Agricultural production, irrigation, climate change, and water scarcity in India

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Abstract

This paper uses an advanced Computable General Equilibrium (CGE) model coupled with biophysical data on future changes in crop yields due to climate change to examine: 1) the consequences of climate change for India's agricultural and food products; 2) the extent to which water scarcity can affect the irrigation adoption and demand for water; and 3) how water scarcity, climate change, and trade jointly alter land use changes across the Indian subcontinent. It shows that when water scarcity is ignored, irrigated areas grows due to changes in crop yields induced by climate change. When water scarcity is introduced, competition for water increases and that largely reduces demand for irrigation across all river basins in India. When available water for irrigation is not limited, climate change alone could moderately increase agricultural outputs at national level and that leads to some welfare gains. However, water scarcity, induced by expansion in water demand in non-agricultural uses and lack of water infrastructure, blocks the demand for irrigation and that generates significant negative impacts on the economy of India and its agricultural activates. The overall welfare losses due to water scarcity for this economy is expected to be about $3.2 billion (at 2007 prices) in 2030. With a 3% discount rate, the net present value of the annual reductions in welfare will be about $24.3 billion for 2008 to 2030.

Keywords: India, Agriculture, Water Scarcity, Climate Change, Irrigation, General Equilibrium

1. Introduction

It is frequently acknowledged that the economy of India and in particular its agricultural sectors will face serious water challenges over the coming decades [1, 2, and 3]. Population growth coupled with economic growth of nearly 7% per year to 2030 will translate into strong growth in food demand and hence crop production in India. Given that roughly 60% of crops produced in India are irrigated this will likely require a major expansion in demand for water. Growing demand for irrigation, when coupled with increases in industrial, residential, and commercial demands for water, is projected to result in intense competition for water in India. However, the intensity of this competition will not be uniform across different River Basins (RB) and Agro Ecological Zones (AEZs) of this country. In particular, in warmer and dryer AEZs, climate change may increase demand for irrigation as an adoption strategy to higher temperature and volatile weather condition. On the other hand, in some AEZs, climate change may positively affect rainfed crop yields and hence reduce demand for irrigation and weaken intensity of water scarcity. Hence, while irrigation adoption is commonly suggested as an important alternative response to climate change, changes in water scarcity (either due to expansion in demand for water in non-agricultural uses, increase in population, higher demand for food, lack of water infrastructure, or induced by climate change itself) can differentially affect both the supply of water and the demand for additional irrigation in agriculture across AEZs in India.

This paper modifies and uses an advanced Computable General Equilibrium (CGE) model coupled with biophysical data on future changes in crop yields due to climate change to examine: 1) the consequences of climate change for India's agricultural and food products; 2) the extent to which water scarcity can affect the irrigation adoption and demand for water; and 3) how water scarcity, climate change, and trade jointly alter land use changes across the Indian subcontinent.

Next following a literature review we introduce our CGE modeling framework and its background along with the biophysical data which we used to measure the impacts of climate change on crop yields in India and future water scarcity in this county. We then define two experiments which were designed to achieve the goal of paper. Finally, we present our analyses along with the numerical results obtained from our simulations followed by conclusions.

2. Background

Many papers have studied the impacts of climate change on crop yields and food security [e.g. 4 and 5]. These studies demonstrate how changes in climate variables and CO_2 concentration in the atmosphere affect food security across the world. However, they do not provide a clear picture on the interactions between climate change, crop yield, and water scarcity. More recent papers (e.g. Willis et al. [6] and Marshal et al. [7]) have taken into account these interactions and show that while climate change can induce incentives for irrigation, water scarcity may limit the extent that irrigation adoption can be implemented. While these papers and the earlier work in this area provide valuable economic and biophysical analyses of the impacts of climate change for crop production and food security, they ignore the interplay between climate change and international trade. Some papers have examined the interaction between trade and climate change. For example, Reilly et al. [8] have shown that trade can improve food security in regions which their crop production will be negatively affected by climate change factors. This paper and its successors (e.g. Baldos and Hertel [9]) usually ignore water scarcity induced by climate change and or economic factors. In a recent paper Liu et al. [10] have shown that trade can mitigate the consequences of future irrigation short falls in regions where water scarcity threaten their food security as well. However, these authors ignored the impacts of climate change on crop yield in the presence of water scarcity.

4

In general, changes in climate variables such as temperature, precipitation, and CO_2 concentration have direct and indirect impacts on crop yields. Many studies have examined and or projected the long run impacts of changes in these variables on crop yields for many climate change scenarios at the global scale [4, 5, 11, and 12]. While these studies indicate that the impacts of climate variables on crop yields vary by region, AEZ, crop, and time and are very uncertain[1] [13], most of the projections indicate that climate change will mainly begin to affect crop yields in a significant way after the mid of 2030s. In a recent report IPCC [12] concluded that climate change will likely affect negatively crop yields in 2030s and the impacts on median yield will grow between 0 to -2% per decade over the rest of 21st century. However, the impacts vary by region and crop. While some regions/crops will experience positive yield impacts, some others will observe negative impacts.

3. Methods

3.1. Model

Water and economic activities interact in several ways. To properly model the links between water and economic activities and examine the economy wide impacts of water scarcity for India in the presence of climate change we modified and implemented a unique advanced CGE model (GTAP-BIO-W) which trace demand for water in its alternative uses by RB and AEZ. This model built on the GTAP-E model [14, 15] which is a static model and allows substitution among energy inputs and assumes energy and capital are substitutable inputs in economic activities, except for primary energy sectors such as gas, coal, and oil. In a series of modifications [e.g. 16, 17, and 18] land, biofuels, and biofuels by-products were introduced in this model to make it suitable to study

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[1] Crop models are usually used to project the impacts of climate change on crop yields. These models project crop yield trajectories for alternative climate scenarios

the economic and environmental impacts of biofuel production and policies. The new model has been identified as GTAP-BIO and widely used to examine the economic and land use consequences of biofuel production at the global scale (examples are: [19, 20, 21, and 22]). Then in an intensive set of modifications, the GTAP-BIO model was modified to trace supplies of and demands for land and water resources within a country at a spatial resolution of RB by AEZ[2] level at the global scale and take into account competition for water across its alternative uses [10, 23, and 24]. The resulting model has been recognized as GTAP-BIO-W. In what follows we explain the major aspects of this model along with the changes we made.

Figure 1 represents the GTAP-BIO-W approach in allocating primary inputs including labor, capital, resources, land and water. In this model competition for labor, capital and resources takes place at the national level. This means that firms compete for these primary inputs at national level. In this model competition for water starts at the RB level. This means that crop industries compete with others water using industries for water at the RB level. Then, irrigated crop industries compete for managed water in each RB at the AEZ level. This means that competition for water takes place at the spatial resolution of RB-AEZ. In this model competition for land starts at the RB-AEZ level as well. In each RB-AEZ forestry, livestock and crop industries compete for accessible land. Then irrigated and rainfed crops compete for cropland. Finally irrigated crops compete for irrigated cropland and rained crops compete for rainfed cropland. In this model water can move from one AEZ to another one in a river basin.

In the earlier versions of this model water was permitted to move freely with no restriction across AEZs of a RB. In deference to the fact that water often cannot move freely across AEZs due to water rights, quotas, and other constraints, we altered the model to restrict movement of

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[2] Henceforth, we refer to this spatial resolution as RB-AEZ

water across AEZs of a RB. Figure 2 represents the nesting structure of supply of water in the new GTAP-BIO-W used in this paper. In this nesting structure three parameters of σ_r, σ_z, and σ_c control the supply side of water in a RB. A tiny value of σ_z restricts water movement across AEZs of a RB.

As mentioned earlier, GTAP-BIO-W is based on the GTAP-BIO model which uses a multi-level nested Constant Elasticity of Substitution (CES) production function. As shown in Figure 3 in this production function inputs are divided into two broad categories of: *intermediate inputs* and *value added and energy*. In general, there is no substitution among intermediate inputs. However, the GTAP-BIO model allows some substitution among feed items used in the livestock industry (for details see [21]). The value added and energy component is a mix of primary inputs including skilled and unskilled labor, land, natural resources, and capital and energy. A non-zero elasticity of substitution is used to mix these inputs and generate the value added-energy nest. As shown in Figure 3, the GTAP-BIO model assumes capital and energy are substitutable inputs. This means that firms can move away from energy and use more capital in response to higher energy prices and vice versa. In this model firms also can select a mix of energy items (including coal, oil, gas, electricity, petroleum products, and biofuels) to maximize their profit according to their energy need and energy prices. For example, when price of natural gas goes down electricity producers could shift away from coal and use more gas to produce electricity.

