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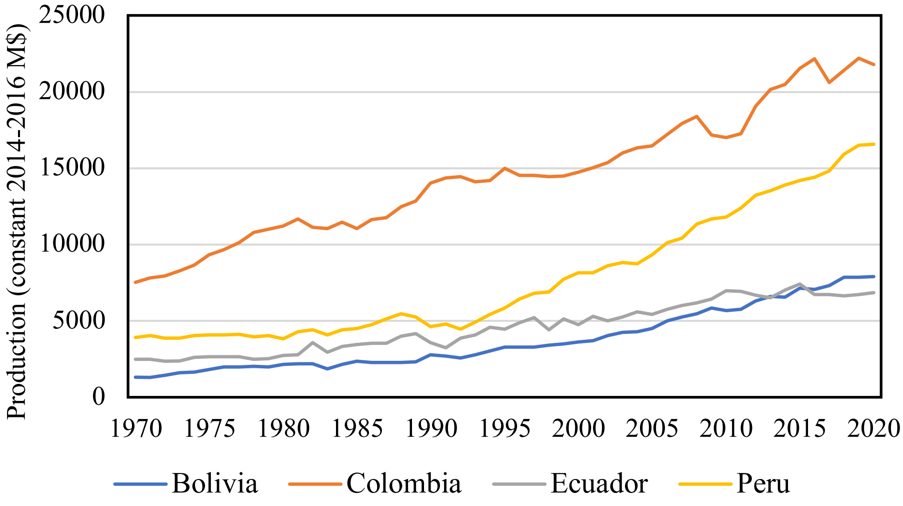
Abstract: How to keep water and land stress within planetary boundaries is a major challenge for sustainable development in Latin American countries. Using an environmentally extended global multi-regional input-output analysis (GMRIO) approach, this study simulates future land and water demand for Bolivia, Colombia, Ecuador, and Peru under three climate-socioeconomic scenarios: SSP1-RCP2.6, SSP2-RCP4.5, and SSP5-RCP8.5. Under all three scenarios, land and water demands in all four countries are projected to increase rapidly in the next few decades. By 2050, the demand for cropland in Peru and Bolivia will exceed those countries' planetary boundaries, with the rise in income being the most significant contributor to the rising demand. In addition, foreign demand will significantly drive the growth of water and land demand in Ecuador and land demand in Colombia. Nonagricultural sectors, most notably the mining sector, will be primarily responsible for the increased water demand in Ecuador and Peru, exacerbating competition between those sectors and the agricultural sector for water. In Peru and Bolivia, there is a significant spatial mismatch of water and land resources at the basin level. With hydraulic infrastructure as a prerequisite, developing irrigated agriculture may lead to a water-land trade-off that can significantly alleviate the land stress in those countries.

I. Introduction

Latin American countries are major producers of food for the world. In recent decades, Bolivia, Colombia, Ecuador, and Peru have shown rapid growth in agricultural production (Figure 1). Meanwhile, these countries have witnessed massive cropland expansion (Ceddia, 2019; Zalles et al., 2021; Potapov et al., 2022; Song et al., 2022). Agricultural production expansion to meet the future domestic and global food demand will continue to increase water and land use. How to keep water and land use within planetary boundaries is a critical challenge for the sustainable development of these countries. When predicting future water and land stress in the area, changes in climate and socioeconomic conditions are crucial factors that must be considered. Based on future coupled climate-socioeconomic scenarios, this study projects future land and water demand in Bolivia, Colombia, Ecuador, and Peru and proposes a water-land trade-off solution that uses irrigated agriculture.

FIGURE 1: AGRICULTURAL PRODUCTION IN BOLIVIA, COLOMBIA, ECUADOR, AND PERU, 1970–2020



Source: Food and Agriculture Organization of the United Nations (FAO).

Changes in climatic conditions, such as temperature and precipitation, will directly affect future agricultural productivity (Ortiz-Bobea et al., 2021; Nguyen & Scrimgeour, 2022). As climatic conditions evolve, more or less land and water may be needed to produce the same amount of crops, depending on the production location. Thus, future climate change needs to be factored into future land and water demand projections.

Changes in socioeconomic conditions, by contrast, have indirect impacts on land and water stress through domestic and global supply chains. The indirect impacts are driven by a variety of trends. First, the growth of agricultural production will be driven by the growing global demand for food and other products, such as biofuels and cloths, through the industrial supply chains. Agricultural products function as both final goods for consumers and as intermediate inputs for the production processes of other industries (Bruckner et al., 2019). Therefore, projecting future agricultural demand requires considering the interindustrial input-output linkages to meet the demand for all industries in the economic system.

Second, demand growth in the future will depend on three main socioeconomic factors in each of countries considered here: population, income, and urbanization. A growing population will lead directly to demand growth in all sectors. A rise in income level will have both scale and structural effects. The scale effect (or income effect) refers to the increase in consumption due to an increase in income. The structural effect (or substitution effect) refers to changes in consumption patterns in response to an increase in income (Fouquet, 2020). The extent of urbanization in a country may also impact people's consumption and lifestyles. When residents migrate from rural to urban areas, changes in consumption patterns could lead to significant environmental impacts (Yu et al., 2016).

What is more, the effect of international trade on land and water demand and competition for water resources between the agricultural and nonagricultural sectors are also of interest. A vital share of the products of Bolivia, Colombia, Ecuador, and Peru are currently being used to meet the demand of foreign countries through international trade and this demand is expected to increase in the future. Hoekstra and Mekonnen (2012) found that about one-fifth of the global water footprint relates to export. Also, about 21 to 37 percent of global land use is associated with international trade (Wiedmann & Lenzen, 2018). In addition, competition for water between the agricultural and nonagricultural sectors is an increasing challenge for Latin American countries (De Oliveira et al., 2009). Although agriculture is the primary user of water resources, Latin American countries are experiencing industrialization and urbanization, which together are driving a rapid rise in water demand.

This study projects the impacts of the above-mentioned factors on water and land resource stress in Bolivia, Colombia, Ecuador, and Peru by constructing future coupled climate-socioeconomic scenarios. Regarding how to coordinate future water or land resource stress, the deployment of irrigated agriculture may be a feasible solution when a region has ample water resources (Zhong et al., 2021). Irrigated agriculture can increase crop yield per unit of land by increasing water use (Zhang et al., 2016).

In terms of analytical tools, environmentally extended global multi-regional input-output analysis (GMRIO) is a framework that has been widely used for projecting future demand for land and water resources and environmental stresses under future scenarios (Marquardt et al., 2021; Bjelle et al., 2021). The environmentally extended GMRIO model is able to map out all the direct and indirect supply-demand relationships at the country-sector level and thus can simultaneously consider changes in land and water use intensity (the land and water required for producing a given amount of crop) induced by climate change and global demand changes due to socioeconomic development.

Future coupled climate-socioeconomic scenarios can be obtained by combining Representative Concentration Pathway (RCP) scenarios and Shared Socioeconomic Pathway (SSP) scenarios (Liu et al., 2021). The four RCP scenarios (RCP2.6, RCP4.5, RCP6.0, and RCP8.5) correspond to a wider possible range of radiative forcing values for the year 2100 proposed in the extant literature (2.6, 4.5, 6, and 8.5 W/m2, respectively) (van Vuuren et al., 2011). The SSP scenarios consist of five narratives describing alternative socioeconomic developments, including sustainable development (SSP1), middle-of-the-road development (SSP2), regional rivalry (SSP3), inequality (SSP4), and fossil-fueled development (SSP5) (O'Neill et al., 2017; Riahi et al., 2017). The climate scenarios represented by the RCPs and the socioeconomic scenarios represented by the SSPs have been considered in tandem in a variety of combinations: the most discussed coupled SSP-RCP scenarios are SSP1-RCP2.6, SSP2-RCP4.5, and SSP5-RCP8.5 (Li et al., 2021).

Therefore, in this report, we use the environmentally extended GMRIO model as the primary analytical framework, combining three coupled climate-socioeconomic scenarios (SSP1-RCP2.6, SSP2-RCP4.5, and SSP5-RCP8.5) and considering four factors (climate change, income, population, and urbanization) to project water and land demand in the year 2050 in Bolivia, Colombia, Ecuador, and Peru and compare those countries' future land and water stress with their planetary boundaries. After making the projections, we identify “the sources categorized by the location of the market (domestic and export) responsible for the changes in water and land demand, show the competition for water between the agricultural and other sectors, and then examine water and land stress in different regions within the countries at the major basin level. Finally, we propose the deployment of irrigated agriculture as a potential solution.

