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Economic consequences of climate change impacts on South Asian agriculture: A computable general equilibrium analysis

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Abstract

South Asia is one of the most vulnerable regions of the globe in terms of climate change, with agriculture the most affected economic sector of the region. This study employs an environmental Global Trade Analysis Project model to simulate the impact of an average global 2°C temperature increase by 2050, with a focus on South Asian countries. The economic costs of climate change in relation to crop productivity losses due to increasing temperature, land productivity losses caused by rising sea levels and heat stress-induced agricultural labour productivity losses are assessed based on model simulations. The results show that the unfavourable climate change impacts on agricultural productivity (crop, land and labour) will reduce food production and create upward pressure on food prices. This will lead to a reduction in food consumption at the household level, threatening future food security in the region. The results further predict a contraction in all South Asian economies by 2050, due to adverse climate change impacts on the agricultural sector. In addition, out of the three climate change damage factors considered, labour productivity causes the greatest economic losses, while land productivity losses caused by rising sea levels impact the least. The study also found that low-income countries would suffer most severely due to the impacts of climate change on the agricultural sector, while high-income countries would be impacted the least.

KEYWORDS
climate change, computable general equilibrium, crop productivity losses, labour productivity losses, sea level rise, South Asia

JEL CLASSIFICATION
C68, E6, Q11, Q54

1 | INTRODUCTION

While the global temperature increased on average by 0.08°C per decade since 1880, the rate of warming over the past four decades has more than doubled, averaging 0.18°C per decade (Lindsey & Dahlman, 2020). If the current emission trend continues, the global temperature will increase by 5°C or more by the end of this century (Intergovernmental Panel on Climate Change, 2007; Wuebbles et al., 2017).

Weather and climate are also the key direct determinants of crop yields and, hence, food production in the agricultural sector (Aryal et al., 2020; Cai et al., 2016). Although there is evidence that temperature increases can enhance the yields of particular crops under certain conditions, when the optimal temperature for growth and reproduction of a crop is exceeded, yield will decline. Climatic factors and weather are the determinants of the start and duration of growth seasons (Fiwa et al., 2014; Lemma et al., 2016). Additionally, climatic factors determine the magnitude and duration of heat and water stress in crops (Schauberger et al., 2017). Global warming is also projected to result in changes to agricultural land areas via an overall increase of between 0.2 m and 1.1 m of sea level by the end of this century (Lindsey, 2018; Wuebbles et al., 2017). Moreover, the negative impact of heat stress on the agricultural labour force will reduce production (Orlov et al., 2020; Roson & Sartori, 2016b).

Although agricultural vulnerability to climate change varies regionally, the above factors are critical in determining the economic impacts of climate change on national agricultural sectors and the consequences for global food security and rural livelihoods (Schmidhuber & Tubiello, 2007). In particular, populations of developing nations are likely to be most affected (Elbehri & Burfisher, 2015; Nelson et al., 2009).

South Asia is home to approximately 1.8 billion people, has a high population growth rate and nearly a third of the regional population still live below the poverty line. Although local GHG emission levels remain comparatively low, the region has been identified as one of the most vulnerable to climate change (Ahmed & Suphachalasai, 2014; World Bank, 2013, 2022). The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report Regional Fact Sheet for Asia projects heat waves, humidity and heat stress of far greater intensity and frequency than current levels for the remainder of the 21st century, as well as increases in monsoonal precipitation and interannual variability (Chaturvedi et al., 2022). Increased regional oceanic temperatures and a decline in mountain glaciers are also predicted (Sivakumar & Stefanski, 2010). The negative impact of climate change on the South Asian economy is predicted to exceed the global average (7% loss in GDP), mainly due to the crucial role that agriculture plays in the South Asian regional economy, with the projected potential losses of GDP by 2099 being: Bhutan 18%, Nepal 13%, India 10% and Pakistan 10% (World Bank, 2021a).

Nearly 65% of the South Asian population, and the majority of its poor, live in rural areas dominated by agriculture. Overall, the sector contributes 18% of the South Asian regional GDP and provides 42% of total employment, constituting the largest source of regional employment (World Bank, 2021b). Several research studies have revealed that crop production in many Asian countries has declined due to changes in climate. Future climate change is likely to multiply these impacts, increasing the risk of hunger and food insecurity, and putting upward pressure on market prices of agricultural products (Aryal et al., 2020; Cai et al., 2016; Gupta et al., 2017; Prasai, 2010). Moreover, sea level increases in the South Asian region threaten low-lying coastal areas such as the Maldives, Sri Lanka, Bangladesh, and several cities in India, decreasing the extent of productive land in these areas (Sivakumar & Stefanski, 2010). Given this current state of affairs and future projections, it is clear that the heavily agriculturally dependent South Asian economies are at grave risk from climate change impacts, warranting comprehensive analyses of the economic and social impacts of climate change in this region.

A quantitative model of economic behaviour is essential in such an analysis as it can effectively trace the various mechanisms through which the consequences of changing climate can impact society (Nelson & Shively, 2014). A general equilibrium formulation of the model can quantify the second-order, or indirect effects based on interdependencies between the economic and other sectors, via the relevant variations in related price changes (Roson & Sartori, 2016a). For this reason, computable general equilibrium (CGE) models have been widely used to analyse the economic impacts of climate change on national and regional agricultural sectors (Bandara & Cai, 2014; Bosello et al., 2012; Cai et al., 2016; Costantini et al., 2018; Khan et al., 2020; Kompas et al., 2018; Pradhan & Ghosh, 2019). Moreover, global CGE models are more suitable for such assessments than single-country models as they capture the direct and indirect inter-regional effects induced by climate change shocks, identifying the gains and losses to particular countries and the comparative national and regional consequences. This study employs a global CGE model known as the GTAP-E, which is an extension of the base model Global Trade Analysis Project (GTAP).

The general objective of the study was to analyse the economic impacts of climate change-induced productivity changes (crop, land and labour) on the agricultural sector. Specific objectives were to analyse the impact of climate change-induced productivity changes in agricultural products (food crops), and the impact on future food prices and food security in the five largest South Asian countries; to identify the impact of rising sea levels on land productivity and the consequences for the South Asian economies; and to evaluate how heat-induced agricultural labour productivity losses could impact on the economic structures of the South Asian region.

The next section of this work reviews the literature on CGE assessments of the impacts of climate change on agriculture. The GTAP-E modelling framework used in the study and the simulation designs are then outlined, and the findings given. The final section comprises concluding observations.

2 | LITERATURE REVIEW

Examining the impacts of climate change on crop productivity and possible adaptation strategies for 12 regions of the world, Lobell et al. (2008) used statistical crop models and climate projections for 2030, coupled with 20 general circulation models. The study indicates that food crops in South Asia need immediate adaptation measures to avoid negative effects. Hertel et al. (2010) analysed the economic and welfare implications of climate change for crop productivity by 2030 using a GTAP CGE model and revealed a decline in food production and increasing food prices in South Asia, which increased poverty levels and reduced social welfare. Bandara and Cai (2014) explored climate-induced variability in food crop productivity and its effects on food prices and food security in South Asian countries using a dynamic GTAP model. They found all countries in the region will experience reduced food production and increased food price inflation, threatening food security in the region. Cai et al. (2016) also investigated the effects of climate-induced crop productivity changes in food production and food prices in South Asia by 2040, combining a global climate model with a global economic model known as GTEM-C. Their results revealed that unfavourable climate change conditions can reduce food crop output, placing upward pressure on future food prices. Zeshan and Ko (2017) also examined the economic effects of climate change-induced crop productivity changes using the GTAP-E model and similarly found reduced food crop productivity, and consequently overall agricultural production, will increase the costs of food. They further highlighted that this will produce a contraction in South Asian economies in the longer term.