We modified this nesting structure to handle firms' demand for water. A major objective of this paper is to examine consequences of water scarcity for India. Several factors such as expansion in demand for water, lack of water infrastructure, and changes in climate conditions could increase water scarcity and intensify competition for water among water users. When water scarcity rises the opportunity costs of water (price of water) is expected to increase compared to the prices of

other factors of production such as labor, capital, and energy and that will induce incentives to save water and substitute this input with other production factors. We made proper changes in the supply side of the GTAP-BIO-W model to make substitution between water and other inputs possible. To accomplish this task we examined several input demand nesting structures and finally implemented the nesting structure presented in Figure 4. The new nesting structure is very similar to the original nesting structure of the GTAP-BIO model. The main difference is a new nest (see blue boxes in Figure 4) which we included to handle demand for water. At the bottom of the new nest we mix managed water (a primary input) and water utility (an intermediate input provided by water utility). Then we mix water and land as two compliment inputs. Finally we defined a nest where the mix of water-land can be combined with the mix of labor-capital-resources-energy.

3.2. Data base

To support our modeling practice we extensively modified the GTAP data base version 8 which represents the world economy in 2007 (Narayanan et al., [25]). The first major modification involves division of crop sectors into irrigated and rainfed categories. The standard GTAP data base does not distinguish between irrigated and rainfed crops. Given that climate change and water scarcity could affect irrigated and rainfed crop activities in different ways following Taheripour et al. [23] we divided each crop sector of the standard GTAP data bases into two groups of irrigated and rainfed. The second important modification includes enhancement of the standard GTAP data base to better represent consumption of water and its distribution by river basin. The standard GTAP data base includes a sector ("wtr": Henceforth Water-Util) which only represents collection, purification and distribution of water. This sector does not represent water used for irrigation and its value added. Following [24] we made proper modifications to represent water used in irrigation. The next major modification entails division of the electricity sector of the standard GTAP data

8

base into two distinct electricity sectors of hydro and non-hydro. This helps us to better model the demand for water in producing non-hydro-electricity. The last important modification is to bring biofuels into the data base. The standard GTAP data base does not represent production and consumption of biofuels. But, currently, many countries including India produce biofuels. Following Taheripour et al. [26] we introduced production and consumption of biofuels into our data bases to make our study more consistent with real world observations.

3.3. Expected changes in India crop yields due to climate change

In addition to the biophysical data which we used to introduce land and water in our data base we used available data to capture the impacts of climate change on crop yield. Several studies have examined the consequences of climate change for crop yields in India. Rajeevan [27] has reviewed some of these studies and concluded that: 1) crops are responding to climate change differently and their responses vary across India, 2) higher temperatures are likely to reduce crop yields, 3) CO_2 fertilization could improve yields and partially eliminate the negative impacts of higher temperatures, 4) the direct impacts of climate change on Kharif[3] crops in India would be small, 5) Rabi crops may suffer from increases in day and night temperature, 6) rainfall is expected to increase, and 7) the mean temperature in India is expected to change moderately (less than 1°) until 2030, even under very pessimistic climate scenarios. Khan et al. [28] which also examined the impacts of climate change on Indian agriculture have reached many of these conclusions. While the literature recognizes that climate change will not significantly affect crop yields in India until the mid of 2030s, several papers argue that climate extremes could increase and that alters the

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[3] Crops (such as rice, corn, and millet) are produced in rainy (monsoon) season in India

expected yields in favor of irrigated crops. This induces demand for irrigation as an important adaptation strategy [7, 11, 12, and 28].

To evaluate the impacts of climate change on India's crop yields we rely on the simulation results developed by Rosenzweig et al. [13]. These authors have evaluated the impacts of climate change on crop yields for a wide range of climate scenarios and several GCM and crop models at the global scale. Villoria et al. [29] have made these simulation results accessible to public on the GOSHARE website under the AgMIP tool (https://mygeohub.org/tools/agmip). We used this tool to assess the impacts of climate change on rainfed and irrigated crop yields in India for the time period of 2007-35 for a representative climate scenario. Since temperature will not significantly increase in India until the mid of 2030s, we concentrate on the RCP 2.6 which represents a moderate climate change scenario. Note that there is no significant differences between this scenario and more pessimistic scenarios until the mid of 2030s. Since we are interested in examining differences between the irrigated and rainfed yields we use results obtained from the pDSSAT crop model which differentiates between these yields. Finally, we concentrate on four major crops including rice, wheat, corn, and soybeans. We include the CO_2 fertilization effect in our evaluation – a factor which is especially important for C3 crops. Yield differences are aggregated from the grid cell to the AEZ level.

To summarize the impacts of climate change on the irrigated and rainfed crop yields, we converted the simulation results obtained from the above climate scenario to the net gains of keeping a hectare of rainfed cropland from switching to irrigation during the time period of 2007-2030. The results are presented in Table 1 by AEZ and crop. For example, this table indicates that yield gains due to keeping a hectare of land under rainfed paddy rice in AEZ1 during the time period of 2007-2030 in the wake of climate change is about 8.8% per year relative the no-climate

change baseline. This means that in this AEZ, climate change will alter the rainfed and irrigated rice yields in favor of the former. The corresponding figure for AEZ3 is about -11.8% which indicates that in this AEZ keeping a hectare of land under rainfed rice will cause yield losses by 11.8% per year, relative to the no-climate change baseline. Table 1 indicates that the impacts of climate change on the relative yields vary considerably by AEZ and crop.

3.4. Expected change in water scarcity in India

As mentioned before, several studies confirm that India will face water scarcity induced by rapid expansion in water demand in agricultural and non-agricultural uses, lack of proper water infrastructure, and climate change. When water scarcity arises, it mainly affects agriculture which is by far the largest user of water in India. In the presence of water scarcity (when supply of water is smaller than its demand) reduction in supply of water to irrigated agriculture usually restores equilibrium in market for water (Liu et al. [10]) as shown in Figure 5. There are four panels in this figure. The top left and right panels represent demand for water for in agricultural and non-agricultural uses, respectively. The bottom left panel shows available water (the water supply frontier) and allocation of water among agricultural and non-agricultural uses. The last panel (bottom and right) is a 45 degree line which acts as a mirror and reflects changes in quantity of water in non-agricultural uses to the water supply frontier panel. This figure shows that with an increase in demand for water in non- agricultural uses (from Q_{nag0} to Q_{nag1}) due to a major shift in this demand category (say due to population growth and expansion in industrial uses), the supply of water for irrigation goes down (from Q_{ag0} to Q_{ag1}), when available water does not grow enough (as depicted by a small shift in water supply frontier from $S0$ to $S1$).

Rosegrant et al. [2] have measured the Irrigation Water Supply Reliability (IWSR) index as a metric for irrigation water scarcity for 2030 and 2050 using the IMPACT-WATER model

11

developed by IFPRI at the global scale by river basin. This index measures the gap between demand and supply of water for irrigation. For our study, we use the "business as usual" scenario developed by these authors to measure changes in irrigation water supply by river basin in India for the time period of 2007-2030. This scenario assumes that the current trends in population and economic growth, water use efficiency, and investment in water infrastructure will continue in future. Figure 6 represents expected changes in irrigation water supply by river basin in India. As shown in this figure water supply for irrigation in 2030 compared with 2007 is expected to fall significantly in several river basins including but not limited to : Luni (-61%), Eastern-Ghat (-22%), Krishna (-20), Chotanagpui (-10.6%), and Ganges (9.2%) .

3.5. Implemented Experiments

To achieve the goals of this paper we developed the following two experiments:

Experiment I: Impacts of climate changes on demand for irrigation if water supply is not limited

Irrigation could eliminate a portion of vulnerability in crop yields induced by extreme weather events, thereby mitigating some of the risk associated with climate change. Farmers switch to irrigation when the expected gains due to irrigation are higher than the costs of irrigation (including initial investment and operation costs). When climate change affects yields in favor of irrigated crops, farmers switch to irrigation if the yield difference is large enough to cover the costs of irrigation and if water is available for irrigation.

This experiment is designed to show the extent to which climate change may affect demand for irrigation in India by 2030, while we assume water is available for irrigation across all river basins in this county. Here, we isolate the impacts of climate change on crop yields from other factors such as population growth, technological progress, and economic growth which may affect

crop yields over time. In addition, it is assumed that the real price of water remains constant to represent an elastic water supply (this assumption will very altered in subsequent experiments). Furthermore, given the fact that the supply of unskilled labor is not a major constraint in India, we assumed that the real wage for this group of labor force remains constant due to the productivity shock. Finally, we impose the differential productivity shocks presented in Table 1 on the economy of 2007 to examine how the Indian economy reacts to these climate change impacts when we assume no water scarcity.

Experiment II: *Impacts of climate changes in the presence of water scarcity.*

This experiment examines the joint impacts of water scarcity and changes in crop yields due to climate change for the economy of India in 2030. To construct this experiment the projected changes in available water for irrigation (presented in Figure 6) were added to the closure of the first experiment as exogenous shocks in supply of water for irrigation and allowed the model to determine the price of water endogenously. In this experiment supply of water for non-agricultural uses remained constant.