Section II describes the model and data sources used in this report. Section III presents the empirical results. Section IV concludes the report with a discussion of potential solutions.

II. Method and Data

1. The environmentally extended GMRIO model

We use the environmentally extended GMRIO model to evaluate how changes in land and water intensity of production induced by climate change and changes in final demand caused by changes in socioeconomic conditions impact land and water demand in four countries.

The basic equation system framework of a GMRIO can be written, following Peters et al. (2011) and Hubacek et al. (2021), as

$$x = (I - A)^{-1} Yl = BYl$$

$$x = \begin{bmatrix} x^1 \\ x^2 \\ \vdots \\ x^n \end{bmatrix};\ A = \begin{bmatrix} A^{11} & A^{12} & \cdots & A^{1n} \\ A^{21} & A^{23} & \cdots & A^{2n} \\ \vdots & \vdots & \ddots & \vdots \\ A^{n1} & A^{n2} & \cdots & A^{nn} \end{bmatrix};\ Y = \begin{bmatrix} y^{11} & y^{12} & \cdots & y^{1n} \\ y^{21} & y^{23} & \cdots & y^{2n} \\ \vdots & \vdots & \ddots & \vdots \\ y^{n1} & y^{n2} & \cdots & y^{nn} \end{bmatrix} \quad (1),$$

where $x = (x_i^s)$ is the total output of sector *i* in region *s*. The technical coefficient submatrix is calculated by $a_{ij}^{rs} = \frac{z_{ij}^{rs}}{x_j^s}$, where z_{ij}^{rs} denotes the intersector monetary flows from sector *i* in region *r* to sector *j* in region *s* and x_j^s is the total output of sector *j* in region *s*. I stands for the identity matrix and B represents the Leontief inverse matrix. The final demand matrix $Y = (y_i^{rs})$ represents domestic and internationally traded final products; specifically, it is the final products produced by sector *i* in region *r* and consumed by the final consumers in region *s*. Finally, l is a unit vector with all elements equal to 1.

By multiplying the environmental intensity vector (the land or water required by USD1 output), we can determine which country's final demand is responsible for a region's land or water use and stress. The land and water use in region *r* induced by the final demand in region *s* can be represented as

$$\begin{aligned} Water^{rs} &= w^r B^{r\cdot} Y^{\cdot s} \\ Land^{rs} &= f^r B^{r\cdot} Y^{\cdot s} \end{aligned} \quad (2),$$

where w^r is the sectoral water intensity vector in region *r* and f^r is the sectoral land intensity vector in region *r*. The water and land intensity capture the agricultural productivity condition, which could be impacted by future climate change in region *r*. The total demand for land and water in region *r* is also affected by the global demand, which is determined by future socioeconomic conditions, including population, income, and urbanization.

2. Scenarios and data

2.1 Baseline

We take the latest GTAP MRIO for 2017 derived from the GTAP v11 database as the data source for our GMRIO model (Aguiar et al., 2022). The GTAP MRIO for 2017 covers 141 regions around the world and 65 sectors, including 8 agriculture sectors: Rice, Wheat, Other Grains, Veg & Fruit, Oil Seeds, Cane & Beet, Fiber Crops, and Other Crops. For water and land use in agriculture, the GTAP-W model provides data for 2011 (Haqiqi et al., 2016). We scale it to 2017 using agricultural water withdrawal and cultivated area from the FAO AQUASTAT database under the assumption of constant structure across eight agricultural sectors (Table 1).

For water use in nonagricultural sectors, we use the industrial and municipal water withdrawal in 2017 from the FAO AQUASTAT database to set an upper bound on the total amount (Hoekstra & Mekonnen, 2012). Because there are no detailed data for water use by industrial sectors in the FAO AQUASTAT database, we take the blue water consumption intensity in 2017 EXIOBASE MRIO for Brazil, Mexico, and the Rest of America region as the point of reference for allocating industrial and municipal water withdrawals across GTAP industrial sectors. We do not consider land use in the nonagricultural sectors, because no data source is available and land use for nonagricultural sectors is relatively small.

TABLE 1: WATER AND LAND USE INDICATORS, 2017

	Bolivia	Colombia	Ecuador	Peru
Land				
Cropland in 2017 (1000 ha)	4488	9892	2464	5718
Boundary for cropland expansion (Kha)	4963	28655	7675	4013
Stress index for cropland	90%	35%	32%	142%
Water				
Freshwater withdrawal in 2017 (km^3)	2	28	10	35
Boundary for freshwater withdrawal	144	590	111	470
Stress index for freshwater	1%	5%	9%	7%

Source: The cropland area and freshwater withdrawal data come from the FAO AQUASTAT database (https://www.fao.org/aquastat).

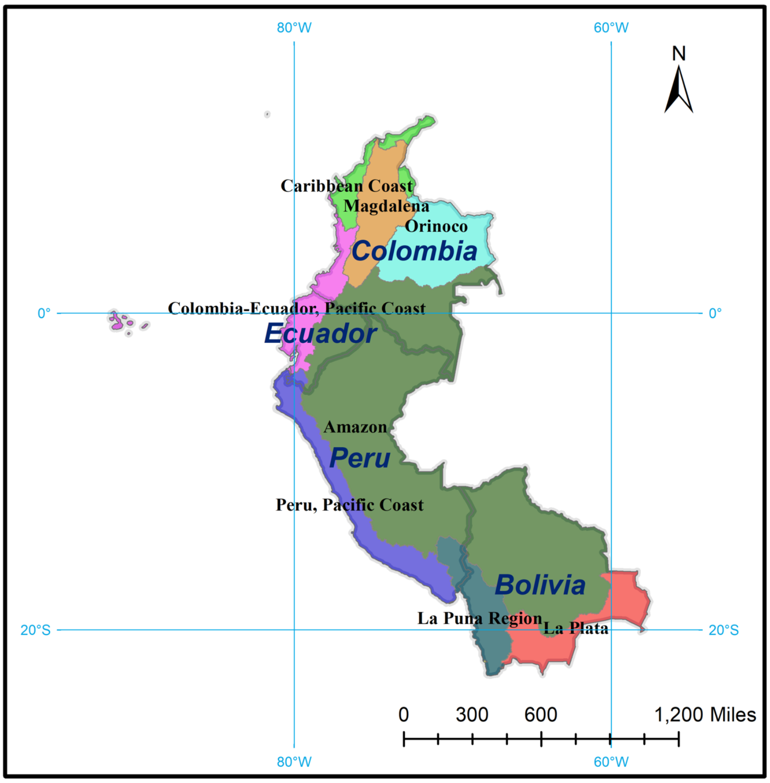
Note: The boundary for cropland expansion is obtained from the low estimation for potentially available cropland in Eitelberg et al. (2015). The boundary for freshwater withdrawal is calculated as 25 percent of total renewable water resources. The stress index is the ratio of the used amount to the boundary.

In terms of the planetary boundaries on freshwater withdrawal, according to the definition in United Nations (2021), when a territory withdraws 25 percent or more of its renewable freshwater resources, it is classified as “water-stress.” Therefore, we calculate the boundaries for freshwater withdrawal as 25 percent of total renewable freshwater resources (Table 1). For the planetary boundaries on cropland expansion, following Shaikh et al. (2021) this report uses the low estimation of potentially available cropland in Eitelberg et al. (2015) as the planetary boundaries for cropland expansion. The reason for choosing the low estimation is that the medium and high estimations in Eitelberg et al. (2015) include a range of natural land-cover classes currently dedicated to biodiversity conservation and other ecosystem services (Lambin et al., 2013; Shaikh et al., 2021).

We define the water/land stress index as the ratio of the used amount to the boundary. When the stress index is smaller than 1, we can say that the resource utilization in the region is sustainable and when the index is greater than 1 resource utilization is unsustainable. Table 1 shows that at the national level, Bolivia, Colombia, Ecuador, and Peru have abundant water resource endowments with ample safe space to their planetary boundaries for freshwater withdrawal. However, in terms of cropland, Peru has already exceeded its boundary for agricultural land use and Bolivia is close to its boundary.