Another set of studies examined the economic effects of rising sea level-induced agricultural changes, focussing on South Asia. Bosello et al. (2012) analysed the economic consequences of a range of agricultural effects of changing climate including rising sea levels, using the intertemporal computable equilibrium model (ICES) on a global scale. They predicted an average contraction of 3.1% in GDP by 2050 due to rising sea level-induced productive land loss and other climate change-induced agricultural productivity declines in South Asian countries. Kompas et al. (2018) investigated the effects of climate change on GDP including rising sea levels, and changes in agricultural land and agricultural labour productivity, using the GTAP-INT model at the global scale. Based on an assumed 3°C temperature increase, the South Asian region will experience reductions in GDP ranging from 1.5% to 3.6% by 2047. Joshi et al. (2016) analysed the global physical and economic consequences of rising sea levels including loss of productive land, loss of capital and forced displacement of populations by 2100 using a CGE model known as GEMINI-E3 coupled with a geographical information system (GIS). They found that the global welfare loss due to the loss of productive land was minimal compared with the loss of capital and forced displacement of populations. Notwithstanding, the study identified India and South Asia more generally among the most affected regions, based on welfare losses as a percentage of household consumption.

Roson and Van der Mensbrugghe (2012) investigated the global economic impacts of a variety of climate change effects (labour productivity, sea level rise, variations in crop yields, water availability, human health, tourism and energy demand), using an integrated assessment that included a CGE and climate model. They found that at the global level, the heat stress-induced reduction in labour productivity would contribute 84% of the global damage from these climate-related effects, equating to 1.8% loss of global GDP by 2050. This effect was also the strongest in the South Asian region. Orlov et al. (2020) examined the global economic costs arising from heat-induced reduction in worker productivity by 2050 and 2100 using a dynamic CGE model known as GRACE. According to their findings, African, Southeast Asian and South Asian countries will be worst affected. Matsumoto et al. (2021) assessed the global-level economic impacts of changes in labour productivity due to heat stress using a dynamic CGE model in conjunction with an Earth system model and concluded that India will be one of the three worst-affected countries.

Babatunde et al. (2017) state that the application of CGE to climate change mitigation policy in South Asia is under-represented compared with other regions in the world.

The findings of the present study contribute to this literature in the following ways. Firstly, most of the above studies examined the impact of climate change on agriculture in the South Asian region as a whole, or specifically in India. The other large countries in South Asia have not been a focus, particularly in terms of a detailed investigation. Hence, this study uses an alternative geographical disaggregation—South Asian countries, other high-income countries, middle-income countries and low-income countries across the world. Secondly, most of the predictions to date are short term. This study predicts the economic impacts of climate change-induced productivity shifts in South Asia for 2050, enabling policymakers to develop longer term strategic plans.

3 | METHODOLOGY

3.1 | GTAP-E Model

The GTAP-E is an extension of the GTAP model (Burniaux & Truong, 2002; McDougall & Golub, 2007). The model captures the global economy in terms of complete commodity and income flows, and apportions available resources among economic agents such as producers, final users, exporters, importers and investors. The model construction is based on different nests that follow economic theory.

On the production side, industries absorb/demand a variety of intermediate inputs from other industries, together with endowment factors, such as land, labour capital and natural resources, for the production of goods and services. These industries minimise their production costs by allowing commodity substitutions based on price changes imposed by shocks. However, this mechanism only allows the substitution of commodities with similar functionality. Hence, the demand side of the production function is divided into constant elasticities of substitution (CES) and Leontief functions at different levels to ensure minimum production costs. In the final demand, households and the public sector make decisions in order to maximise their utility under budget constraints. Hence, the household demand for commodities is dependent on income levels and price changes, and the public sector demand on price changes only. In CGE models, we consider the basic price (without taxes) and the market price (including taxes). Producers pay taxes based on their production, export and import levels, whereas consumers pay taxes based on their consumption level. The public sector receives these taxes as revenue, while households earn income by supplying labour.

An overview of the model's production structure is given in Figure 1. At the top nest of the production function, the output is a Leontief function of nonenergy intermediate inputs and endowment factors. This allows industries to use inputs in fixed proportion to their outputs. At the Armington nest, each intermediate input is a CES combination of imported and domestic goods. At the value-added nest, land, labour, capital–energy and natural resources are combined using a CES function to produce endowment factors. The capital–energy endowment factor is a CES function of capital and energy subproducts. Energy subproducts are a CES combination of electricity and nonelectricity products, with nonelectricity another CES combination of noncoal and coal products. At the bottom level, noncoal product is a CES function of crude oil, gas and petroleum products (Figure 1).

Since GTAP-E is the energy–environmental version of the GTAP model (which is more suited to trade issues), it can be used to analyse the economic consequences of climate change effects and policies. Kremers et al. (2002) have discussed the suitability of the GTAP-E model for climate change policy analysis in detail. The applications of the GTAP-E model on the impacts of climate change are abundant; for example, see Zeshan and Ko (2017), Bosello et al. (2006), Roson (2003), Ludena and Mejia (2010) and Nijkamp et al. (2005).

3.2 | Database

The database employed in this study is the GTAP-E version 10 for 2014 (Aguiar et al., 2019). The GTAP-E version 10 represents 141 countries/regions and distinguishes 65 sectors and eight production factors. For simulation, we divided the world into 10 regions (Table 1). Production in each region was aggregated into 16 sectors (13 industries: rice, wheat, cereals, other food crops, animal-based products, forestry, fisheries, coal, oil, gas, oil products, electricity, energy-intensive industries, agriculture-based manufacturing industries, other manufacturing industries and service sector), while labour was disaggregated into three categories (skilled, unskilled and agricultural). Since the GTAP-E version 10 represents the world economy in 2014, the entire database was updated for 2050 following Siriwardana and Nong (2021).

To update the entire database from 2014 to 2050, we used the macroeconomic forecasts on GDP and population associated with the Shared Socioeconomic Pathway 2 (SSP2) (Table 1). This provides a middle-of-the-road scenario for the 21st century in terms of economic development, population growth, land use and energy consumption (IIASA, 2018). These variables