4. Results

4.1. Experiment I

Impacts on demand for water

In this experiment, demand for water (including both agricultural and non-agricultural uses) at the national level increases slightly by 0.4% (about 2.3 billion cubic meter (BCM)) compared to the base year due to changes in the relative productivities of rainfed and irrigated crops induced by climate change. However, the impacts vary significantly across river basins as shown in Table 2. As shown in this table demand for water in Brahmaputra, Brahmari, and Godavari goes up by

about 4 BCM, 6.4 BCM and 9 BCM compared to the base year, respectively. While it drops in Ganges and Luni by 10 BCM and 8.2 BCM compared to the base year, respectively. Hence, when water supply is not limited, climate change can significantly alter the demand for water by river basin. In some river basins the size of change is relatively large compare to base year. For example, in Brahmaputra demand for water goes up by about 41.9%, while in Luni it goes down by 41.2%. In the next section we show how water scarcity affects these changes. Table 1 also indicates that the imposed crop productivity chocks affect the demand for water in both agricultural and non-agricultural uses. The impacts on non-agricultural uses represents secondary general equilibrium impacts of changes in the supply side of the economy due to changes in agricultural sectors.

Impacts on crop production

When there is no water scarcity and additional water is available at a constant price, changes in the rainfed and irrigated relative yields induced by climate change alter the mix of irrigated and rainfed crops in market at the national level as shown in first column of Table 3. This table indicates that, if water is available, climate change will encourage paddy rice farmers to shift to irrigation at the national level. For other crops, climate change will promote rainfed farming again at the national level. This means when water is available climate change encourage farmers in India to produce more irrigated rice, a very water intensive crop, which is the main crop in this county. One can examine these changes at the RB-AEZ level across India using the simulation results as well. In the next section we indicate how water scarcity could alter this picture.

Some macro impacts

When water is available, changes in irrigated and rainfed crop yields induced by climate change increases demand for irrigation which in return boosts irrigated crop outputs and that has some positive economic impacts. Climate change also could improve some rainfed yields which

will generate economic gains. Of course in some river basins or AEZs, climate change negatively hits crop yields with some negative economic losses. Our simulation results indicate that if there is no restriction in water scarcity, the economy of India will gain from changes in crop yields induced by climate change. For example, climate change could increase GDP of India by about 0.16% and reduce consumer price index by 0.1% compared to the base year. This will improve India's welfare by about 1.86 billion $ per year. Hence, if water is available, climate change may not hurt India's aggregate agricultural sector until 2030. However, as we see in the next section, when we factor in water scarcity, we will see a very different story.

4.2. Experiment II

Impacts on water demand and price

In the presence of water scarcity, demand for irrigation drops to meet the restricted water supply as presented in Figure 6. In the previous section, we learned that climate change increases demand for irrigation (by 0.3%) at the national level. However, in the presence of water scarcity the available water for irrigation is expected to drop by %5.1 in 2030 compared to base year at the nation level. Hence, water scarcity blocks the demand for irrigation and increases the opportunity costs of water across India. Since the intensity of water scarcity varies among river basins and water cannot move freely over them, the shadow price of water will change at different rates across river basins as shown in Figure 7. This figure indicates that the price of water for irrigation changes from 12% (in Luni) to 44% (in Brahmaputra).

Impacts on crop and food outputs and prices

Reductions in available water for irrigation which increases the shadow price of water encourages farmers to shift, at the margin, from high to low water intensity crops. Table 3

compares the changes in crop outputs for the two simulations which we examined in this paper. This table shows that when water for irrigation is limited, irrigated crops, in particular water intensive items, fall down more. For example, when water for irrigation has no limit, climate change reduces productions of paddy rice (by 630 thousand metric tons) and wheat (by 1 thousand metric tons) in favor of expansions in coarse grains (by 485 thousand metric ton) oilseeds (by 2871 thousand metric ton. However, when we add the reduction in water supply, the output of paddy rice and wheat (two main irrigated crop in India) fall by 3,153 thousand metric tons and 1,586 million metric tons. This shows water scarcity cuts supplies of water intensive crops.

Climate change and water scarcity jointly reduce food production in India by $2,132 million in 2030 compared to the base year. In addition, these factors increase the net food imparts of this country by about $572.7 million again 2030 compared with the base year. Assuming a linear trend, the total reduction in food production between 2007 and 2030 adds up to about $25.6 billion. The sum of additional net food imports due to water scarcity, over this entire time period is expected to be about $6.6 billion. These figures indicates that while water scarcity negatively affects domestic food production, increased international trade (net food import) could eliminate about 26 percent of this reduction. Hence, trade partially mitigates the negative impacts of water scarcity on food security. Trade could reduce the adverse impacts of climate extremes as well.

Changes in crop yields induced by climate change plus water scarcity jointly alter the prices of paddy rice, wheat, coarse grains, oilseeds, sugar crops, and other crops by 10%, 3%, -3%, -5.3, 7.8%, and 1.3% in 2030 compared to the base year. These figures indicate that climate change and water scarcity affect crop prices in different direction. For example, while the price of paddy rice goes up by 10%, the price of oilseeds drops by 5.4% due to these factors. Our simulation results indicate that these price impacts would be much higher in the absence of trade.

Land use impacts

Climate change and water scarcity could affect distribution of available land across forest, pasture, and cropland and also reallocate the exiting cropland between irrigated and rainfed crops all across India's river basins and AEZs. These factors jointly increase demand for cropland by 239 thousand hectares at the national level with reductions in forest (by -116 thousand hectares) and pasture land (by 123 thousand hectares) as shown in Table 4. Hence, water scarcity and climate change could jointly increase deforestation in India. A large portion of these changes is expected to occur in a few river basins including Ganges, Indus, and Brahmari with increases in cropland by 128 thousand hectares, 59.8 thousand hectares, and 25.1 thousand hectares, respectively (Table 4). As shown in Table 5, climate change and water scarcity increase demand for cropland in a few AEZs mainly AEZ2, AEZ4, and AEZ8 to AEZ11 with relatively larger length of growing period and higher moistures. Three maps are prepared to represent changes in forest, cropland, and pasture at the river basin level for India. Figure 8 represents these maps which show potentials for deforestation in north of India and reforestation in south.

As mentioned before in this paper, relative changes in rainfed and irrigated yields induced by climate change increase the demand for irrigation. However, water scarcity squeezes this demand and forces farmers to shift to producing rainfed crops. Here, we investigate the extent to which water scarcity can alter the mix of irrigated and rainfed cropland. First, consider the changes in harvested areas of irrigated and rainfed crops by river basin in Figure 9 between the time period of 2007-2030. As shown in this figure irrigated harvested area is expected to drop significantly in Ganges (by 2.5 million hectares), Krishna (by 1.1 million hectare), and 0.7 million hectares) in favor of expansion in rainfed harvested area. These shifts from irrigation to rainfed cropping will significantly magnify the vulnerability of Indian agriculture to adverse weather events. As

mentioned before while the existing projections indicates that climate change will not greatly affect average crop yields in India until the middle of 2030s, it is frequently argued climate change will increase frequency of extreme weather events. Hence, the lack of water for irrigation which increases the share of rainfed cropping in combination with higher volatility in weather condition could negatively affect the food security of India.

Now, consider changes in the mix of irrigated and rainfed harvested areas by AEZ as shown in Figure 10. This figure shows that the largest shifts are expected to see in AEZ2, AEZ3, AEZ4, AEZ8, and AEZ9 with longer length of growing time period and more moisture. Finally, consider the maps of changes in the mix of rainfed and harvested area at the by river basin in Figure 10.

Economy wide impacts

Earlier in this paper, we showed that if there is no water scarcity, changes in crop yields induced by climate change could prompt irrigation and that generates some economic gains and improves welfare. We now show that introducing water scarcity will greatly alter this picture. Reduction in water for irrigation due to expansion in non-agricultural uses of water and lack of water infrastructure will negatively affect output of agricultural sector which has a relatively large share in Indian economy and that leads to reductions in outputs of industrial and service sectors with an overall reduction in GDP by 0.28% and an increase in the consumer price index by about 0.4% in 2030 compared to the base year. The overall negative welfare impact of water scarcity is expected to be about $3.2 billion (at 2007 prices) in 2030. With a 3% discount rate, the net present value of annual reductions in welfare due to water scarcity between 2007 and 2030 will be about $24.3 billion at 2007 prices. These wide economy impacts do not cover the adverse impacts of extreme weather events induced by climate change.

5. Conclusions

In this paper we first examined the impacts of changes in the irrigated and rainfed crops yields induced by climate change on demand for water. We showed that the impacts of climate change on crop yields vary across crops and agro ecological zones. From this experiment we learned that, if water for irrigation is available, climate change alone may not significantly hurt the long run trends in crop yields until the middle of 2030s. However, we understand that climate changes could increase risks of extreme weather event. From the first experiment we also learned that while changes in irrigated and rainfed crop yields induced by climate change surge demand for irrigation in some river basins (mainly in Brahmaputra, Brahmari, and Godavari), they reduce demand for irrigation in some other river basins (mainly Ganges and Luni). We also showed that, if water for irrigation is not limited, climate change alone could moderately increase agricultural outputs at national level and that leads to some welfare gains.