To determine the land stress at the basin level, we use the Land Cover Maps V2.1.1 produced by the European Space Agency (ESA) Climate Change Initiative (CCI) (Bontemps et al., 2013) to identify the cropland area at the basin level. Because ESA CCI and FAO use different methods to generate the cropland data (Liu et al., 2018), in order to maintain consistency between basin-level and national-level analysis we scale the basin-level cropland in ESA CCI to the total cropland record in the FAO AQUASTAT database. For water stress at the basin level, we employ the Aqueduct Water Stress Projections Data produced by the World Resource Institute (WRI) to get the water demand and supply at the basin level (Luck et al., 2015). Also, to maintain consistency with the national level, we scale the water supply and demand to the record in the FAO AQUASTAT database. In other words, we obtain the national-level information from the FAO AQUASTAT database and downscale it to the basin level based on the spatial distribution structure from ESA CCI and WRI. Such treatment does not introduce new bias into the magnitude of land/water stress estimates. However, the specific water and land use numbers do depend on FAO's statistical methodology. For the boundaries of basins, we use the global major hydrological basin boundary shape file in the FAO AQUASTAT database to divide the countries into multiple basin regions. As shown in Figure 2, there are eight major basins associated with Bolivia, Ecuador, Colombia, and Peru: Caribbean Coast; Magdalena; Orinoco; Colombia-Ecuador, Pacific Coast; Amazon; Peru-Pacific Coast; La Puna Region; and La Plata. It should be noted that some basins extend over multiple countries. For example, all four countries contain portions of the Amazon Basin.

FIGURE 2: **THE MAJOR HYDROLOGICAL BASINS IN COLOMBIA, ECUADOR, PERU, AND BOLIVIA**



Source: FAO AQUASTAT database (https://www.fao.org/aquastat).

Note: The different colors represent the different basins.

2.2 Coupled climate-socioeconomic scenarios.

The climate scenarios in this report are based on the Representative Concentration Pathway (RCP). The Fifth Assessment Synthesis Report of the Intergovernmental Panel on Climate Change (2014) adopted the RCP for simulating greenhouse gas concentration trajectories. Depending on the amount of greenhouse gases (GHG) emitted in the coming years, the pathways describe various climate futures that are all thought to be plausible. A range of radiative forcing values predicted for the year

2100 (2.6, 4.5, 6, and 8.5 W/m2, respectively) is used to name four RCPs: RCP2.6, RCP4.5, RCP6, and RCP8.5.

The potential changes in agricultural productivity in 2050 are projected on the basis of future climate scenarios and the improvement of agricultural technology. This procedure obtains the agricultural productivity under future RCP climate scenarios from the GAEZ v4 model (FAO & IIASA, 2020). The GAEZ v4 model projects the water and land demand in 2050 for 51 crops under four climate scenarios: RCP2.6, RCP4.5, RCP6, and RCP8.5. To obtain the productivity changes for 8 agricultural sectors in GTAP MRIO, we first match the data for 51 crops in the GAEZ v4 model to the 8 sectors in GTAP MRIO. Then, by comparing the land and water demands of the eight aggregated sectors for 2020 and 2050, we get the predictions of productivity changes caused by climate changes (see Tables A.1 and A.2).

Apart from the climate factor, future agricultural productivity will also be impacted by the improvement of technology. For example, green water and land management improvements will reduce the water and land requirements for agricultural production. However, it is difficult to predict how technology will evolve. Therefore, we can only assign exogenous assumptions of technological progress. Similar to Distefano & Kelly (2017), we assume that improvements in irrigation technology can improve water use efficiency by 30 percent and land management technology can improve land use efficiency by 30 percent in 2050 compared to 2017. We modify the land and water intensity in formula (2) to reflect the land and water use impacts caused by the changes in agricultural productivity. For example, under a future climate scenario, the land required to produce 1 ton of cereal grains increases by 10 percent, but at the same time technology improvement reduces the land needed by 30 percent. The new land intensity would equal 77 percent ([1 + 0.1] * [1 – 0.3]) of the original land intensity.

The socioeconomic scenarios in this report are based on SSPs. In terms of broad societal trends, the five SSP narratives provide a textual description of how the future might develop. Riahi et al. (2017) summarize the narratives as follows:

- SSP1 is defined as Sustainability – Taking the Green Road. Slowly but surely, the world is moving toward a more sustainable path, emphasizing more-inclusive development that honors perceived environmental boundaries.
- SSP2 is defined as the Middle of the Road. The world travels along a path where social, economic, and technological trends do not diverge noticeably from past trends. Some nations make relatively good progress toward development and income growth, while others fall short of expectations.
- SSP3 is defined as Regional Rivalry – A Rocky Road. Countries are being pushed to concentrate more on domestic or, at most, regional issues by a resurgence of nationalism, worries about competitiveness and security, and regional conflicts.

- SSP4 is defined as Inequality – A Road Divided. High disparities in human capital investments, along with expanding gaps in economic opportunity and political influence, contribute to rising inequality and stratification between and within nations.
- SSP5 is defined as Fossil-fueled Development – Taking the Highway. In order to achieve rapid technological advancement and human capital development, this world places an increasing amount of faith in competitive markets, innovation, and participatory societies.

Each SSP scenario describes different plausible socioeconomic trends. For example, in SSP1 Sustainability, the world will become more inclusive and sustainable, which means the income inequality within and between countries will be reduced and production activities will be more environment friendly due to the energy transition. In SSP2 The Middle of the Road, world economic development will follow the past trend: some countries will see faster growth than others and income inequality will persist. In SSP5 Fossil-fueled Development, the world will fall into a resource- and energy-intensive development track, in which the global economy will achieve fast growth benefits from the massive use of fossil fuels.[1]

Some experts have developed population, economic growth, and urbanization projections for each SSP narrative at the national level (Samir & Lutz, 2017; Dellink et al., 2017; Jiang & O'Neill, 2017). All these predictions have been synthesized into

[1] O'Neill et al. (2017) provide a detailed description of the SSP narratives.

a unified SSP database by the International Institute for Applied Systems Analysis (IIASA). Thus, to model the future demand change induced by changes in socioeconomic conditions, we use the projections for the national population, GDP, and urbanization projection by SSPs from the SSP Scenario Database, IIASA (see Figures A.1–A.3 for the global projections of GDP, population, and urbanization).[2]

Different SSP scenarios also imply different climate change mitigation challenges. For example, the sustainable pathway represented by SSP1 will have the lowest mitigation challenge. In contrast, the fossil-fueled pathway represented by SSP5 will be more likely to cause high emissions and thus have a higher mitigation challenge. As discussed in Rogelj et al. (2018), there are multiple possibilities for coupling SSP and RCP scenarios. However, in general, a lower SSP scenario is more likely to be combined with a lower RCP scenario. In this report, similar to Li et al. (2021), we consider three coupled SSP-RCP scenarios for 2050: SSP1-RCP2.6, SSP2-RCP4.5, and SSP5-RCP8.5.

What should be noted is that when looking at the growth in demand arising from income growth, we need to consider changes in consumption patterns. Here, we use the income elasticity data set provided by GTAP to predict the intersectoral distribution of demand growth. Also, we assume that countries can maintain their comparative advantage and that the future global trade structure will not change

[2] More detail on the national-level projections can be found on the website of the SSP Scenario Database, IIASA (https://tntcat.iiasa.ac.at/SspDb).

(Distefano & Kelly, 2017). In addition, in order to consider the impact of urbanization, we assume that the demand of urban households is twice that of rural households (Yu et al., 2016).

Finally, as shown in Table 2, in this report we perform stepwise simulations to obtain the water and land demands driven by different factors under future scenarios. For example, the effect of changes in agricultural productivity is the difference between the S1 and Baseline scenarios. Similarly, the population effect is the difference between the S2 and S1 scenarios, the income effect is between the S3 and S2 scenarios, and the urbanization & lifestyle effect is between the S4 and S3 scenarios.

TABLE 2: STEPWISE SIMULATION FOR FOUR FACTORS BY COUPLED SSP-RCP SCENARIOS

	Agricultural Productivity	**Population**	**Income**	**Urbanization & Lifestyle**
Baseline	2017	2017	2017	2017
S1	2050	2017	2017	2017
S2	2050	2050	2017	2017
S3	2050	2050	2050	2017
S4	2050	2050	2050	2050

III. Results

1. Growth and drivers of future land and water demand

Under the three coupled SSP-RCP scenarios, all four countries experience significant land and water demand growth. In Bolivia, water demand grows fastest under SSP1-RCP2.6 and SSP5-RCP8.5, while land demand grows fastest under SSP1-RCP2.6. In Colombia, water demand grows fastest under SSP5-RCP8.5, while land demand grows fastest under SSP1-RCP2.6. The fastest-growing scenario for both water and land demand in Ecuador and Peru is SSP1-RCP2.6. As shown in Table 3, under SSP1-RCP2.6, water demand in Bolivia, Colombia, Ecuador, and Peru will significantly increase from 2017 to 2050—by 268, 164, 155, and 122 percent, respectively. Cropland demand will increase by 204, 89, 117, and 93 percent in the same time period.