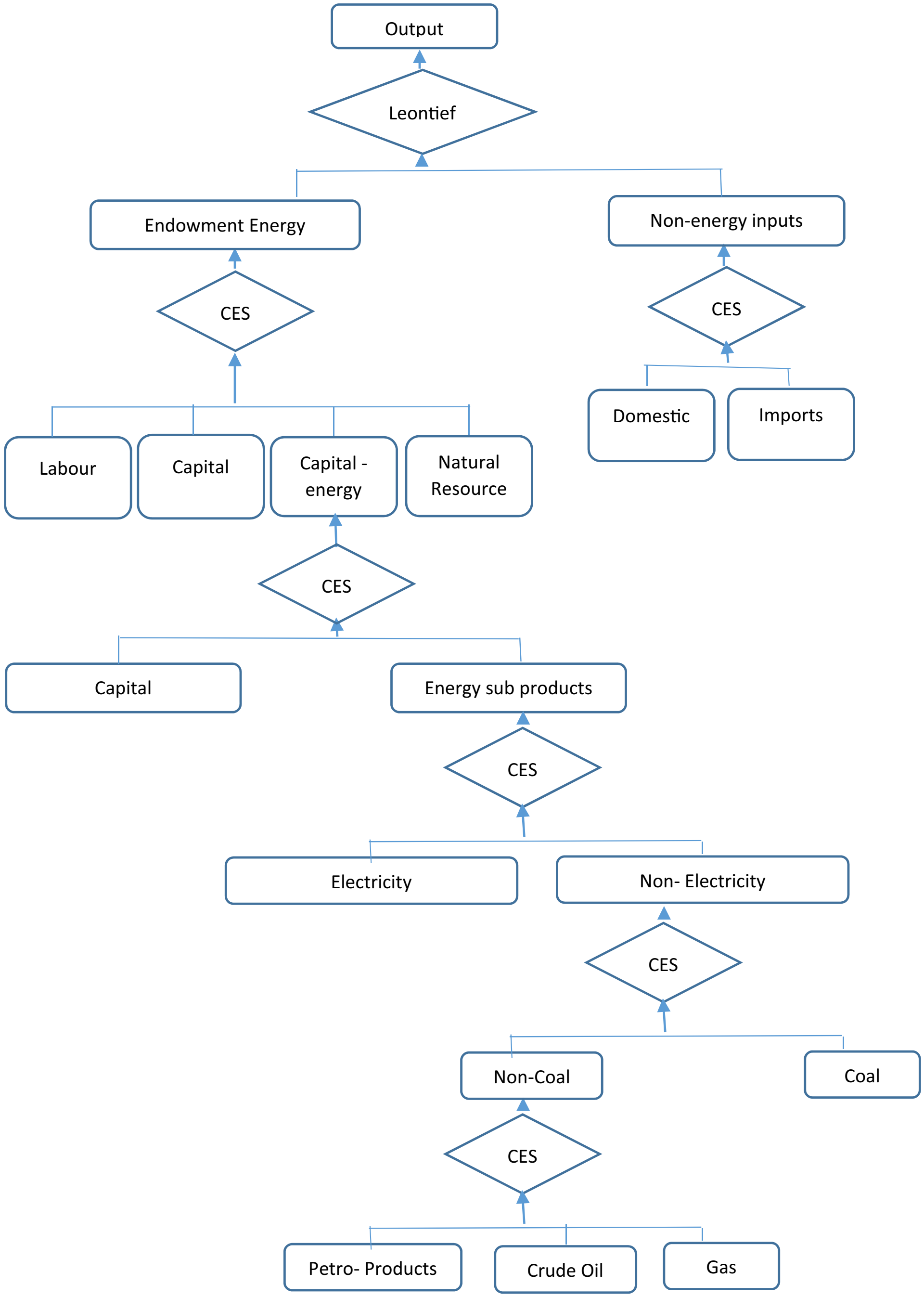

FIGURE 1 Production structure of the GTAP-E model. [Colour figure can be viewed at wileyonlinelibrary.com]

(GDP and Population) were shocked exogenously to produce the world economy in 2050. The updated database was then used as the baseline scenario for 2050 in order to analyse the impacts of climate change at that point in time.

This study does not consider any adaptation scenario. It assumes that no defensive mechanism (e.g. infrastructure) is developed to prevent sea level rise, no changes in cultivation

TABLE 1 Macroeconomic growth projections used to update the GTAP-E database from 2014 to 2050 (percentage changes).

Region	GDP	POP
Bangladesh	429.545	19.277
India	395.317	28.503
Nepal	534.819	47.223
Pakistan	430.374	48.366
Sri Lanka	277.756	7.95
Rest of South Asia	445.408	58.75
High-income countries	97.289	16.531
Middle-income countries	254.157	17.265
Low-income countries	734.329	64.31
Rest of the World	326.917	31.288

Source: IIASA (2018), Samir and Lutz (2017) and Dellink et al. (2017).

methods, crop varieties or technological changes and no protective measures or acclimatisation to increasing temperature take place. The calibration for the GTAP database to 2050 does not consider any adaptation strategies or technological progress in agriculture. Therefore, the results presented in the next section indicate the worst impacts/scenarios that could happen due to climate change.

3.3 | Simulation scenarios and closure

We formulated four climate change impact scenarios:

- Scenario 1—Crop productivity changes due to increased temperature.
- Scenario 2—Agricultural land productivity changes due to rising sea levels.
- Scenario 3—Agricultural labour productivity changes due to high temperature.
- Scenario 4—Overall climate change impact, which includes all of the above.

The study utilised temperature-induced changes in crop productivity, land productivity affected by rising sea levels and labour productivity impacted by heat stress. These projections are based on the work of Roson and Sartori (2016a), which have been widely used in various vulnerability assessment studies related to climate change (for references, see Kompas et al., 2018; Matsumoto et al., 2021; Zeshan & Ko, 2017). It is important to note that these projections solely consider temperature variations and do not account for other crucial factors affecting crop productivity, such as precipitation, CO_2 fertilisation, floods or droughts. However, some studies have incorporated temperature and precipitation variations (Abeysekara et al., 2023; Alvi et al., 2021; Weerasekara et al., 2021), while others have focussed solely on temperature changes (Ottman et al., 2012; Porter & Gawith, 1999; Zhao et al., 2017), or employed controlled experiments and crop models specific to certain regions or crops (Iglesias et al., 2012). Consequently, the limitations mentioned above do not undermine the findings of Roson and Sartori (2016b) for this particular analysis. This is because temperature holds the strongest negative impact on crop productivity, and climate models provide more reliable predictions for temperature than for precipitation (Ottman et al., 2012; Zhao et al., 2017). The simulation of all the following scenarios in this study adhered to the methodologies employed in previous related studies (Bosello et al., 2012; Cai et al., 2016; Kompas et al., 2018; Orlov et al., 2020).

3.3.1 | Scenario 1 (Crop productivity changes due to increased temperature)

The projections of temperature, CO_2 concentrations and precipitation patterns directly affect crop productivity. The crop productivity estimates of Roson and Sartori (2016a) were based on the meta-analysis included in the IPCC Fifth Assessment Report and provide estimates for maize, wheat and rice yields. These values were calibrated to estimate outputs per hectare in each country in the GTAP database. The projected crop productivity changes were mapped for the 10 aggregated regions in Table 2. These changes were then simulated as percentage-change shocks to the output-augmenting technical changes for the maize, wheat and rice sectors for each aggregated region in the GTAP-E model.

3.3.2 | Scenario 2 (Agricultural land productivity changes due to sea level rise)

Relevant effects on productive land from sea level rise include erosion, inundation and salt intrusion. Impacts are country-specific and based on the composition of the shoreline, length of the coast, share of agricultural land along the coastline and vertical land movement. Roson and Sartori (2016a) mainly focussed on the impact on productive agricultural land and did not consider the negative impact on capital stock near the coast. The impact of rising sea levels on productive land can be considered as a loss of productive land or a loss of land productivity. Since both salt intrusion and erosion reduce the productivity of agricultural land, in this study we consider the impact of sea level rise to be the reduction in land productivity (Table 2). The manufacturing and services sector input factors comprise materials, energy, labour and capital, while the agricultural sector comprised the same input factors plus land. Hence, the loss of productivity in agricultural land due to rising sea levels was incorporated as a percentage shock in the input-augmenting technical change for the factor land. This shock was region-specific.

TABLE 2 Estimated crop productivity changes, sea level rise impacts and labour productivity changes.

	% change in crop productivity			% change in land productivity due to sea level rise	% change in labour productivity
Region	**Maize**	**Wheat**	**Rice**		
Bangladesh	−5.00%	−5.20%	−2.60%	−0.0005%	−11.12%
India	−5.19%	−5.13%	−2.56%	−0.0003%	−10.84%
Nepal	−4.50%	−5.40%	−2.70%	−0.0000%	−3.53%
Pakistan	−4.25%	−5.50%	−2.75%	−0.0003%	−7.28%
Sri Lanka	−7.00%	−4.40%	−2.20%	−0.0041%	−17.23%
Rest of South Asia	−5.19%	−5.13%	−2.56%	−0.0001%	−10.84%
High-income countries	−2.68%	−6.13%	−3.06%	−0.1126%	−2.09%
Middle-income countries	−4.96%	−5.22%	−2.61%	−0.0035%	−6.44%
Low-income countries	−6.63%	−4.55%	−2.27%	−0.0005%	−4.38%
Rest of the World	−5.37%	−5.05%	−2.53%	−0.0542%	−8.74%

Note: The base year for crop productivity and sea level rise was 2014 as the estimates were based on the IPCC (2014) report. The base year for labour productivity was 2015. The labour productivity values for 2014 were recalculated with respective temperature values and rounded to two decimal points. There were no significant changes compared with the original data due to a negligible difference between 2014 and 2015 mean temperature data.

Source: Roson and Sartori (2016a).

3.3.3 | Scenario 3 (Agricultural labour productivity changes due to high temperature)

A desirable working environment enhances productivity, while an undesirable environment decreases productivity. Higher temperatures and humidity levels lead to heat stress and impact negatively on labour outputs. The projected labour productivity estimates of Roson and Sartori (2016a) were based on the study by Kjellstrom et al. (2009), which estimated *work ability*, defined as the maximum percentage per hour that a worker should be engaged working (Kjellstrom et al., 2009). Roson and Sartori (2016a) converted this proxy for labour productivity into a function of wet bulb globe temperature (WBGT), a combination of average temperature and average absolute humidity. They presented these estimates for three labour sectors (agriculture, manufacturing and service) in each of the GTAP countries. Since our study focusses on the impacts of climate change on the agricultural sector and the economic consequences, we only considered heat stress-induced agricultural labour productivity changes. We aggregated the results of Roson and Sartori (2016a) into the 10 regions (Table 2) and shocked the model to produce the input-augmenting technical change for the factor agricultural labour. This shock was also region-specific.