Then we examined the combined impacts of effect of climate change and water scarcity on India's agricultural activities and their economy wide consequences. We showed that water scarcity, induced by expansion in water demand in non-agricultural uses and lack of water infrastructure, will block the demand for irrigation and that generate significant negative impacts on the economy of India. Our detailed analyses indicate that:

- The extent of future water scarcity varies across river basins. Water scarcity is expected to be most significant in Luni, Eastern-Ghats, Krishna, Chotanagpui, Ganges, and Indus by 2030.

- Water scarcity is expected to increase the shadow price of water for irrigation across India different rates, ranging from 44% to about 11%.

- Water scarcity will decrease production of rice and wheat, two major staple crops in India.

- Climate change and water scarcity jointly reduce food production of India by $2,132 million in 2030 compared to the base year. In response to this reduction, imports of food will be increased about $572.7 million again 2030 compared with the base year.

- Prices of paddy rice, wheat, sugar crops and other crops are expected to increase, while prices of coarse grains and oilseeds may drop.

- A portion of crop production is expected to shift from irrigation to rainfed cropping due to water scarcity. This will magnify the exposure to drought and heat extremes in the future.

- The overall welfare losses due to water scarcity (evaluated at 2007 price) is expected to be about $3.2 billion in 2030.

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Table 1: Percent changes in rainfed crop yields versus their irrigated counterpart due to climate change in India by AEZ in 2007-2030

AEZ	Paddy rice	Wheat	Corn	Soybeans
1	8.8	4.1	24.2	11.3
2	30.4	7.0	48.8	50.0
3	-11.8	0.3	-16.9	21.8
4	-24.6	3.5	-3.7	14.0
5	-16.4	2.8	-43.5	-9.2
6	-50.0	-5.5	-50.0	-22.1
7	24.9	9.5	19.8	1.0
8	47.1	0.9	50.0	50.0
9	18.6	-1.7	8.4	50.0
10	13.1	-1.9	50.0	50.0
11	32.4	-3.3	50.0	50.0
12	50.0	-8.1	-6.4	50.0
13	0.0	-2.2	0.0	0.0
14	0.0	-15.5	0.0	0.0
15	0.0	-20.8	19.6	-17.8
16	-50.0	-48.5	50.0	43.6
17	0.0	0.0	0.0	0.0
18	0.0	0.0	0.0	0.0

Table 2: Changes in water demand by river basin induced by changes in rainfed and irrigated yields due to climate change, 2007-2030

Basin	Change in billion cubic meters			% Change compared to base year		
	Water used in agriculture	Water used in Non-agriculture	Total	Water used in agriculture	Water used in Non-agriculture	Total
Brahmaputra	2.4	1.6	4.0	45.1	37.8	41.9
Brahmari	5.2	1.2	6.4	30.5	24.5	29.1
Cauvery	-0.4	-0.2	-0.5	-4.0	-5.4	-4.3
Chotanagpui	1.4	1.0	2.4	16.8	17.3	17.0
Easten_Ghats	1.9	0.3	2.2	21.1	17.2	20.5
Ganges	-8.2	-1.8	-10.0	-3.3	-4.2	-3.4
Godavari	7.9	1.2	9.0	16.1	13.4	15.7
India_East_Coast	-1.1	-0.4	-1.4	-7.2	-9.8	-7.7
Indus	0.2	-0.2	0.0	0.2	-3.3	0.0
Krishna	-1.0	-0.3	-1.3	-1.9	-3.1	-2.1
Langcang_Jiang	0.0	0.0	0.0	76.8	68.6	72.2
Luni	-6.7	-1.4	-8.2	-40.4	-45.8	-41.2
Mahi_Tapti	-1.4	-0.4	-1.9	-4.1	-6.5	-4.5
Sahyada	1.5	0.4	2.0	7.6	4.2	6.5
Thai_Myan_Malay	0.0	0.0	0.0	19.7	15.7	17.6
Others	-0.1	0.0	-0.1	-1.2	-5.3	-1.2
Total	1.8	0.9	2.7	0.3	0.8	0.4

Table 3. Changes in crop production due to climate change with and without water scarcity, 2007-2030 (1000 metric ton)

Crops	With no water scarcity	With water scarcity
Irrigated paddy rice	10,179.0	4,493.5
Rainfed paddy rice	-10,808.7	-7,647.0
Total	-629.7	-3,153.4
Irrigated wheat	-218.7	-2,292.6
Rainfed wheat	217.9	706.3
Total	-0.9	-1,586.4
Irrigated coarse grains	-1,492.8	-2,608.8
Rainfed coarse grains	1,977.5	2,835.5
Total	484.6	226.8
Irrigated oilseeds	-4,198.7	-5,840.9
Rainfed oilseeds	7,069.7	8,036.2
Total	2,871.0	2,195.3
Irrigated sugar crops	-20.6	-5,470.3
Rainfed sugar crops	339.1	2,406.3
Total	318.5	-3,063.9
Irrigated other crops	-1,547.1	-8,564.2
Rainfed other crops	2,112.5	6,343.6
Total	565.4	-2,220.6

Table 4: Land use changes induced by climate change and water scarcity by river basin, 2007-2030 (figures are in thousand hectares)

Basins	Forest	Cropland	Pasture
Brahmaputra	10.7	-8.9	-1.7
Brahmari	-18.9	25.1	-6.2
Cauvery	-1.5	1.2	0.3
Chotanagpui	-8.0	8.1	-0.1
Easten_Ghats	-2.5	2.3	0.1
Ganges	-66.2	128.4	-62.1
Godavari	-2.4	-1.6	4.0
India_East_Coast	0.0	-0.8	0.8
Indus	-12.8	59.8	-47.0
Krishna	3.9	-10.8	6.8
Langcang_Jiang	0.0	0.0	0.0
Luni	-1.9	13.2	-11.3
Mahi_Tapti	-10.1	15.1	-5.1
Sahyada	-5.0	5.6	-0.7
Thai_Myan_Malay	0.1	-0.2	0.0
Others	-1.6	2.4	-0.8
Total	-116.2	239.0	-122.8

Table 5: Land use changes induced by climate change and water scarcity by AEZ, 2007-2030
(figures are in thousand hectares)