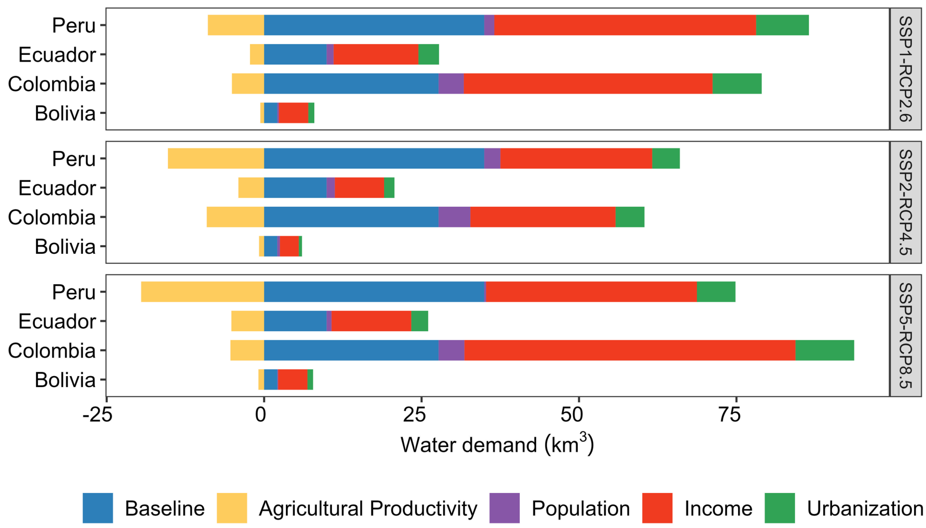
In this report, we calculate the stress index as the ratio of used water/land to the planetary boundary. In Table 3, it can be observed that all four countries remain within their planetary boundaries for water use due to their abundant water resources, despite the noticeable increase in the water stress index of each relative to 2017. With respect to land use, Colombia and Ecuador will remain within their boundaries. Bolivia and Peru, however, will be significantly beyond their planetary boundaries of land use under all three SSP-RCP scenarios.

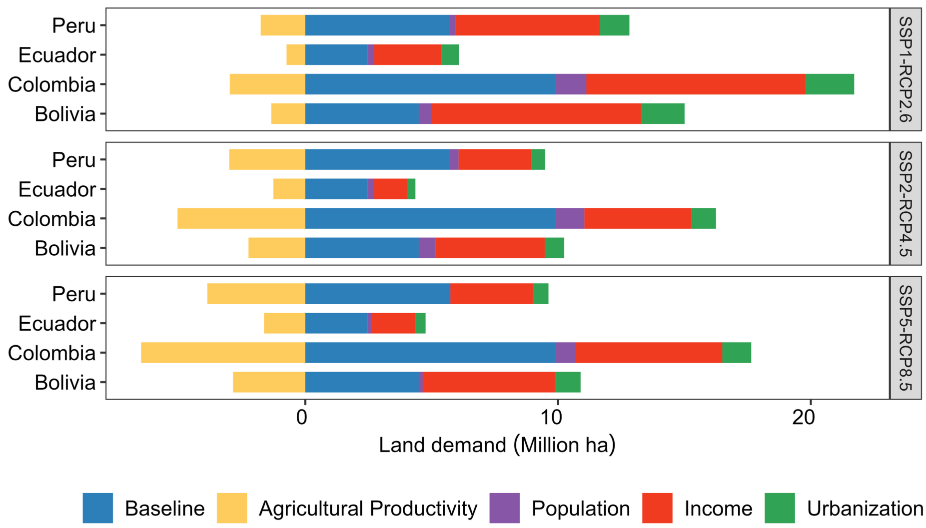
TABLE 3: WATER AND LAND STRESS UNDER FUTURE COUPLED SSP-RCP SCENARIOS

		Water		Land	
		Amount (km^3)	Stress index	Amount (1000 ha)	Stress index
Bolivia	SSP1-RCP2.6	7.37	5.1%	13662	275.3%
	SSP2-RCP4.5	5.21	3.6%	7995	161.1%
	SSP5-RCP8.5	6.87	4.8%	8032	161.8%
Colombia	SSP1-RCP2.6	79.90	12.5%	18729	65.4%
	SSP2-RCP4.5	51.28	8.7%	11193	39.1%
	SSP5-RCP8.5	88.34	15.0%	11150	38.9%
Ecuador	SSP1-RCP2.6	25.53	23.1%	5338	69.6%
	SSP2-RCP4.5	16.61	15.0%	3093	40.3%
	SSP5-RCP8.5	20.85	18.9%	3128	40.8%
Peru	SSP1-RCP2.6	77.57	16.5%	11058	275.6%
	SSP2-RCP4.5	50.74	10.8%	6484	161.6%
	SSP5-RCP8.5	55.32	11.8%	5748	143.2%

Figure 3 shows the growth of water and land demand under the various coupled SSP-RCP scenarios and the contributions from four socioeconomic and climate factors. Income growth will have the most significant impact on both future land and water demand. Growth of population and development of urbanization, on the other hand, will lead to a relatively small increase in water and land demand. Changes in agricultural productivity will inhibit the growth of both water and land demand to some extent, but not enough to offset the contribution of the other factors. On average, for all countries and scenarios the income level, population, and urbanization factors will by 2050 lead to increases in water demand of 21.72, 1.80, and 4.21 km^3 and increases in land demand of 4.51, 0.48, and 0.94 million ha, respectively. At the same time, the agricultural productivity factor will reduce water demand by 6.43 km^3 and land demand by 2.78 million ha.

FIGURE 3: DRIVERS OF WATER AND LAND DEMAND GROWTH UNDER THE COUPLED SSP-RCP SCENARIOS





Note: The baseline represents the situation in 2017. The corresponding colors reflect the contribution of each of the four factors (agricultural productivity, population, income, and urbanization) to the level of water and land demand in 2050 compared to 2017.