3.3.4 | Scenario 4 (Overall climate change impact)

This scenario analyses the overall economic impacts of climate change and the cumulative effect of changes in crop productivity, rising sea levels and heat-induced agricultural labour productivity, assuming a 2°C temperature increase by 2050 in the ten study regions. Although we analysed the economic consequences of climate change influences separately, in practice, all these impacts are likely to occur simultaneously. Hence, the assessment of the cumulative economic impact is vital to comprehend the total impact caused by the effects of climate change on South Asian agricultural sectors.

Table 2 presents the estimates of Roson and Sartori (2016a) on climate change-induced crop productivity changes, rising sea level-induced land productivity changes and heat stress-induced labour productivity changes with a 2°C temperature increase, which we used as shocks in our GTAP-E model. According to their estimates, climate change will impact negatively on crop productivity, productive land and agricultural labour productivity in all considered regions. Of the three crops considered, the least affected was rice. The greatest decline in wheat and rice productivity was observed in high-income countries, while Sri Lanka experienced the greatest decline in maize productivity, and with the island suffering the most due to heat stress-induced labour productivity losses. The impact of the rising sea level on Sri Lankan productive land was very low, while the high-income countries experienced the greatest negative impact from this factor. Of the three climate change functions considered, the greatest impact was on labour productivity. The reduction in agricultural labour productivity in most South Asian countries exceeded 10% under the modelled 2°C temperature increase. Sea level rise impacts were minimal as it is a long-term process.

We followed Siriwardana and Nong (2021) in setting up long-run closure for the simulations. The employment level and land stock were set as exogenous and, hence, the real wage rate and land rent were endogenous. Moreover, the capital stock was endogenous, while the rate of return on capital was set to be exogenous. We set the trade balance as exogenous for all regions except the Rest of the World (ROW).

4 | RESULTS AND DISCUSSION

All GDP projections, outputs, prices and consumption are reported as a percentage deviation from the baseline scenario.

4.1 | Changes in GDP

The overall impact on GDP (Figure 2) provides an overview of the economic impacts of climate change. The agricultural sector plays an important role in the South Asian economy, contributing 18% of total GDP compared with the 2.4% total contribution of all national agricultural sectors to the global economy. It is not surprising that the projected impacts of climate change on the agricultural sector affect GDP negatively. The Maldives, Bhutan and Afghanistan (denoted by the Rest of South Asia) will experience the greatest negative economic impacts, reflected in an average reduction in GDP of 4.03%. Of the other five South Asian countries, Sri Lanka will suffer the most (3.86% decline in GDP), with Nepal being the least affected (2.23% decline in GDP). Sri Lanka and the Maldives (Rest of South Asia) are the only two nations classified as islands in South Asia, which are also considered developing nations. Hence, the results of this study confirm the findings of numerous studies that conclude islands and developing nations should be considered 'hot spots of climate change' or 'frontlines of climate change' (Barnett & Waters, 2016; Kelman & West, 2009; Walshe & Stancioff, 2018).

Furthermore, by considering the economic effects of climate change vulnerabilities according to levels of income, our study shows that the most negative effects will be experienced in low-income countries (3.25% decline in GDP), with high-income countries the least vulnerable group (0.46% GDP loss). This confirms previous findings highlighting that poor, developing nations are more vulnerable to climate change-induced economic impacts than wealthier developed nations (Kompas et al., 2018; Moore & Diaz, 2015; Orlov et al., 2020; Roson & Van der Mensbrugghe, 2012). India, Pakistan and Sri Lanka are considered middle-income countries, while Bangladesh is considered low-income country (note, as we focussed on South Asia, these countries were analysed separately to the categories of income groups, which focussed on the rest of the world (ROW) (See Annex.SS1)). Our results indicate that South Asian countries will experience greater climate change-induced negative economic impacts compared with their respective income group from the ROW (estimated GDP decline for middle-income countries is 2.62%).

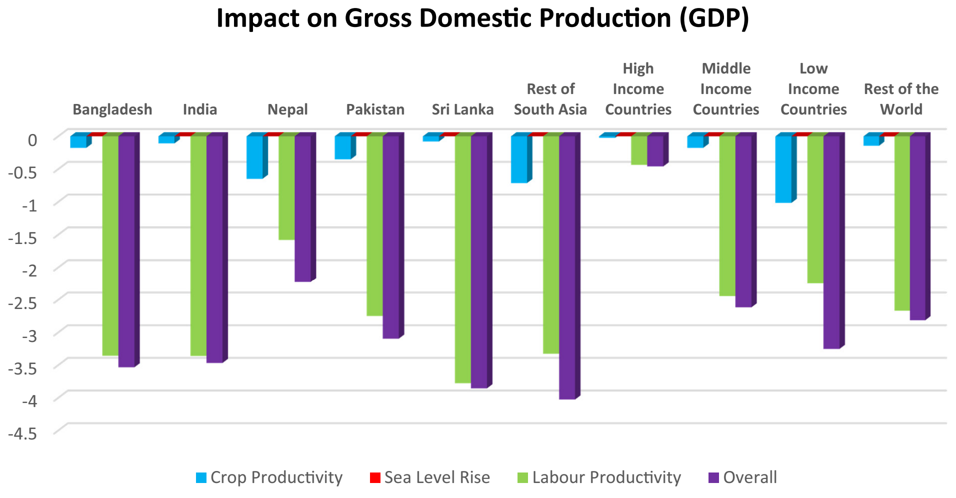

FIGURE 2 Climate change impacts on GDP (as a % change from the baseline scenario). [Colour figure can be viewed at wileyonlinelibrary.com]

4.2 | Scenario 1 (Crop productivity changes due to increased temperature)

The results in Figure 3 show that the output of many agricultural industries is likely to be affected by climate change-induced crop productivity changes. This will produce a shift to the left of the supply curve, increasing the market price of these products. Households will respond by reducing their consumption of expensive products and shifting to low-priced substitutes. Firms will try to increase production by adjusting operations, technological or other factors, or by increasing their firm capacity (increasing land, labour, capital and/or intermediate inputs).

According to the results, climate change will reduce South Asian rice production. However, it is also important to note that the impact on the rice sector is less than that on wheat and other cereals. The optimum temperature for rice cultivation is 30°C daytime and 24°C nighttime temperatures, while the biomass production of wheat is greatest below 25°C daytime and 19°C nighttime temperatures (Nagai & Makino, 2009). The average projected temperature range in the study region is 23–30°C. Hence, a 2°C increase in temperature by 2050 impacts rice production less than other crops. In terms of rice production losses, Nepal and low-income countries are likely to be the most affected, and Nepal will continue to be a net rice importer at least until 2050. Nepal, India and Bangladesh have restricted their rice exports during the past two decades in order to maintain their rice supply to meet the domestic demand (Liu et al., 2022). Imposing these restrictions again in the future is likely, if climate change threatens their rice production as projected in this study. It is noteworthy that Sri Lanka is an exception with increased rice production relative to the baseline scenario. There are several reasons for this. First, as outlined earlier, Sri Lanka will experience less climate change-induced rice productivity loss than the other nations in the region. Second, the projected rice land rental increase (2.55%) for Sri Lanka is the least compared with the other nations; hence, the increse in cost of production in Sri Lanka will be lower. Third, Sri Lanka will have a comparative advantage in global trade, due to its lower prices before trade. Fourth, the export demand for Sri Lankan rice is projected to increase by a greater percentage than for the other nations. Therefore, the country will increase its production as trade expands.