AEZs	Forest	Cropland	Pasture
AEZ1	0.0	0.4	-0.4
AEZ2	-20.6	53.5	-32.9
AEZ3	-13.5	4.6	8.9
AEZ4	-38.2	38.4	-0.1
AEZ5	10.9	-12.2	1.3
AEZ6	10.0	-11.5	1.5
AEZ7	0.0	1.2	-1.2
AEZ8	-15.0	47.0	-32.0
AEZ9	-19.2	33.5	-14.2
AEZ10	-12.7	42.7	-30.0
AEZ11	-10.8	34.0	-23.2
AEZ12	-7.2	7.4	-0.2
AEZ13	0.0	0.0	0.0
AEZ14	0.0	-0.1	0.1
AEZ15	0.0	0.3	-0.3
AEZ16	0.0	0.0	0.0
AEZ17	0.0	0.0	0.0
AEZ18	0.0	0.0	0.0
Total	-116.2	239.0	-122.8
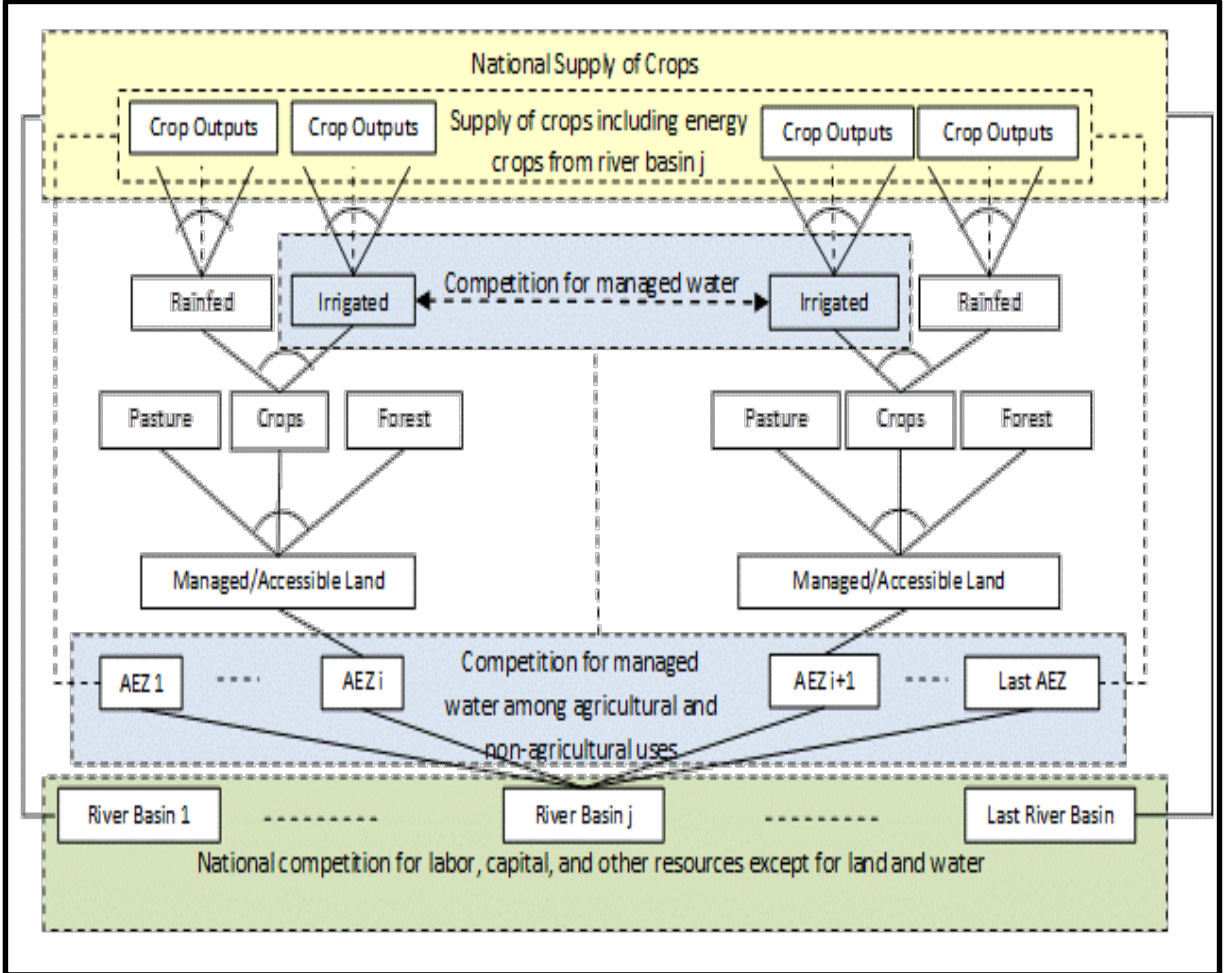
Figure 1: Structure of the GTAP-BIO-W model
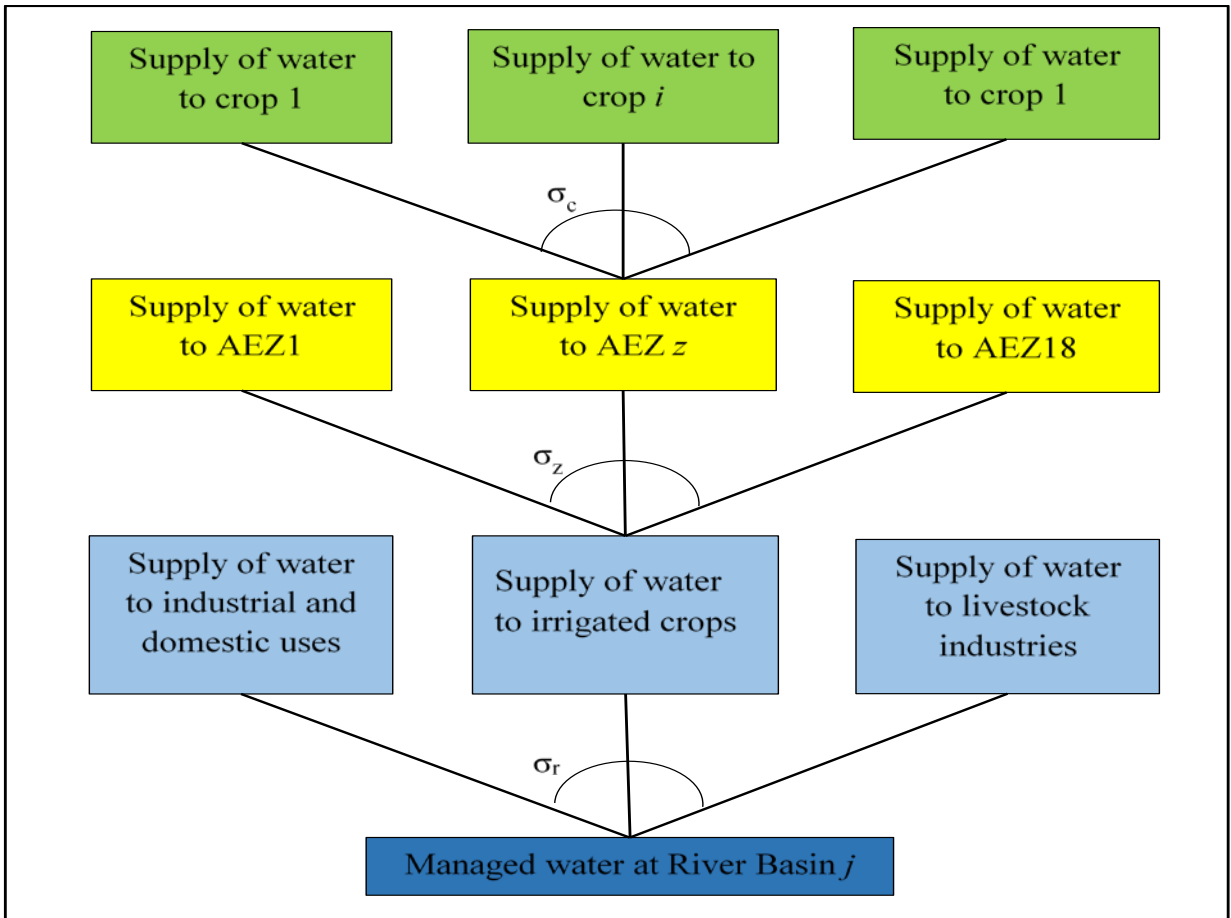
Figure 2: Water supply in the new GTAP-BIO-W model
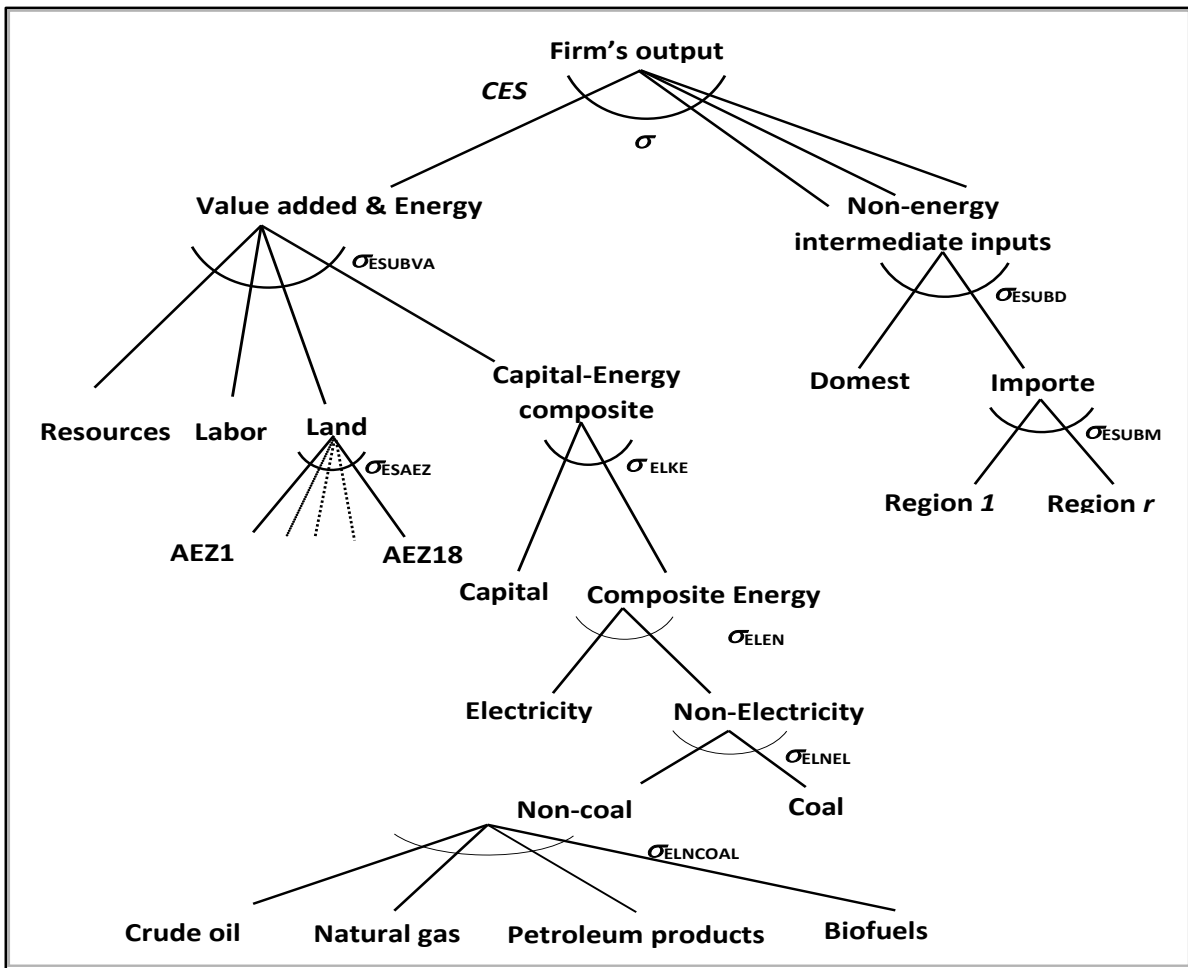
Figure 3: Production function and input demand structure in GTAP-BIO model
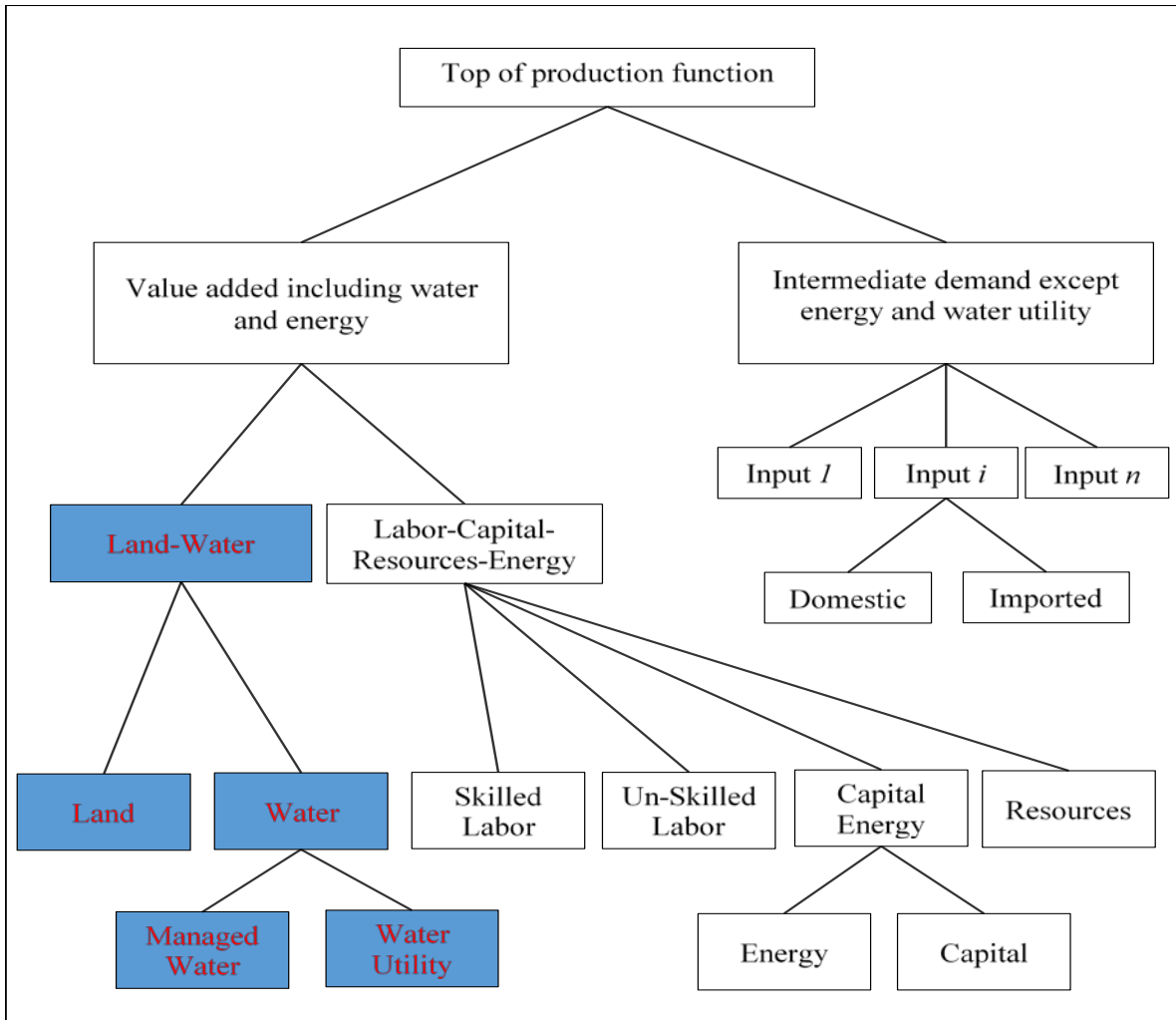
Figure 4: Production function and input demand structure in new GTAP-BIO-W model
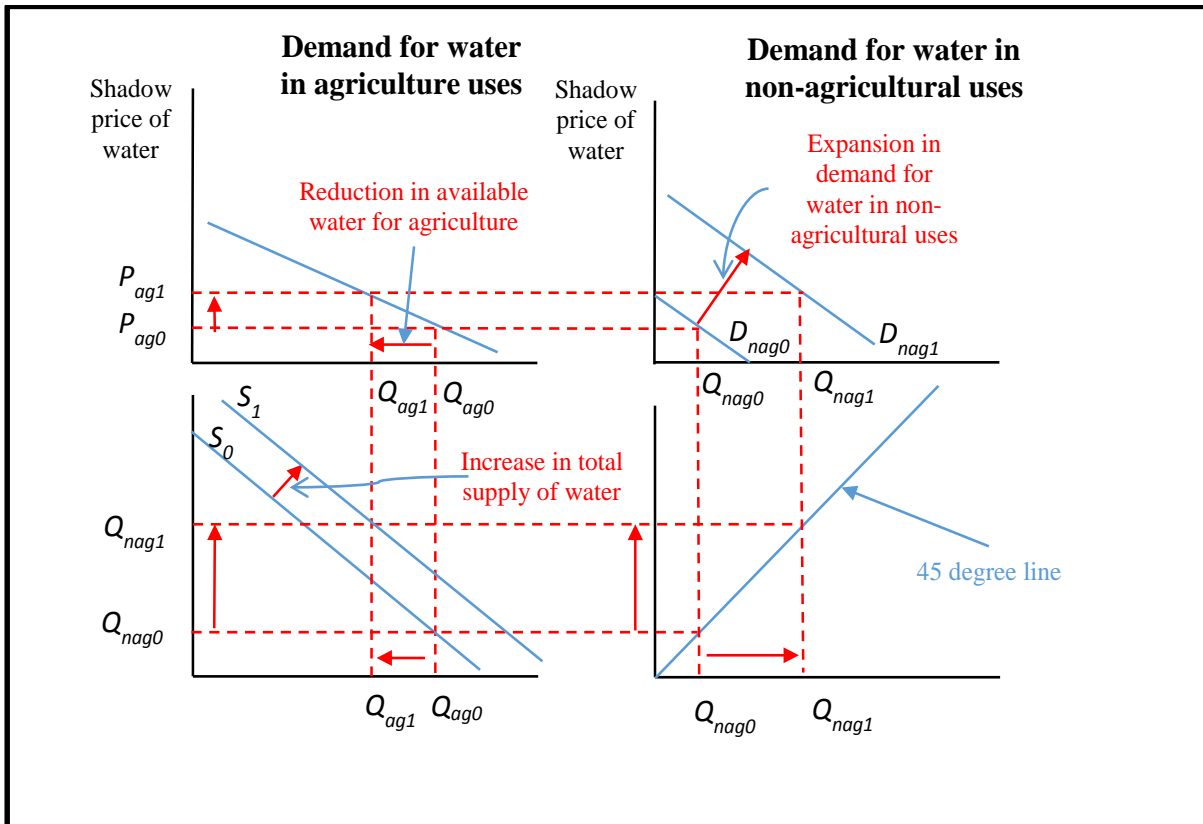
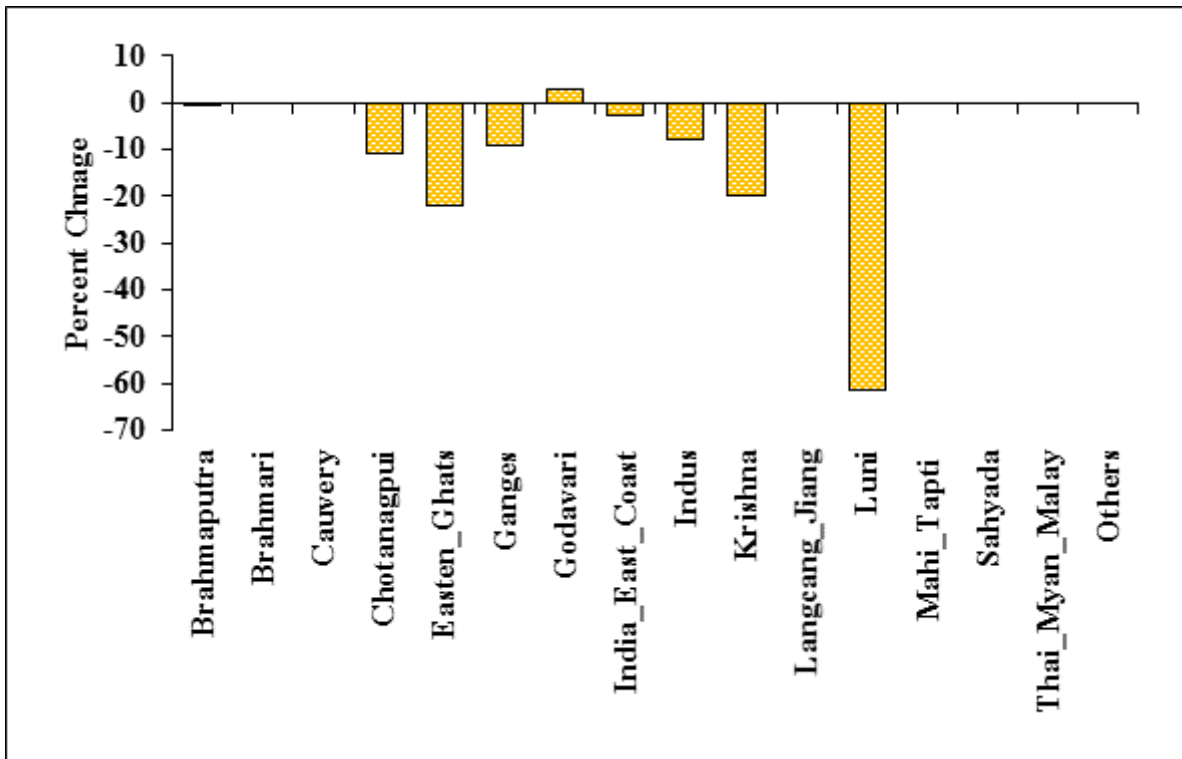Figure 5. Competition for water among agricultural and non-agricultural users