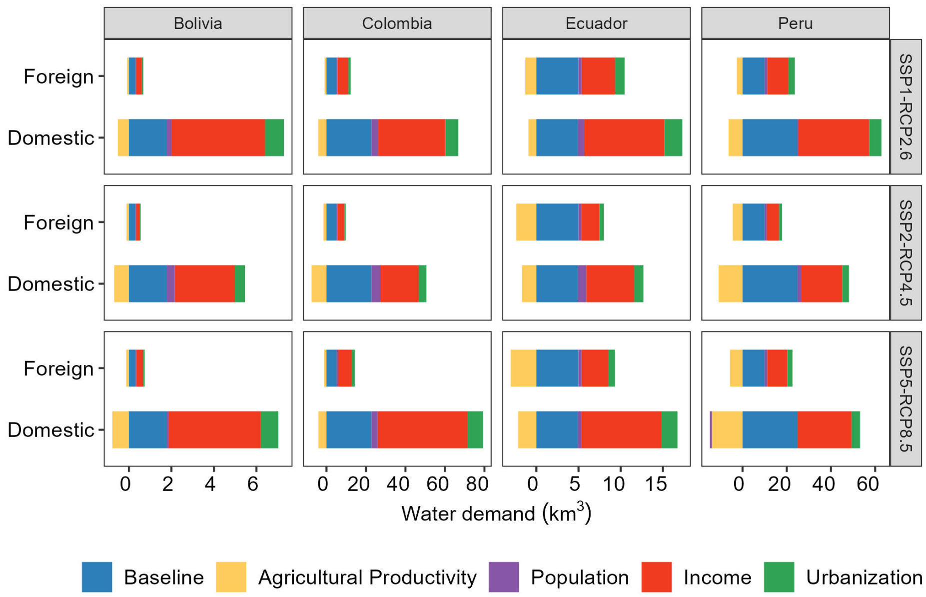
2. The role of foreign trade

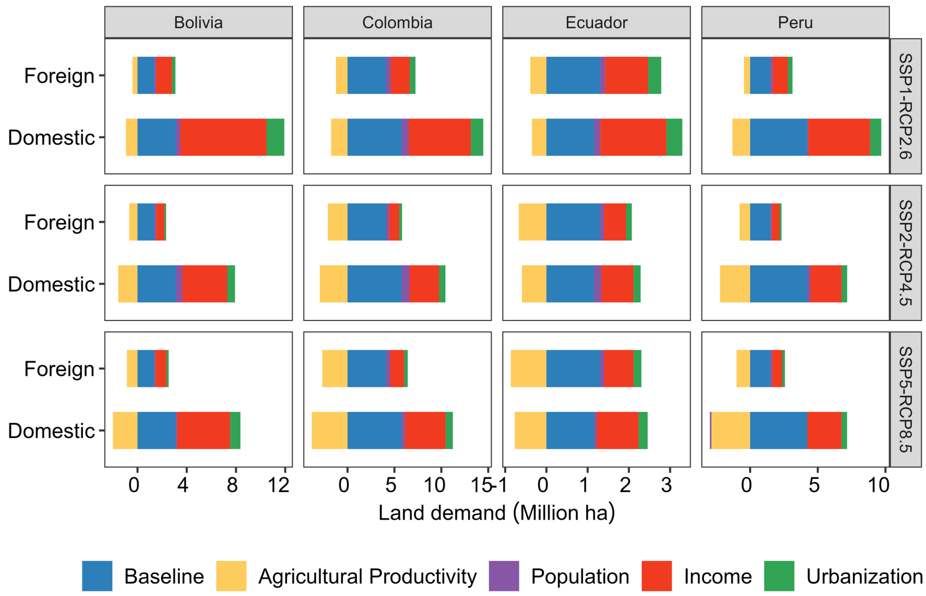
We distinguish the resource use induced by domestic and foreign demand to identify the impact of international trade on water and land use expansion in Bolivia, Colombia, Ecuador, and Peru. Figure 4 shows the impacts of various geographical sources.

Ecuador will be the country most affected by foreign demand for water resources, with about 36 percent of its water demand associated with export production activities under the SSP1-RCP2.6 scenario. Regarding land resources, the countries most affected by foreign demand will be Colombia and Ecuador, where about 30 and 45 percent of the land demand, respectively, under the SSP1-RCP2.6 scenario are associated with export production. Moreover, among the four socioeconomic factors of foreign demand, growth of foreign income levels will play the most critical role. This is because Ecuador and Colombia's trading partners are mainly developing economies that are expected to experience rapid income growth. Comparing different climate-socioeconomic scenarios, foreign demand will drive the growth of water and land demand more strongly in the four countries under SSP1-RCP2.6.

It should be noted that although foreign factors will play an important role in water and land demand growth in Ecuador and Colombia, the growth induced by local demand will largely be responsible for the increased consumption of water and land. All four countries discussed here are developing countries that are experiencing rapid local income growth and urbanization. These will be the main drivers of future water and land stress in the region.

FIGURE 4: THE IMPACT OF DOMESTIC AND FOREIGN DEMAND ON LAND AND WATER DEMAND IN BOLIVIA, COLOMBIA, ECUADOR, AND PERU





Note: The water and land demand induced by foreign demand are also commonly referred to as the "virtual water trade" and "land embodied in trade," respectively (Liu et al., 2019; Yu et al., 2013).

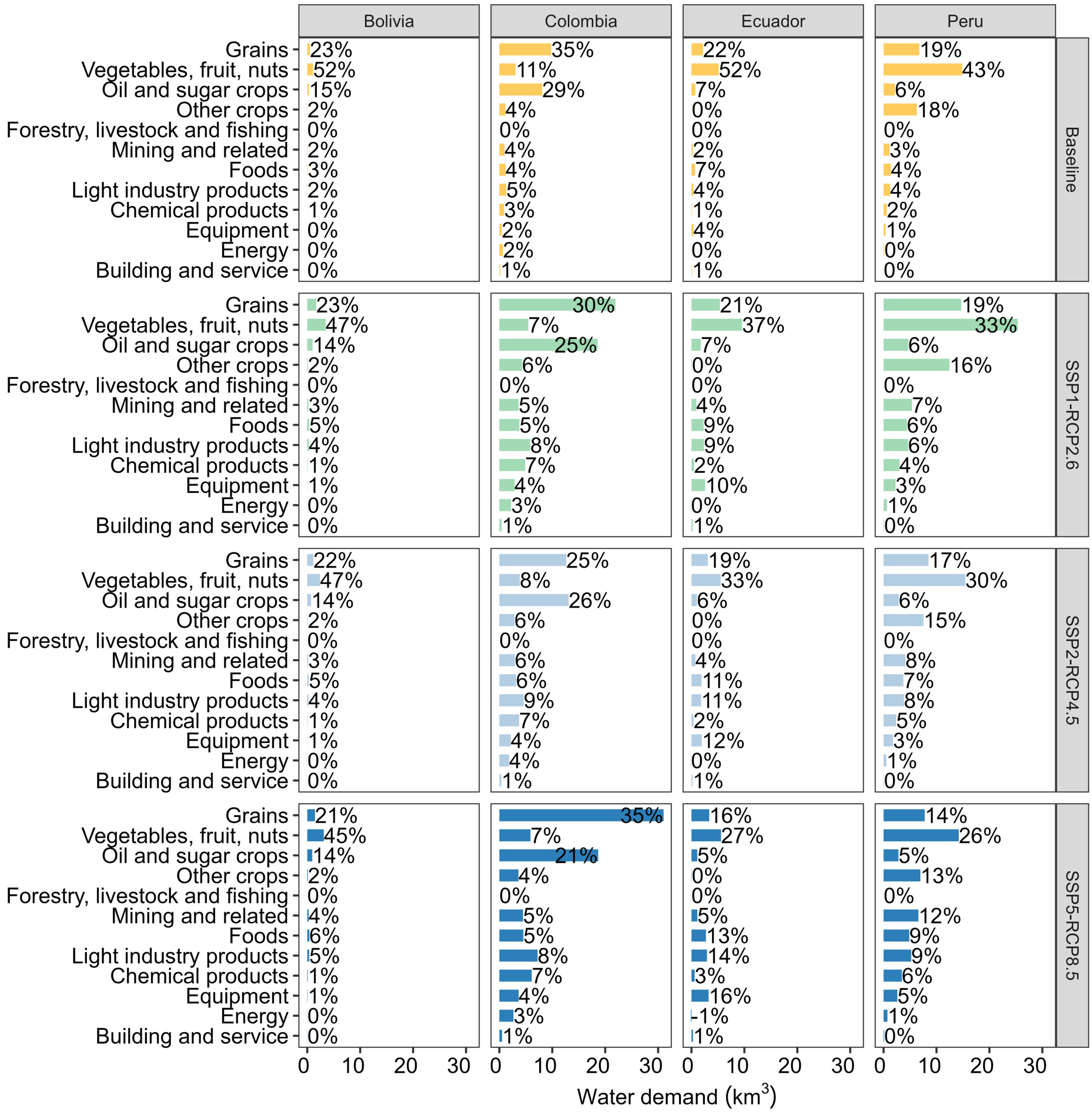
3. Water competition

Figure 5 compares water demand in agriculture and other sectors across the four countries. For the sake of clarity, we have aggregated the 65 sectors in GTAP MRIO into 11 sectors. Table A.3 shows the concordance tables.

In the baseline scenario, agricultural sector dominates water demand and water competition between agricultural and nonagricultural sectors is relatively moderate. In 2017, the share of water used for agricultural products (the sum usage for Grains; Vegetables, fruit, nuts; Oil and sugar crops; Other crops; and Forestry, livestock, and fishing) in Bolivia, Colombia, Ecuador, and Peru accounted for 95, 84, 88, and 90 percent, respectively, of the total freshwater withdrawals in these countries. In Bolivia, Ecuador, and Peru, Vegetable, fruit, and nuts crops account for the largest agricultural water use, whereas Grains and Oil and sugar crops dominate water use in Columbia.

However, the water demand of the nonagricultural sectors will grow much faster than that of the agriculture sector in all of these countries under the four scenarios. For example, the proportions of nonagricultural sector water use in total water use are projected to increase from 5, 16, 12, and 10 percent in the baseline to 12, 28, 39, and 34 percent in Bolivia, Colombia, Ecuador, and Peru, respectively, under the SSP5-RCP8.5 scenario. The increases in water use in the agricultural sectors of each country are projected to be 204, 174, 46, and 17 percent, respectively, under this scenario, while the increases in water use in the nonagricultural sectors are projected to be 723, 454, 590, and 429 percent, respectively. Nonagricultural sectors will make comparable contributions to the growth of total water use as the agricultural sectors in Ecuador, Colombia, and Peru, while the agricultural sector will remain the main contributor in Bolivia.