With regard to the projections for wheat production (Figure 3), India, middle-income countries and low-income countries will increase production, while other countries will reduce production. Bangladesh will experience the third most negative impact of climate change on

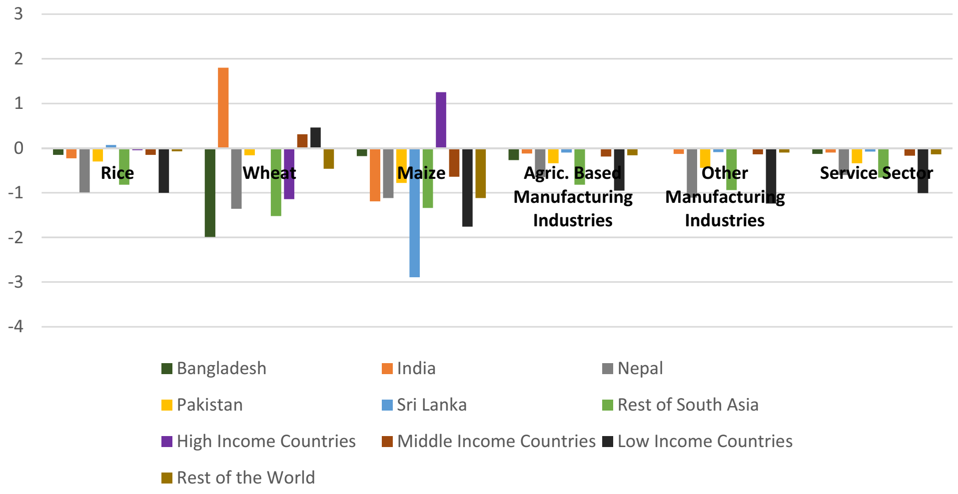

FIGURE 3 Impact of climate change-induced crop productivity changes on firm outputs (commodity production as a % change from the baseline scenario). [Colour figure can be viewed at wileyonlinelibrary.com]

wheat productivity in South Asia (Roson & Sartori, 2016a). However, the price increase on imported wheat will be less than the price increase on domestically produced wheat. Therefore, consumers and producers who use wheat as an intermediate input will shift from domestically produced wheat to imported. Moreover, the price increase on wheat will be higher than the price increase on rice and other cereals in Bangladesh. This will cause a shift in the demand for wheat to alternative, lower priced substitutes. Hence, Bangladesh will reduce domestic wheat production. India, currently one of the top wheat-producing countries, will increase its wheat production due to the projected high export demand for Indian wheat.

Figure 3 shows how climate change impacts on maize productivity resulting in changes in maize production levels for the nations and groupings included. The highest predicted maize productivity loss is in Sri Lanka, while high-income countries are the only grouping indicating growth in maize production. This will result in high-income countries gaining a comparative advantage in trading that will increase production.

Climate change induced rice, wheat and maize productivity and production changes will lead to price spikes in all agricultural products in all regions. The projected price increase for rice is low compared with wheat and maize. In the study region, the rest of South Asia (Afghanistan, Bhutan and the Maldives), Pakistan and Sri Lanka will experience the greatest price increases for rice, wheat and maize, respectively. These increases are mainly because these food products are considered necessities in the South Asian countries. These findings concur with those of Cai et al. (2016) and Abeysekara et al. (2023). According to Elliott (2006), rice and wheat account for over 50% of the calorie intake of South Asians. Hence, food inflation, inclusive of the price increases of these two commodities, indicates serious problems with food affordability and food security in the region. South Asia as a region recorded the second-highest Global Hunger Index (GHI) rating, according to the most recent report (Global Hunger Index, 2019). As a result of food price increases, households are projected to reduce food consumption, which will further increase hunger levels across the region. As mentioned earlier, high-income countries will experience the highest climate change induced rice and wheat productivity losses. Hence, the highest price increases for rice and wheat products will be observed in the high-income countries.

Climate change impacts on the agricultural sector will also affect the manufacturing and services sectors (Figure 3; Table 3), as all three sectors are interconnected. Climate-induced productivity changes will reduce the outputs of the manufacturing and service sectors, with a greater negative impact on the manufacturing sector. These changes are projected to increase most commodity prices in these two sectors. Commodity prices in the manufacturing industries that use agricultural products as their main intermediate inputs will increase the most, compared with other manufacturing sector products, due to the prices of these inputs being projected to increase significantly by 2050.

When food crop (rice, wheat and maize) productivity decreases, yield per unit land area is reduced. Thus, producers must respond to the demands of the increasing population by increasing the area utilised for food production. In turn, this will increase agricultural land prices. Higher land prices increase production costs and, consequently, firms will reduce wages (Figure 4). However, the increase in land rentals is projected to be exceeded by the reduction in wages and prices of natural resources, resulting in a net decrease in national income due to climate change-induced crop productivity changes.

4.3 | Scenario 2 (Agricultural land productivity changes due to rising sea levels)

The rise in sea levels will create significant impacts over a longer period of time. The damage caused to agricultural land by rising sea levels will be minimal compared with the effects of the

TABLE 3 Impact of climate change-induced crop productivity changes on commodity prices (as a % change from the baseline scenario).

Region	Rice	Wheat	Cereal	Other food crops	Animal-based products	Agriculture-based manufacturing industries	Other manufacturing industries	Service sector
Bangladesh	3.43	6.58	6.28	0.41	0.92	0.28	−0.01	−0.03
India	3.25	6.50	6.45	0.27	0.35	0.10	0.03	0.00
Nepal	3.52	7.19	5.95	0.33	0.37	0.15	0.19	0.01
Pakistan	3.28	7.37	5.10	0.17	0.25	0.11	0.10	0.05
Sri Lanka	2.61	7.30	8.60	0.15	0.12	0.09	0.02	0.00
Rest of South Asia	3.74	7.35	7.48	0.45	0.53	0.27	0.24	0.06
High-income countries	3.98	7.44	3.36	0.24	0.39	0.02	0.00	−0.01
Middle-income countries	3.26	6.30	5.84	0.17	0.36	0.10	0.01	0.00
Low-income countries	2.78	5.30	7.90	0.14	0.23	0.24	0.19	0.03
Rest of the World	3.06	6.65	6.09	0.10	0.21	0.06	0.00	−0.02

FIGURE 4 Changes in prices of production factors due to climate change-induced crop productivity changes (as a % change from the baseline scenario). [Colour figure can be viewed at wileyonlinelibrary.com]

other two categories of climate change damage, and as expected, our results project minimal economic impact due to rising sea levels by 2050 (Figure 2).

However, rising sea levels do indicate an unfavourable effect on the GDP of all regions considered in our study. The greatest economic impact of a rise in sea level for the South Asian region (% decline in GDP) will be a GDP reduction of 0.001% (a small percentage) experienced by Sri Lanka (Figure 2).

The production of rice, wheat and cereal of high-income countries and production of cereal in Sri Lanka will decline due to sea level rise (Figure 5). As noted in the estimates provided by Roson and Sartori (2016a), this is due to high-income countries and Sri

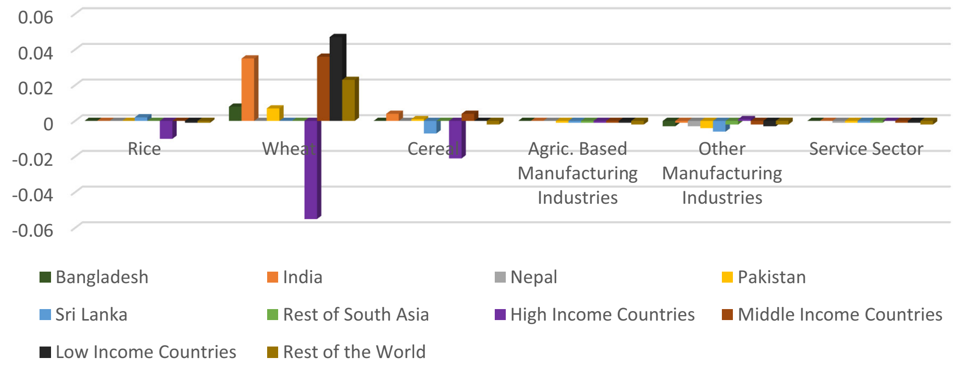

FIGURE 5 Impact of rising sea level on firm outputs (as a % change from the baseline scenario). [Colour figure can be viewed at wileyonlinelibrary.com]

