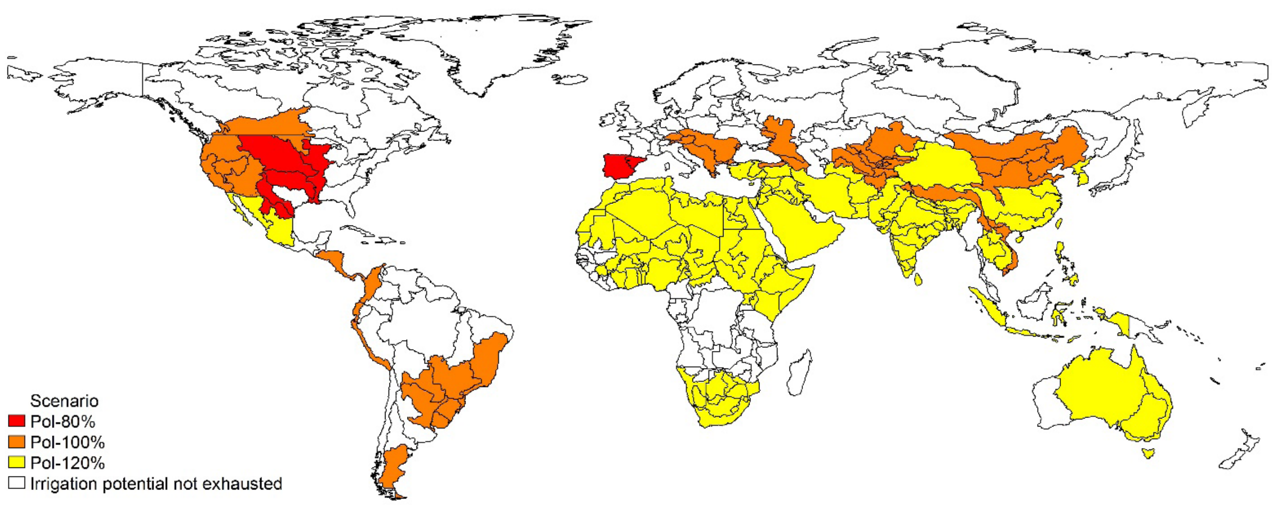

**Figure 10.** Global land use in 2050.

small compared with other land uses. There are a number of 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.

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**). Yellow regions 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. Orange regions are also at their maximum at 100% of currently available water, and red regions 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




**(a)**




**(b)**

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

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.

## 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 costlier and may be curtailed.

This paper advances the understanding of food, bioenergy, water and land outcomes by representing irrigated land supply curves 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.

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# APPENDIX

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

| 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 | SouthKoreaPenisula | | |
| **BRA** | AMA | Amazon | NEB | NortheastBrazil | SAN | SanFrancisco | TOC | Toc |
| **CAN** | CAN | Canada | CCA | CentralCanada | GLA | GreatLakes | RWI | RedWinnipeg |
| **CHN** | 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 | NorthKoreaPenisula | SRL | SriLanka | | |
| | IND | Indus | ROW | Rest of World | | | | |
| **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 | | |
| **USA** | ARK | Arkansas | COL | Colorado | MOU | Missouri | SEU | SoutheastUS |
| | 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).

| | River Regions | | | |
|---|---|---|---|---|
| **EPPA Region** | **1** | **2** | **3** | **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, ZHJ | 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 | |

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