FIGURE 5: WATER DEMAND BY SECTORS AT BASELINE AND UNDER COUPLED SCENARIOS SSP1-RCP2.6, SSP2-RCP4.5, AND SSP5-RCP8.5



Note: The proportions indicate the share of each sector in the country's total water demand.

Across the four countries the sectors that presently compete with agriculture for water resources are mainly the manufacturing sectors. An increase in the water use of manufacturing results from industrialization and urbanization. However, due to the different economic structure of the four countries, the major water-consuming manufacturing sectors vary significantly. For example, in Bolivia the water demand of manufacturing is mainly driven by the Foods and Light industrial products sectors; in Colombia, the Light industrial and Chemical products sectors are the main contributors; in Ecuador, they are the Foods, Light industrial products, and Equipment sectors; and in Peru, the Mining and related sector is the dominant manufacturing sector in terms of water demand.

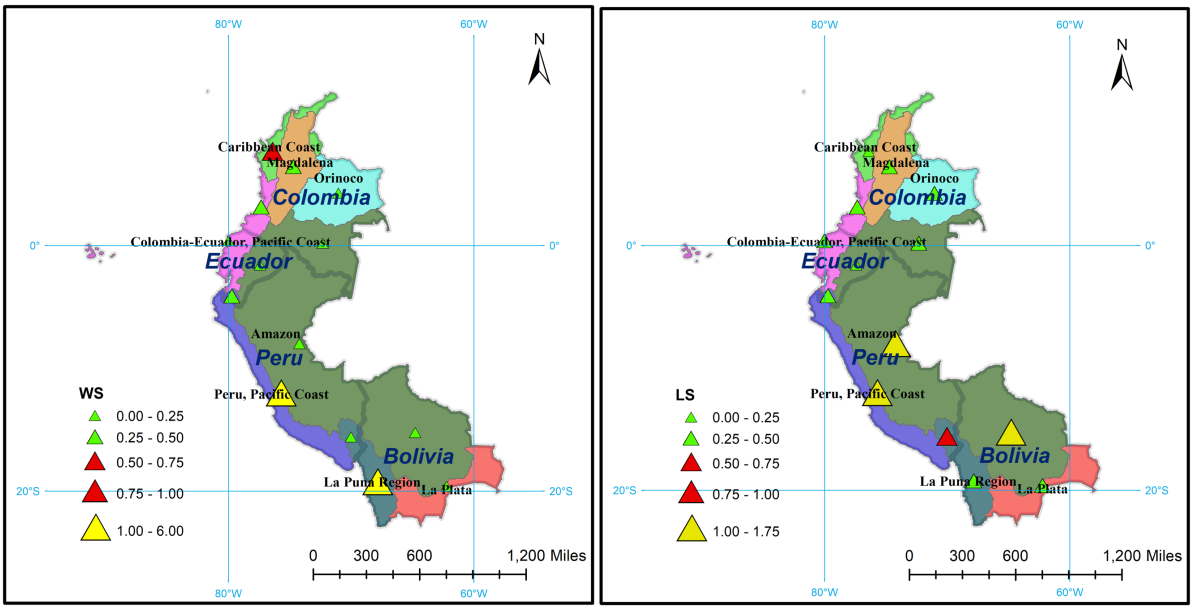
Water competition between the mining and agricultural sectors in Peru has received attention in numerous studies and reports (Bebbington & Williams, 2008; Budds & Hinojosa, 2012). Our study estimates that freshwater use in the mining sector in Peru will increase from 3 percent in 2017 to 7, 8, and 12 percent in 2050 under the three scenarios discussed. With Peru being a globally important mineral supplier, the rapid development of the mining industry in the country will further intensify the competition for water resources between the agricultural and mining sectors.

4. Water and land stress at the basin level

To further examine the spatial differences within countries, we downscale water and land stress to the major basin level. Figure 6 shows the land and water stress at the basin level for 2017. Under the future coupled climate-socioeconomic scenarios, the growth of pressure in each basin will be consistent with the trend at the national level (Figure 3) and therefore will not be shown repeatedly in this report.

In terms of water stress, the Pacific Coast Basin in Peru and the La Puna Region in Bolivia currently have a water stress index bigger than 1, which means water use in these basins has already exceeded their planetary boundaries. In addition, water use in the Caribbean Coast Basin and the Colombia-Ecuador, Pacific Coast Basin in Colombia is close to the planetary boundaries, which means the future growth of water demand will create significant pressure on water resources in these regions. In terms of land stress, the Amazon Basin and Peru, Pacific Coast Basin in Peru and the Amazon Basin in Bolivia have already exceeded the boundaries. The La Puna Region in Peru will also face severe land resource constraints in the recent future.

FIGURE 6: WATER AND LAND STRESS AT THE BASIN LEVEL ACROSS COLOMBIA, ECUADOR, PERU, AND BOLIVIA, 2017



Note: WS = water stress, LS = land stress. The red triangles indicate light pressure, green triangles that the basin is close to the planetary boundary, and yellow triangles that the basin has exceeded the planetary boundary.

It is worth pointing out that some countries have spatial mismatches between water and land resources. In particular, Peru, despite having the eighth-largest freshwater resource in the world, has an uneven spatial distribution of freshwater, with 97 percent of the country's available freshwater being in the Amazon Basin (OECD, 2021). The Amazon Basin needs to be protected from agricultural development due to its essential ecosystem service values. In 2017, the agricultural expansion in the Amazon Basin in Peru had already exceeded the planetary boundary, which means further expansion of agricultural land in the Amazon Basin will significantly damage the ecosystem of the Amazon Rainforest. Moreover, in the west of Peru, the Peru, Pacific Coast Basin faces huge water and land stress simultaneously. Thus, although average water scarcity is not a problem in Peru, water stress is still a challenging issue at the subnational level, in particular the water-scarce west in Peru. A similar situation is observed in Bolivia.

5. The trade-off between water and land

As shown in Table 3, Bolivia and Peru will face severe pressure on land resources under the future climate-socioeconomic scenarios discussed in this report. The trade-off between water and land resources can be achieved by deploying irrigated agriculture. This report simulates the water and land outcomes for Bolivia and Peru when the share of irrigated agriculture in the total cultivated area increases by 10, 20, and 30 percent compared to 2017 (Table 4). When conducting the simulation, we use the ratios of irrigated and rain-fed yields to reflect the productivity difference between irrigated and rain-fed agriculture. The FAO AQUASTAT database shows that the ratios of irrigated to rain-fed yields in Bolivia, Colombia, Ecuador, and Peru are 2.00, 1.60, 1.77, and 1.99, respectively.

Table 4 shows that expanding irrigated agriculture can effectively save land and balance water and land stress. For example, in the SSP1-RCP2.6 scenario, if Bolivia expands its irrigated agriculture by 10 percent, its land stress index would decrease by 22.1 percent, while its water stress index would only increase by 2.8 percent. The improvement would be even more pronounced in Peru. Because Peru is water rich in general, a 1 percent increase in the water stress index can offset a much larger land stress index. For example, under the SSP1-RCP2.6 scenario, with a 30 percent expansion of irrigated agriculture in Peru, the land stress index would decrease by 114.5 percent and the water stress index would increase by just 0.4 percent.

TABLE 4: WATER AND LAND STRESS INDEXES UNDER THREE IRRIGATED AGRICULTURE SCENARIOS

Scenario	Stress Index	No irrigation	10%	20%	30%
Bolivia					
SSP1-RCP2.6	Land	275.3%	253.2%	234.5%	218.3%
	Water	5.1%	8.1%	10.7%	12.9%
SSP2-RCP4.5	Land	161.1%	135.9%	116.1%	100.3%
	Water	3.6%	9.7%	17.9%	27.3%
SSP5-	Land	161.8%	124.8%	98.1%	78.5%

RCP8.5					
	Water	4.8%	23.2%	63.9%	126.2%
Peru					
SSP1-RCP2.6	Land	275.5%	217.3%	184.5%	161.0%
	Water	16.5%	16.7%	16.8%	16.9%
SSP2-RCP4.5	Land	161.6%	104.6%	76.5%	58.8%
	Water	10.8%	11.0%	11.1%	11.2%
SSP5-RCP8.5	Land	143.2%	77.1%	48.7%	33.0%
	Water	11.8%	12.1%	12.2%	12.4%

Note: The 10, 20, and 30 percent column headings represent the scenarios in which the share of irrigated cropland in total cultivated cropland is increased by 10, 20, and 30 percent, respectively. The results of the simulations for different irrigated agriculture scenarios presented in this table are based on the land and water stress index data shown in Table 3.