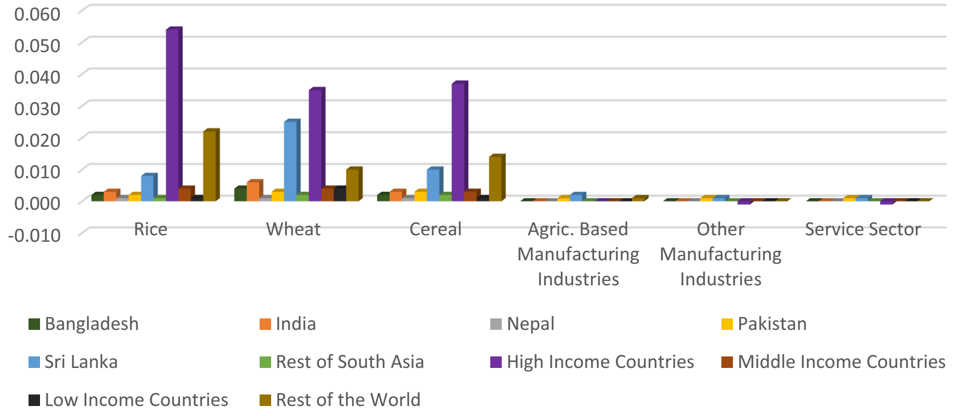

FIGURE 6 Impact of sea level rise on commodity prices (as a % change from baseline scenario). [Colour figure can be viewed at wileyonlinelibrary.com]

Lanka being relatively heavily impacted by sea level rise compared with the other areas examined.

With the predicted decline of wheat production in high-income countries for both domestic consumption and export (such as the United States, Russia, Canada, France and Germany), other countries will tend to produce more. India, low-income countries and middle-income countries will increase outputs by increasing labour used for wheat production. The export demand for wheat in these countries will also increase.

As depicted in Figure 6, food prices in Sri Lanka and the high-income countries are projected to increase due to a decline in production. However, food price inflation is also projected for other regions. Even though production is projected to increase to offset food shortages, the unit cost of production will increase due to increases in land prices in all regions. Producers will increase the prices of these agricultural products. Since most of the food products are considered to be necessities and have low price elasticity of demand, there will be minimal impact on household demand for these products. However, the percentage changes in firm outputs and commodity prices due to sea level rise will be minimal compared with the economic consequences of the other climate change induced impacts.

Rising sea levels will reduce land productivity, and the output obtainable from a unit of land area will decrease. To maintain output levels, cultivated land areas must be increased, which will increase the demand for agricultural land. This will increase land prices and, consequentially, production costs. As a result, firms will attempt to reduce production costs by reducing their wage bill paid (Table 4). Ultimately, these factors will reduce GDP for all study regions, in accordance with the projected decline in national incomes (Figure 2).

4.4 | Scenario 3 (Agricultural labour productivity changes due to high temperature)

Roson and Sartori (2016a) indicated the negative impact a 2°C temperature increase will have on agricultural labour productivity in the 10 regions examined. The predicted reduction in agricultural labour productivity in our study significantly impacted GDP compared with the other categories of damage due to climate change. This was pronounced in South Asia; that is, the reductions in real GDP exceeded 2.5% for all South Asian countries except Nepal, for which the reduction was 1.58% (Figure 2). These findings are similar to studies such as Matsumoto et al. (2021) and Orlov et al. (2020). Sri Lanka (−3.78%), India (−3.36%), Bangladesh (−3.36%), Rest of South Asia (−3.33%) and Pakistan (−2.75%) will experience the most substantial GDP losses, respectively. This is mainly due to the high agricultural labour productivity losses projected due to the hot, humid climate of South Asia (Roson & Sartori, 2016a). The least negative economic impact due to agricultural labour productivity losses was observed in the high-income countries group (−0.43%). Both middle-income and low-income countries will experience higher GDP losses in excess of 2%, but the impact is less than for the South Asian region. As already mentioned, this is due to the middle-income, low-income and South Asian countries contribution of agriculture to GDP and the percentage of the population employed in that sector being larger than in high-income countries. This notable impact will add to already adverse conditions as most of the region already suffers from high levels of poverty, informal or subsistence agricultural employment and low social security coverage (Kjellstrom et al., 2009). These estimates are based on a 2°C temperature increase by 2050; greater increases in temperature would produce more negative economic impacts.

Numerous studies have shown that agriculture is the economic sector most affected by heat stress induced labour productivity losses and that the impact is greater in developing countries where agriculture is the most labour intensive, or where most of the work occurs outdoors (Kjellstrom et al., 2009; Orlov et al., 2020; Roson & Sartori, 2016a). Thus, a reduction in agricultural output is not surprising. However, the results presented in Figure 7 make it clear

TABLE 4 Changes in prices of factors of production due to sea level rise (as a % change from the baseline scenario).

Region	Land rental	Wages of unskilled labour	Wages of skilled labour	Wages of agricultural labour	Natural resources rental
Bangladesh	0.017	−0.001	−0.001	0.000	−0.002
India	0.015	−0.001	−0.001	0.000	−0.001
Nepal	0.003	−0.001	−0.001	0.000	−0.003
Pakistan	0.017	−0.001	−0.001	0.001	−0.003
Sri Lanka	0.057	−0.001	−0.001	0.002	−0.004
Rest of South Asia	0.004	−0.001	−0.001	0.000	−0.003
High-income countries	0.269	−0.001	−0.001	−0.001	−0.001
Middle-income countries	0.042	−0.001	−0.001	0.000	−0.002
Low-income countries	0.007	−0.001	−0.001	0.000	−0.004
Rest of the World	0.161	−0.002	−0.002	−0.002	−0.004

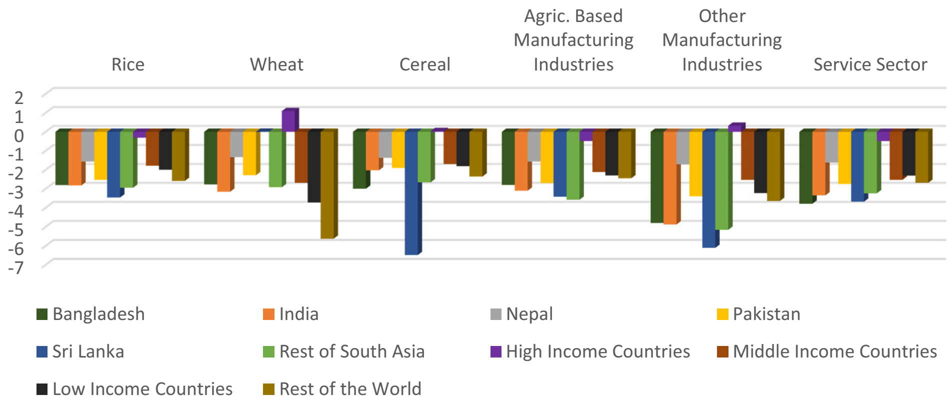

FIGURE 7 Impact of agricultural labour productivity loss on firm output (as a % change from the baseline scenario). [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 5 Impact of agricultural labour productivity losses on commodity prices (as a % change from the baseline scenario).

Region	Rice	Wheat	Cereal	Agriculture-based manufacturing industries	Other manufacturing industries	Service sector
Bangladesh	2.39	1.67	2.22	0.67	1.79	0.66
India	2.61	2.01	1.83	0.48	2.21	0.22
Nepal	2.83	2.45	2.46	0.71	1.38	0.61
Pakistan	2.84	2.7	2.41	0.92	1.78	0.68
Sri Lanka	4.98	0.78	4.87	1.56	2.53	0.7
Rest of South Asia	4.74	3.95	3.67	1.33	2.57	0.72
High-income countries	1.2	1.19	0.89	0.65	0.85	0.59
Middle-income countries	2.16	2.12	2.23	0.72	1.29	0.75
Low-income countries	1.69	2.07	1.86	1.17	1.57	0.3
Rest of the World	2.77	3.36	3.21	0.63	1.46	0.56

that while the agricultural sector declines in output, the effect is less than the reduction in agricultural labour productivity. The only indication of gains occurs in high-income countries (Figure 7). Due to cross-regional interaction through trading, high-income countries gain a comparative advantage in the production of agricultural commodities, while the other regions will experience considerable losses due to declining agricultural labour productivity. This can be seen as a slight to moderate increase in wheat and cereal production, and less of a reduction in rice production, resulting in the export demand for these agricultural products increasing in high-income countries. Due to the intersectoral interactions, manufacturing and service sectors will also experience reduced production from heat-induced agricultural labour productivity losses.