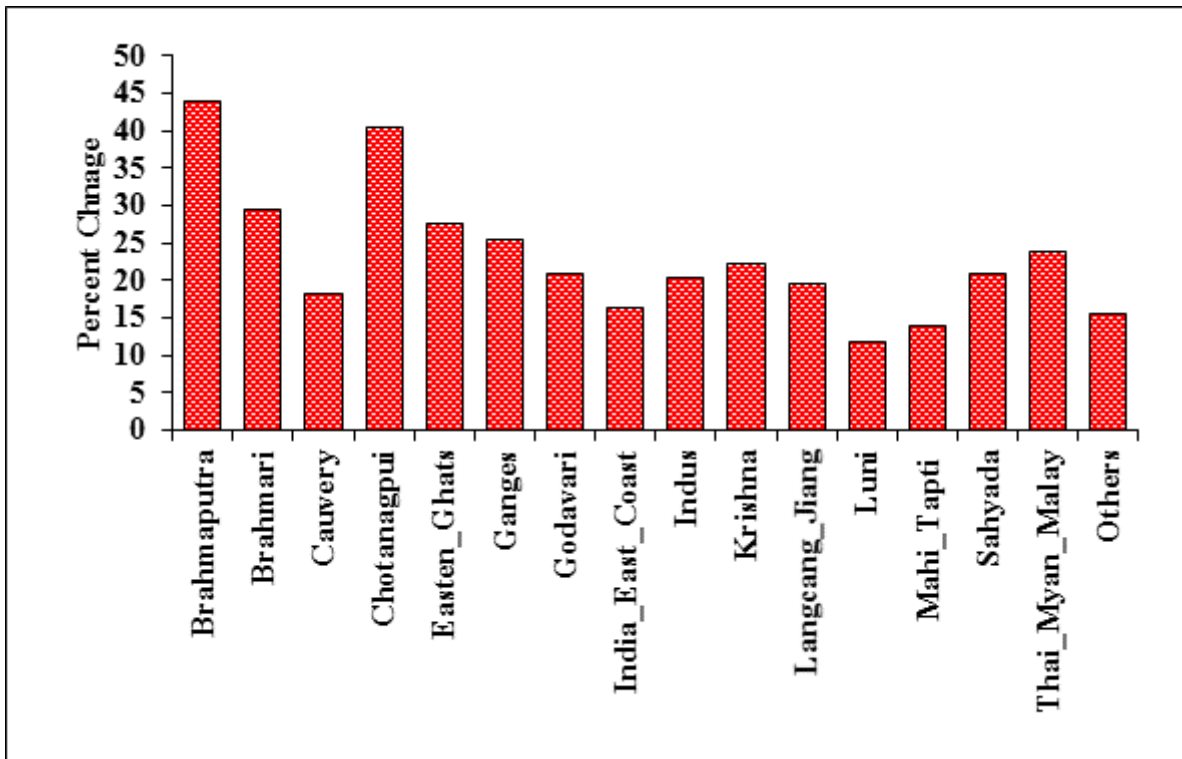Figure 6: Projected %change in available water for irrigation in India by river basin in 2007-2030