However, as mentioned above there is a significant spatial mismatch of water and land resources in Peru and Bolivia. For example, the Amazon Basin has plenty of water but limited available cropland. In contrast, Peru, Pacific Coast Basin and the La Puna Region lack water resources. Thus, it needs to be borne in mind that the expansion of irrigated agriculture faces some operational difficulties. A potential solution is to construct large-scale hydraulic infrastructure similar to China's South-North Water Transfer Project. Similar interbasin water transfer projects have been or are being built in Peru and Bolivia, such as the Olmos Irrigation Project and Majes Siguas Special Project in Peru and the Yungas de Vandiola transfer project in Bolivia.

However, despite progress, the building of large-scale water transfer projects in these developing countries faces many institutional and financial challenges.

IV. Conclusion

Based on the environmentally extended GMRIO model, this report simulates future land and water demand in Bolivia, Colombia, Ecuador, and Peru using three coupled climate-socioeconomic scenarios: SSP1-RCP2.6, SSP2-RCP4.5, and SSP5-RCP8.5. Under all scenarios, land, and water demand in all four countries will increase rapidly. In the SSP1-RCP2.6 scenario, Bolivia will see the most rapid growth, with water and land demand increasing by 268 and 204 percent, respectively. By 2050, the demand for cropland in Peru and Bolivia will exceed those countries' planetary boundaries.

Increasing income is the most significant factor contributing to rising water and land demand. With regard to the geographical source of demand, foreign demand will play an important role in the growth of water demand in Ecuador and that of land demand in Ecuador and Colombia. The rise in water demand in Ecuador and Peru will be driven largely by water demand from the nonagricultural sectors of those countries with the result that water competition between the agricultural and nonagricultural sectors will increase. In Peru specifically, competition for water resources between the mining and agricultural sectors will continue to escalate.

At the basin level, there is presently a significant spatial mismatch of water and land resources in Peru and Bolivia. The cropland expansion in the Amazon Basin in Peru and Bolivia has already exceeded the planetary boundary of the basin. Although extensive hydraulic infrastructure development may be required, Bolivia and Peru have the potential to achieve substitution of abundant water resources for scarce land resources through the deployment of irrigated agriculture.

We acknowledge that some limitations exist in this report.

First, the input-output model used in this report incorporates the fixed production structure assumption, fixed trade pattern assumptions, and fixed price assumptions, which means the input structure, trade pattern between nations, and the relative price between products would remain the same. As land and water resources become increasingly scarce, the rise in their prices will cause the prices of the products that use them as inputs to rise as well, thereby reducing demand. It should thus be kept in mind that relying on these assumptions produces overestimations of future water and land stress to some degree.

Second, due to the poor availability of industry-level water and land use data, although this report uses total water and land demand from the FAO AQUASTAT database for 2017, the distribution structure between industries is derived from 2011 data provided by GTAP-W. This may introduce a slight bias in the results. Also, this report does not consider land use in nonagricultural sectors due to the unavailability of data. Considering the increasing contribution of urban expansion to land stress, in this report future land stress is underestimated in this respect.

Third, regarding the assumption of future improvement in agricultural productivity, we suppose that the land and water intensity can be decreased by 30 percent in 2050 compared to 2017. Actually, technological progress can be faster or slower, so that the intensity of either or both could be decreased by either more or less than 30 percent. For example, Grafton et al. (2018) show that efficiency improvements in irrigation can lead to higher water consumption (also known as the Jevons paradox). This phenomenon could cause future land and water stress to be understimated.

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Annex

1. The changes in agricultural productivity projected by the GAEZ v4 model

TABLE A.1: CHANGES IN AGRICULTURAL WATER INTENSITY UNDER FUTURE CLIMATE SCENARIOS

		RCP2.6		RCP4.5		RCP8.5	
		Irrigated	Rain-fed	Irrigated	Rain-fed	Irrigated	Rain-fed
Bolivia	Rice	0.999	1.202	1.238	1.308	1.378	2.334
Bolivia	Wheat	0.906	1.095	1.201	1.718	1.293	1.498
Bolivia	Other Grains	0.995	1.152	1.180	1.231	1.235	1.927
Bolivia	Veg & Fruit	0.972	1.030	1.215	1.535	1.301	1.896
Bolivia	Oil Seeds	0.985	1.023	1.219	1.340	1.308	1.640
Bolivia	Cane & Beet	0.975	0.975	1.229	1.462	1.348	1.480
Bolivia	Fiber Crops	1.024	1.364	1.215	1.473	1.388	3.573
Bolivia	Other Crops	0.978	1.037	1.220	1.348	1.335	1.516
Colombia	Rice	1.034	1.016	0.977	0.903	2.540	1.103
Colombia	Wheat	1.280	1.437	0.966	1.151	0.767	0.420
Colombia	Other Grains	1.118	0.885	0.913	1.387	0.890	1.215
Colombia	Veg & Fruit	1.061	1.109	1.171	1.127	1.546	0.962
Colombia	Oil Seeds	1.025	1.127	1.118	1.056	1.429	1.292
Colombia	Cane & Beet	1.155	1.101	1.176	1.119	1.475	1.066
Colombia	Fiber Crops	1.398	1.192	1.200	1.340	1.128	1.035
Colombia	Other Crops	1.010	1.177	1.139	1.086	1.426	1.381
Ecuador	Rice	1.054	0.974	1.012	0.975	1.073	1.047
Ecuador	Wheat	1.057	0.984	0.863	0.926	0.866	1.007
Ecuador	Other Grains	1.068	1.085	0.978	0.929	1.055	1.171
Ecuador	Veg & Fruit	1.020	1.020	0.964	1.026	1.011	0.956
Ecuador	Oil Seeds	1.031	1.009	0.966	0.990	1.022	1.038
Ecuador	Cane & Beet	1.034	1.028	1.017	0.956	1.056	0.997
Ecuador	Fiber Crops	1.065	1.048	1.029	1.046	1.116	1.083
Ecuador	Other Crops	1.026	1.021	0.979	1.014	1.031	1.061
Peru	Rice	1.002	1.000	0.992	1.079	1.030	1.105
Peru	Wheat	0.983	1.017	0.893	0.970	0.875	0.889
Peru	Other	0.995	0.939	0.966	0.996	0.961	0.969

	Grains						
Peru	Veg & Fruit	1.002	0.913	0.997	1.189	1.015	1.240
Peru	Oil Seeds	1.002	1.066	0.990	1.320	1.021	1.415
Peru	Cane & Beet	1.012	0.884	1.038	1.235	1.070	1.569
Peru	Fiber Crops	1.006	0.899	0.991	0.913	0.996	0.891
Peru	Other Crops	1.010	1.005	1.013	1.083	1.026	1.249

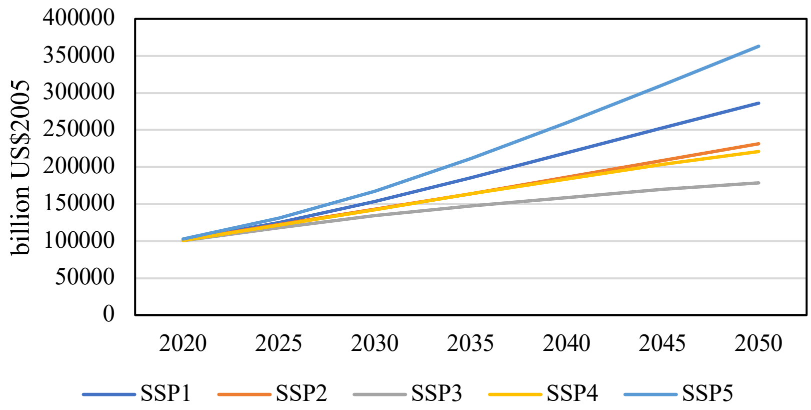
TABLE A.2 CHANGES IN AGRICULTURAL LAND USE INTENSITY UNDER FUTURE CLIMATE SCENARIOS