It is evident that the reduction in commodity outputs leads to an increase in commodity prices (Table 5). The percentage change in food prices is also relatively larger than the percentage change in output. This is because demand for most agricultural products tends to be relatively price inelastic as they are considered to be necessities. With the heat-induced agricultural labour productivity loss incurring economic costs to producers, they compensate partially by increasing the commodity price. Reduction in firms output and price increases in both agricultural and nonagricultural products lead to a reduction in household consumption.

The model results predict a reduction in household real disposable income, which follows a similar pattern to the reduction in household consumption. Notably, the reduction in household consumption is more attributable to heat-induced agricultural labour productivity losses than the other considered climate change factors.

Labour is a key input in agricultural production, particularly in developing nations such as the South Asian countries (Kjellstrom et al., 2009; Orlov et al., 2020). The reduction in agricultural labour productivity will incur a considerable cost to producers. This may cause some small producers to abandon their business, contributing to the overall decline in agricultural production. This would reduce the demand for land and, thus, reduce land prices. Since heat-induced agricultural labour productivity losses are minimal in high-income countries, and as the model predicts an increase in some agricultural crops, the demand for agricultural land in high-income countries will increase, pushing up the price of land, and ultimately increase production costs (Figure 8). In some situations, this may also result in a reduction in wages. However, in Nepal, the heat stress-induced agricultural labour productivity loss is very low compared with other South Asian countries (Table 2). A decline in land rentals, thus reducing production costs, can also be observed for Nepal. Hence, Nepal could increase the wages of agricultural labour relative to any reduction in land rental costs, and both retain their labour stock and attract more labour.

4.5 | Scenario 4 (Overall climate change impacts)

This scenario demonstrates that the GDP declines are due to the combined impacts of climate change on the agricultural sector, by decomposing the GDP results according to the contributing factors. The income approach sums up the rents, wages, interest and profits to determine GDP.

$$\text{GDP} = \text{Rents} + \text{Wages} + \text{Interests} + \text{Profits} \tag{1}$$

In the GTAP-E framework, firms are assumed to have zero profits, and according to our long-run model closure, the interest on capital is set to be exogenous. Hence, we focus on the first two components of Equation (1): rent of land and natural resources, and wages of skilled,

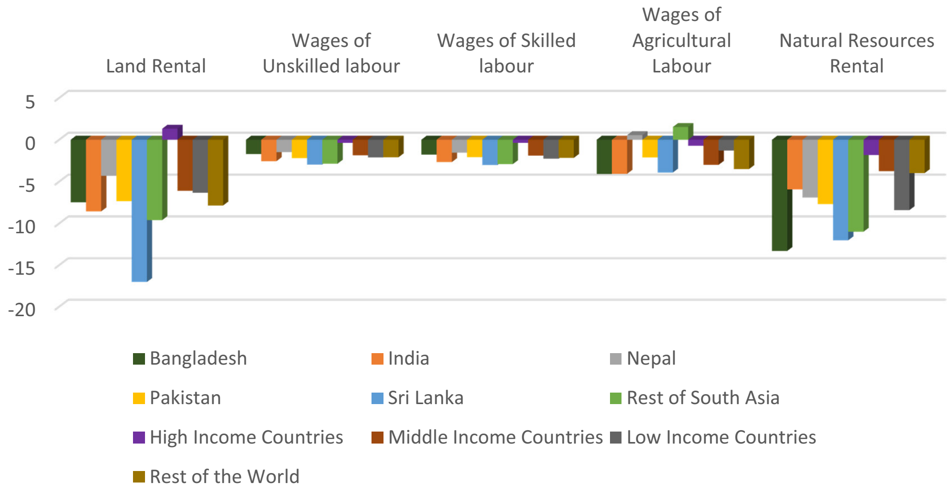

FIGURE 8 Changes in prices of factors of production due to agricultural labour productivity loss (as a % change from the baseline scenario). [Colour figure can be viewed at wileyonlinelibrary.com]

unskilled and agricultural labour. As discussed above, the impacts of crop productivity losses and rising sea levels will ultimately increase the costs of land rental. However, the agricultural labour productivity losses will decrease rentals due to the reduction in demand, except for the high-income countries. Hence, the impact of labour productivity losses exceeds the other two damage factors, and overall land rental values will decrease. It is also evident that climate change will reduce labour wages in most of the countries, leading to a considerable decline in disposable household income. As implied in Equation (1), the reduction in land rentals, labour wages and the cost of natural resources will reduce the national income, which is predicted as the decline in overall GDP (Figure 9).

Table 6 summarises the changes in key macroeconomic variables such as export volume, import volume, Consumer Price Index (CPI) and terms of trade (TOT). Climate change impacts macroeconomic variables unfavourably, particularly for South Asian countries. Changes in exports and imports are directly related to the movement of GDP and constitute one of its main components Equation (2).

$$\text{GDP} = \text{Private Consumption} + \text{Government Consumption} + \text{Investment} + (\text{Exports} - \text{Imports}) \tag{2}$$

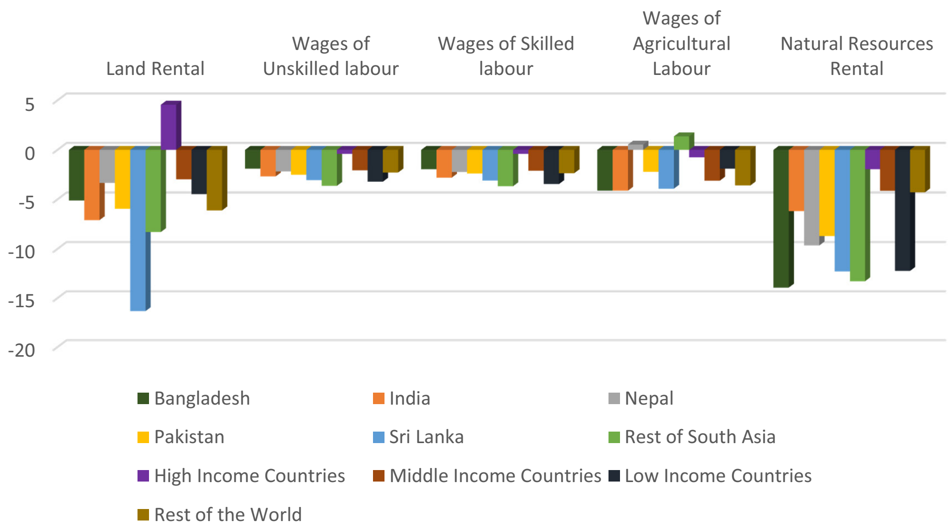

FIGURE 9 Changes in prices of factors of production due to overall climate change impacts (as a % change from the baseline scenario). [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 6 Overall climate change impacts on macroeconomic variables (as a % change from the baseline scenario).

	Bangladesh	India	Nepal	Pakistan	Sri Lanka	Rest of South Asia	High-income countries	Middle-income countries	Low-income countries	Rest of the World
Export volume	−4.88	−4.00	−3.53	−4.88	−5.77	−4.01	−0.53	−2.34	−4.02	−2.46
Import volume	−3.18	−2.72	−1.81	−2.17	−2.73	−2.34	−0.70	−2.15	−2.81	−2.5
CPI	0.04	0.59	1.21	1.03	1.04	1.66	0.65	0.90	1.38	0.81
TOT	0.56	0.63	0.32	0.98	0.85	0.40	−0.18	0.29	0.35	−0.04

Abbreviations: CPI, Consumer Price Index; TOT, terms of trade.