Figure 7: Impacts of water scarcity on the shadow price of water for irrigation by river basin, 2007-2030
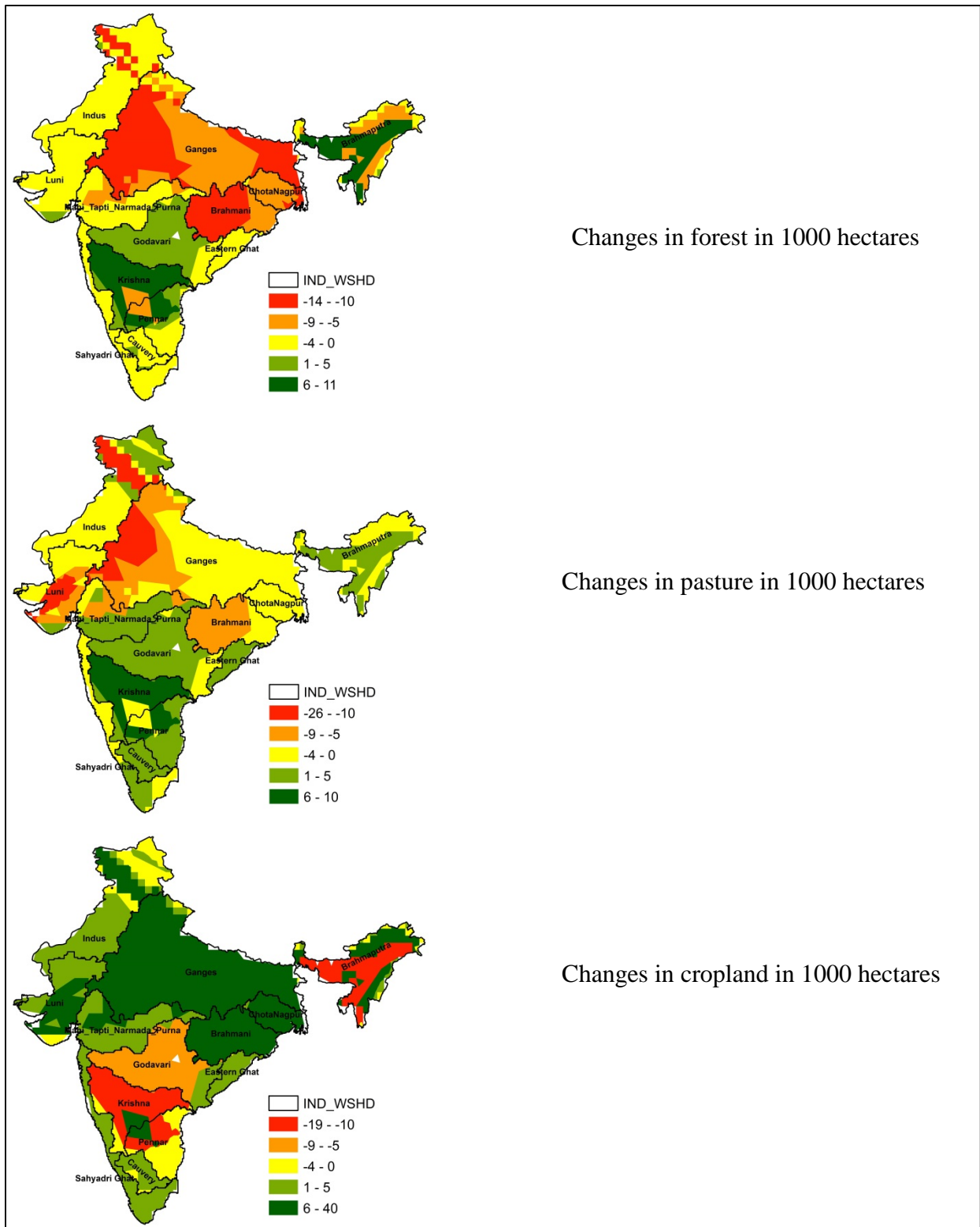
Changes in forest in 1000 hectares