		RCP2.6		RCP4.5		RCP8.5	
		Irrigated	Rain-fed	Irrigated	Rain-fed	Irrigated	Rain-fed
Bolivia	Rice	0.995	0.997	0.979	1.005	0.963	1.035
Bolivia	Wheat	0.966	0.962	0.931	0.948	0.897	0.914
Bolivia	Other Grains	1.002	0.999	0.978	0.993	0.959	0.993
Bolivia	Veg & Fruit	0.998	1.006	0.989	1.042	0.980	1.062
Bolivia	Oil Seeds	1.005	1.007	1.002	1.033	0.982	1.070
Bolivia	Cane & Beet	1.001	0.998	1.021	1.137	1.027	1.149
Bolivia	Fiber Crops	0.986	0.996	0.922	0.942	0.899	0.939
Bolivia	Other Crops	1.007	1.000	0.988	1.010	0.980	1.021
Colombia	Rice	0.993	0.987	1.014	0.992	1.038	1.001
Colombia	Wheat	0.987	0.987	1.013	0.997	0.953	0.948
Colombia	Other Grains	0.995	0.990	0.995	1.001	0.950	0.979
Colombia	Veg & Fruit	0.998	0.994	1.015	0.991	1.021	0.983
Colombia	Oil Seeds	0.997	1.009	1.006	1.000	1.005	1.016
Colombia	Cane & Beet	1.008	1.006	1.021	1.016	1.059	1.055
Colombia	Fiber Crops	1.051	1.000	0.987	0.975	0.876	0.954
Colombia	Other Crops	1.000	1.004	1.009	1.013	1.020	1.026
Ecuador	Rice	0.997	0.988	0.990	0.981	0.988	0.981
Ecuador	Wheat	0.996	0.974	0.977	0.941	0.959	0.896
Ecuador	Other Grains	0.994	0.993	0.987	0.988	0.974	0.978
Ecuador	Veg & Fruit	1.008	0.998	1.013	0.991	1.017	0.973
Ecuador	Oil Seeds	0.999	0.997	0.990	0.989	0.983	0.987
Ecuador	Cane & Beet	1.022	1.009	1.040	1.008	1.044	1.022
Ecuador	Fiber Crops	1.010	1.010	0.991	0.988	0.980	0.960

Ecuador	Other Crops	1.000	0.996	0.999	0.995	1.009	1.001
Peru	Rice	0.991	0.974	0.986	0.976	0.981	0.990
Peru	Wheat	0.969	0.941	0.923	0.857	0.882	0.812
Peru	Other Grains	0.987	0.974	0.977	0.977	0.962	0.969
Peru	Veg & Fruit	0.993	0.989	0.981	0.985	0.964	0.971
Peru	Oil Seeds	1.000	1.001	1.000	1.006	0.987	1.005
Peru	Cane & Beet	1.009	1.009	1.034	1.055	1.050	1.086
Peru	Fiber Crops	0.993	0.968	0.977	0.957	0.961	0.927
Peru	Other Crops	1.004	0.993	1.004	0.991	1.000	0.990

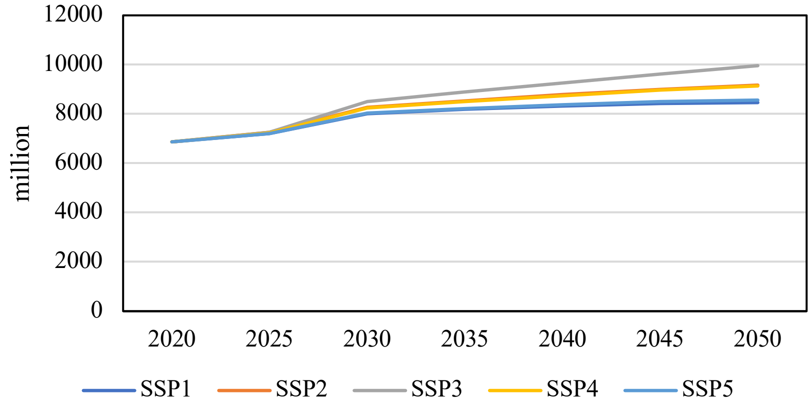
2. GDP, population, and urbanization trajectories under the five SSP scenarios

FIGURE A.1: GLOBAL GDP PROJECTIONS UNDER THE FIVE SSP SCENARIOS



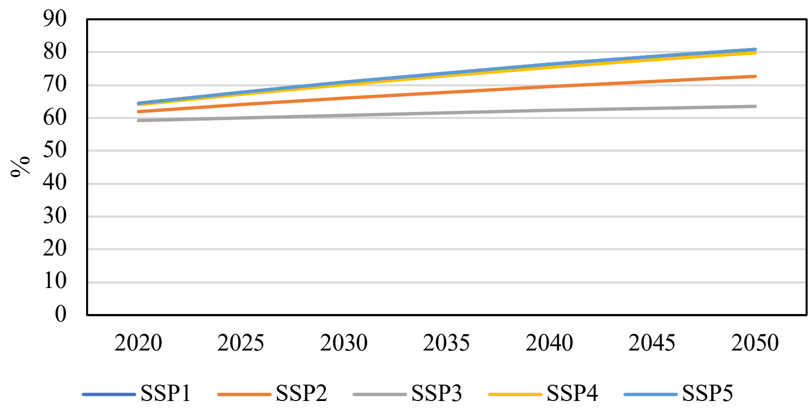
Source: SSP Scenario Database.

FIGURE A.2: GLOBAL POPULATION PROJECTIONS UNDER THE FIVE SSP SCENARIOS



Source: SSP Scenario Database.

FIGURE A.3. GLOBAL URBANIZATION RATE PROJECTIONS UNDER THE FIVE SSP SCENARIOS



Note: The global urbanization rate projection is calculated as the average projected urbanization rate for 193 countries in the SSP Scenario Database.

3. Sector classifications of GTAP MRIO

TABLE A.3: SECTOR CLASSIFICATIONS

No.	GTAP sector	Aggregated sector
1	Paddy rice	Grains
2	Wheat	Grains
3	Cereal grains nec	Grains
4	Vegetables, fruit, nuts	Vegetables, fruit, nuts
5	Oil seeds	Oil and sugar crops
6	Sugar cane, sugar beet	Oil and sugar crops

7	Plant-based fibers	Other crops
8	Crops nec	Other crops
9	Bovine cattle, sheep and goats, horses	Forestry, livestock, and fishing
10	Animal products nec	Forestry, livestock, and fishing
11	Raw milk	Forestry, livestock, and fishing
12	Wool, silk-worm cocoons	Forestry, livestock, and fishing
13	Forestry	Forestry, livestock and fishing
14	Fishing	Forestry, livestock and fishing
15	Coal	Mining and related
16	Oil	Mining and related
17	Gas	Mining and related
18	Other extraction	Mining and related
19	Bovine meat products	Foods
20	Meat products nec	Foods
21	Vegetable oils and fats	Foods
22	Dairy products	Foods
23	Processed rice	Foods
24	Sugar	Foods
25	Food products nec	Foods
26	Beverages and tobacco products	Foods
27	Textiles	Light industry products
28	Wearing apparel	Light industry products
29	Leather products	Light industry products
30	Wood products	Light industry products
31	Paper products, publishing	Light industry products
32	Petroleum, coal products	Chemical products
33	Chemical products	Chemical products
34	Basic pharmaceutical products	Chemical products
35	Rubber and plastic products	Chemical products
36	Mineral products nec	Mining and related
37	Ferrous metals	Mining and related
38	Metals nec	Mining and related
39	Metal products	Mining and related
40	Computer, electronic and optical products	Equipment
41	Electrical equipment	Equipment
42	Machinery and equipment nec	Equipment
43	Motor vehicles and parts	Equipment
44	Transport equipment nec	Equipment
45	Manufactures nec	Equipment
46	Electricity	Energy
47	Gas manufacture, distribution	Energy
48	Water	Energy
49	Construction	Building and services
50	Trade	Building and services
51	Accommodation, food and service activities	Building and services

52	Transport nec	Building and services
53	Water transport	Building and services
54	Air transport	Building and services
55	Warehousing and support activities	Building and services
56	Communication	Building and services
57	Financial services nec	Building and services
58	Insurance	Building and services
59	Real estate activities	Building and services
60	Business services nec	Building and services
61	Recreational and other services	Building and services
62	Public administration and defense	Building and services
63	Education	Building and services
64	Human health and social work activities	Building and services
65	Dwellings	Building and services