Hence, a decline in exports reduces the GDP, while a decline in imports increases the GDP. In all South Asian, middle-income and low-income countries, the reduction in export volume exceeds the reduction in import volume, resulting in a negative effect on GDP. The highest export volume reduction occurred in Sri Lanka, followed by Pakistan and Bangladesh, while the highest import volume reduction was recorded in Bangladesh followed by the low-income countries, Sri Lanka and India. The changes in these values were instituted to maintain the balance on the current account assumed in the model. Hence, the negative impacts of climate change are partially compensated for by regulating the increases in the net trade balance. Consumption is the major factor that determines the movement of GDP due to its highest share. Figure 10 shows how the climate change impacts reduce the level of consumption and, thus, the overall GDP. The projected increase in the CPI is a key reason for the decline in consumption. Hence, the Rest of South Asia and the low-income countries show the greatest increases in the CPI, and those two regions also exhibit the greatest decline in household consumption.

As the model is linear, the overall climate change impacts (Simulation 4) will provide a summation of the results obtained from the other three simulations (Simulations 1, 2 and 3). Figure 10 shows the negative impacts of climate change on firm outputs and household consumption due to the overall impacts of climate change. It also indicates inflation in all study regions. Interestingly, it is clearly visible that the increases in food prices are far greater than the reduction in production outputs and household consumption (demand). This proves the relatively price-inelastic demand of these food products. India, Pakistan and Sri Lanka are classified as middle-income countries. However, according to Figure 10, the decline in output and household consumption and the increase in commodity prices in these countries exceed the respective averages for the middle-income countries. In addition, even though the high-income countries experienced the greatest impacts from rising sea levels and climate change-induced wheat and rice productivity losses (Table 2), they experienced the least negative economic impacts (Figure 10). This is due, to the average heat stress-induced agricultural labour productivity losses being minimal for the high-income countries (aggregated), relative to all other countries. In addition, the output reduction due to climate change impacts in these countries was very low. Even with the most severe impacts, costly inputs produced a considerable level of output that avoided greater reduction in firm outputs. In these wealthier countries, firms partially compensate for increased production costs by increasing commodity prices. Further, since the per capita income in these countries is high, the majority

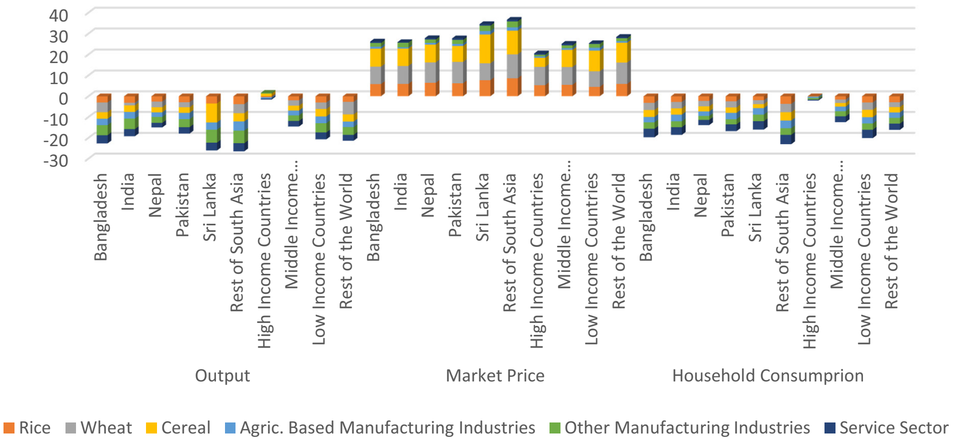

FIGURE 10 Overall climate change impact on firm outputs, commodity prices and household consumption (as a % change from the baseline scenario). [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 7 Sensitivity analysis results when the elasticity of transformation for sluggish primary factor endowment parameter was adjusted by 50%.

Region (1)	Centre parameters for GDP (2)	Lower bound (3)	Upper bound (4)	Difference between upper and lower bounds (5)
Bangladesh	−3.533815	−3.53384	−3.53379	0.00005
India	−3.467093	−3.46741	−3.46673	0.00068
Nepal	−2.22664	−2.22924	−2.22444	0.00480
Pakistan	−3.095571	−3.09597	−3.09524	0.00073
Sri Lanka	−3.855761	−3.85787	−3.85398	0.00389
Rest of South Asia	−4.026243	−4.03328	−4.02024	0.01304
High-income countries	−0.459619	−0.45965	−0.45959	0.00006
Middle-income countries	−2.617262	−2.61785	−2.61676	0.00109
Low-income countries	−3.252713	−3.25509	−3.25069	0.00440
Rest of the World	−2.813483	−2.81429	−2.81279	0.00150

Note: Columns (3) and (4) report the 95% confidence interval for results from varying the ETRAE parameter for land and natural resources by 50%.

of households could purchase higher priced commodities, resulting in a greater capacity to bounce back from financial shocks.

4.6 | Sensitivity analysis

We conducted a systematic sensitivity analysis to examine how the findings of this study would shift when parameters were altered. In particular, the elasticity of transformation for sluggish primary factor endowments (ETRAE) was examined in respect to the climate change impact scenarios.

We used the ETRAE parameter values in the default setting, where skilled and unskilled labour and capital were treated as perfectly mobile, and natural resources and agricultural land were treated as sluggish factors of production. As the model allocates land across several agricultural sectors within each region, the sluggishness of land is relevant for our analysis.

The robustness of the results was tested by changing the ETRAE parameter for land and natural resources by ±50% from the baseline case. Overall, GDP estimates were affected only marginally by the assumed elasticity parameters, while higher elasticity tended to increase welfare outcomes (Table 7), as found in other CGE analyses.

5 | CONCLUSION

Using the GTAP–E CGE model, we assessed the overall economic cost of climate change-induced crop productivity losses, rising sea levels and heat-induced agricultural labour productivity losses by 2050, based on a 2°C temperature increase, with particular focus on South Asia. To shock the model, we used the productivity change estimates of Roson and Sartori (2016a).

This work provides several important messages regarding food security in South Asia. Our model predicts a decline in the production of most food crops in the region by 2050 due to climate change. This reduction in food production will put pressure on food prices, with the model predicting food price inflation. This will lead to a reduction in household food consumption, posing a threat to regional food security. Due to the considerable contribution of the agricultural sector to GDP and employment in South Asia, the adverse impacts of climate change on this sector will impact national GDP negatively.

Of the three climate change damage factors considered, the projected agricultural labour productivity reduction due to heat stress will cause the highest economic losses, while sea level rise will have the least impact. However, all three factors will impact negatively on the overall regional economy. The negative economic impacts on South Asian countries exceeded the projected global averages for their respective income groups. This is in line with previous studies that concluded South Asia is one of the most vulnerable regions of the globe in terms of climate change.

This work also analysed the economic impacts of climate change on low-, middle- and high-income countries. The results indicate that low-income countries are projected to be most vulnerable to the negative impacts of climate change, while high-income countries are likely to be least affected.

The findings suggest that policymakers in South Asian and low-income countries should develop policies to mitigate or adapt to the impacts of climate change. Given the impact of heat-induced agricultural labour productivity losses in the model, policies that encourage investment in farm mechanisation, innovation and the development of low-cost farm machinery, as well as those that encourage cooperative farming, should be investigated. However, policymakers need to ensure that farm mechanisation will not impact negatively on agricultural workers, their terms of employment and their income security. Moreover, policies encouraging the development of climate-smart and climate change-resilient crop varieties will reduce crop productivity losses.

Several limitations apply to the above results. Calibration for the GTAP database to 2050 did not consider any adaptation scenario or technological progress in agriculture, which is not realistic. It is likely that the actual climate change impacts caused by the considered climate change damage functions will be lower than the estimated values.

CODE AVAILABILITY

The model code for this study has been developed using GEMPACK software. The database has been sourced from GTAP Version 10 data which is publicly available at a cost from GTAP. The code can be provided on request.

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CONSENT FOR PUBLICATION

All authors gave their consent for publication.

DATA AVAILABILITY STATEMENT

Data and materials comply with field standards.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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