Changes in pasture in 1000 hectares

Changes in cropland in 1000 hectares

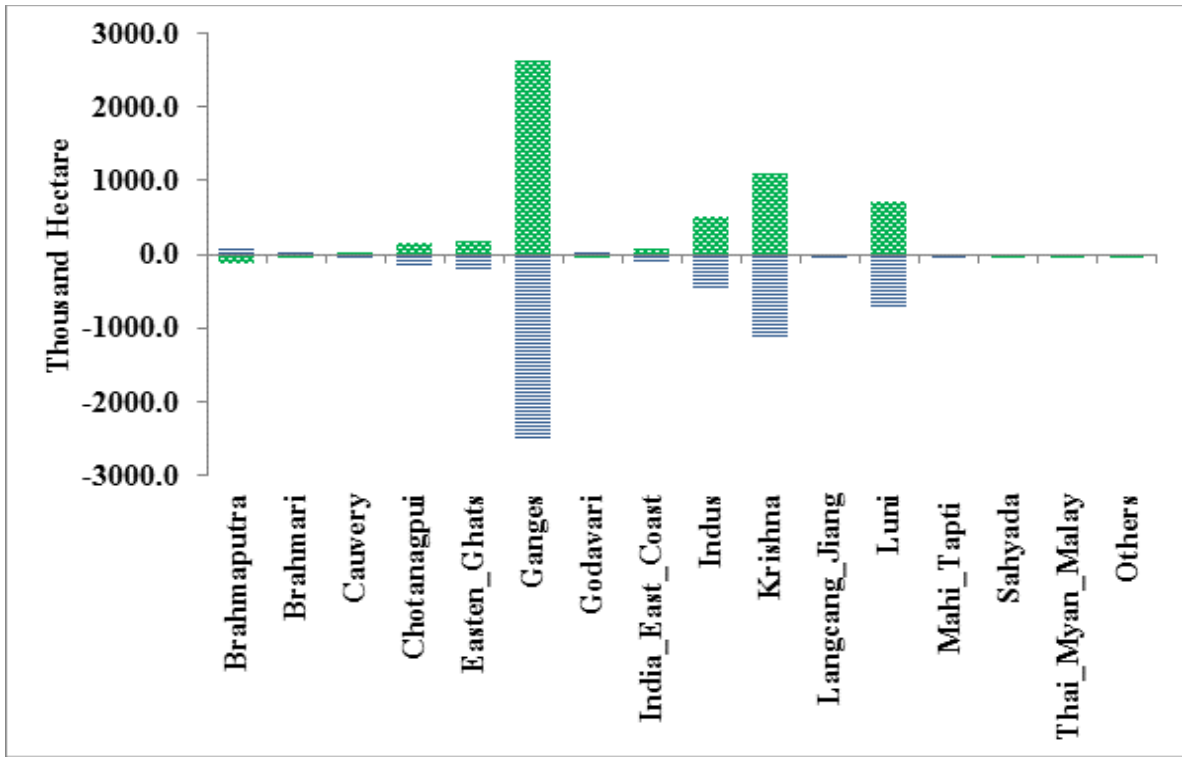Figure 8: Changes in forest, pasture, and cropland induced by climate change and water scarcity, 2002-2030.

Figure 9: Change in rainfed and harvested areas induced by climate change and water scarcity by river, 2007-2030 (figures are in thousand hectares)
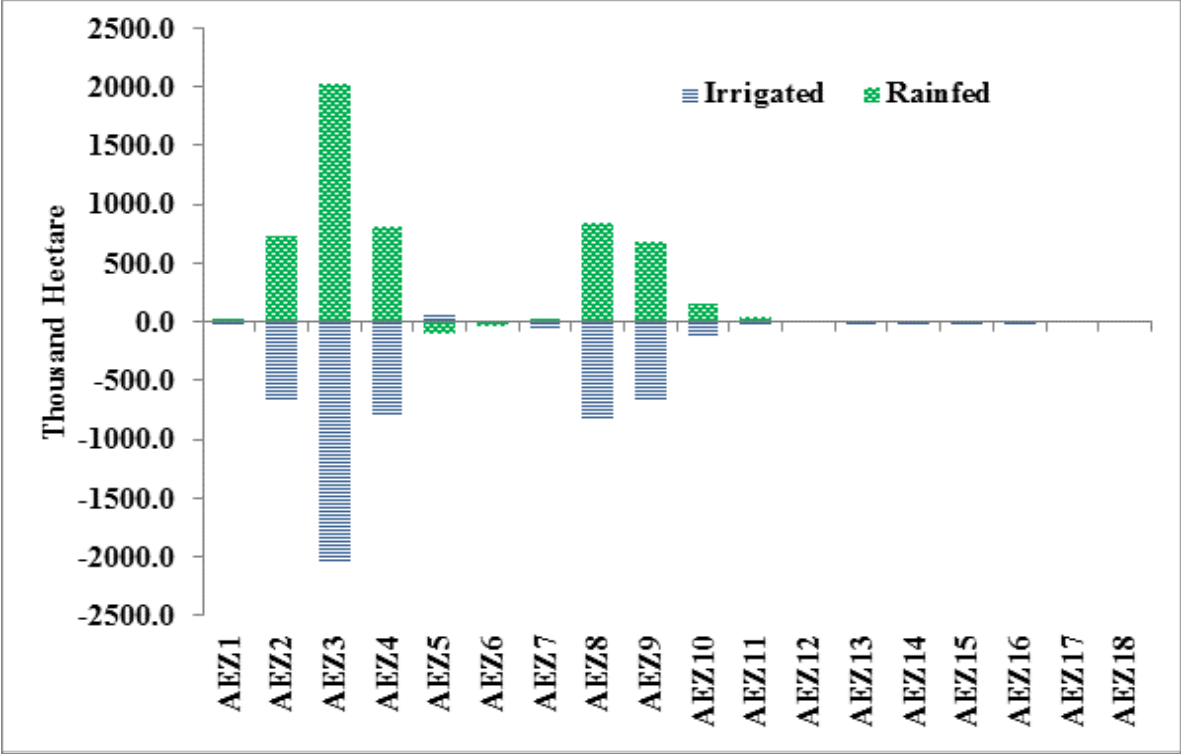
Figure 10: Change in rainfed and harvested areas induced by climate change and water scarcity by AEZ, 2007-2030 (figures are in thousand hectares)

Changes in rainfed area in 1000 hectares

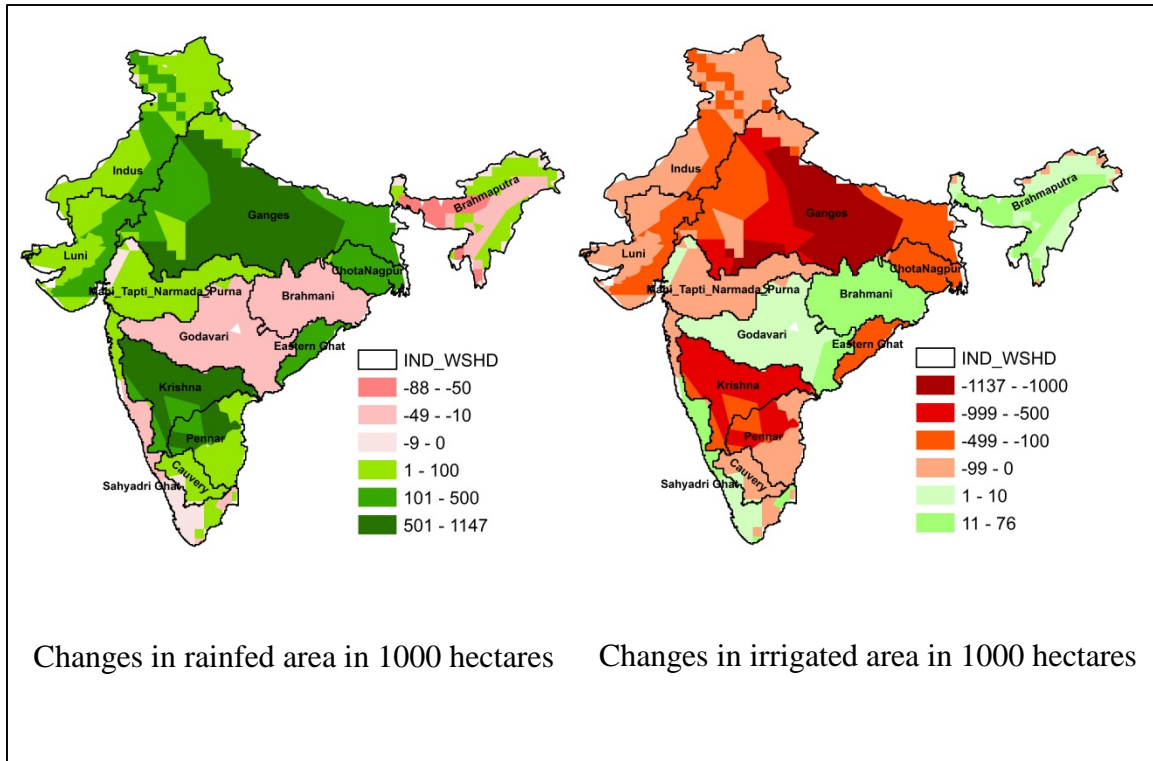Changes in irrigated area in 1000 hectares

Figure 11: Changes in irrigated and rainfed harvested areas induced by climate change and water scarcity at River basin level, 2002-2030.