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An Analysis of the Water-Energy-Food Nexus in Latin America and the Caribbean Region: Identifying Synergies And Tradeoffs through Integrated Assessment Modeling

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ABSTRACT

The nexus between water, energy and food (WEF) is the focus of growing concerns on the availability of vital resources derived from these intertwined systems, and how to manage the nexus resources to respond to the challenges posed by future human demands, aggravated by the perspective of climate change. This paper uses the recent Paris Climate Agreement as a WEF nexus case study, in which we assess the near-term and medium-term implications of the Paris pledges on the WEF nexus in the region of Latin America and the Caribbean (LAC). For this purpose, we employ the Global Change Assessment Model (GCAM), a state-of-the-art integrated assessment model of human and natural processes that captures the national-level WEF synergies and tradeoffs and allows the understanding of the key drivers of the WEF sectoral interactions and the role of climate policies such as the Nationally Determined Contributions (NDC) that are included in the Paris pledges. Our findings indicate that under the emissions mitigation scenario explicitly modeled to represent the Paris pledges framework, potential conflicts regarding the use of nexus resources in LAC countries may be exacerbated by the induced changes in the energy and food sectors that would impact water availability and use. Despite the differential implications of the Paris pledges across the LAC region, increased water demands for crop irrigation and electricity generation were identified as the pivotal sources of the nexus conflicts that may emerge under the climate policy NDC scenario. Hence, this study underscores the need to refine national climate policies fully-integrated within a WEF nexus resource planning framework such that a balance between the rational use of the nexus resources and stringent climate policies can be found.

KEYWORDS:*water, energy, food, nexus, Latin America and Caribbean*.

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I. BACKGROUND AND OBJECTIVES

The interdependency between water, energy and food is growing in importance as demand for water, energy and food (WEF) securities increases. Several regions of the world are already experiencing WEF security challenges, which adversely affect sustainable economic growth. For instance, in the Latin America and Caribbean (LAC) region, population and income per capita continue to grow, which in turn increases demand for water, energy and food, especially in fast-growing countries. At the same time, scarcity in water, energy or food is caused not only by physical factors, but there are also political and economic issues at play that effect the allocation, availability, and use of these resources.

Almost all primary energy production and electricity generation processes require significant amounts of water, and the treatment and transport of water require energy (mainly in the form of electricity); food production requires both water and energy resources. For instance, even though water use for energy generation is non-consumptive, temperature changes in return flows have impacts on aquatic ecosystems, and conflicts with other uses of water (such as food production) may arise in water scarce regions and basins due to different demand regimes. Climate change will further exacerbate problems like this, as local climate dictates spatial and temporal variations of water availability, and lead to intensified flooding and drought events. This is likely to increase competition for water across sectors, such as agriculture, the biggest consumer of water worldwide, but also energy generation, potable water supply, as well as the environment.

Specifically, in the LAC region, a number of key interactions illustrate the relevance of the WEF nexus. *Water is needed for food production*: 90 percent of the region's agricultural land is rain-fed. In the water-constrained Andes, there is sufficient water to produce a diet of 3,000 kcal with 20 percent animal products. But changing precipitation patterns and growing demand for food are increasing the need for irrigation. Combined with urbanization, this is increasing pressures on rural landscapes and on water supplies.*Water is needed for energy* *generation*: Hydropower supplies 46 percent of the region's electricity, far above the 16 percent global average, but only 38 percent of the region's potential hydropower has been tapped. In addition, growing and producing biofuels can require large amounts of water.*Energy is needed for food production*: This is the least well understood link, but food production, harvesting, transport, processing, packaging, and marketing all use up significant energy resources.*Energy is needed for access to water sources*: Energy is needed for desalination (which could become important mostly in the Caribbean), water distribution, and irrigation.

The LAC region is a net water exporter: the water footprint (Hoekstra and Mekonnen, 2011) varies widely among countries and there are significant water exchanges within the region. For instance, Mexico is one of the major virtual water importers in the world (91 Gm^3/year; Konar et al. 2011). According to Chapaign and Hoekstra (2004), the LAC regional water footprint is 1,136 m^3/person/yr. To give an idea of its variability, the country water footprints of the following countries are: Argentina (1,404 m^3/person/yr), Brazil (1,381 m^3/person/yr), Ecuador (1,218 m^3/person/yr), Perú (777 m^3/person/yr), Mexico (1,441 m^3/person/yr), Honduras (778 m^3/person/yr), Chile (803 m^3/person/yr), Colombia (812 m^3/person/yr) and Venezuela (883 m^3/person/yr).

As a consequence, there is a pressing need for integrated planning of WEF resource development and use, to avoid unwanted and unsustainable scenarios in the coming years. Although the WEF nexus is now fairly evident, these three sectors have historically been regulated and managed separately; and despite growing concern over these trends, decision makers often remain ill-informed about their drivers and ill- equipped to deal with possible outcomes.

II. RESEARCH QUESTIONS

This research is focused on the development ofan integrated analytical model for strategic assessment of the WEF nexus in the LAC region. This model places a focus on soft (policy) and hard (infrastructure and technology) measures towards planning and management in key development sectors such as urban water supply, energy generation and agricultural/food production. The model incorporates physical, economic, and social aspects in the analysis of WEF synergies and tradeoffs in the region.

The key research questions that guided the development of this WEF analytical model can be stated as follows (Miralles-Wilhelm, 2014, 2016):

What are the synergistic opportunities and constraints posed by the mutual interaction and inter- dependency of water, energy and food?

The analytical model developed focuses on scenario planning in order to identify primary opportunities and constraints to water, energy and food supply and demand, yielding priorities for more detailed analysis as well as providing characterization of alternative sequences of impacts in each sector.

What are the impacts of the WEF nexus interactions on policy and decision-making, particularly with respect to development investments?

The developed model employs economic analysisto quantify the implicationsof integrated (nexus) planning approaches on sector investments in water, energy and food. This is an important step toward improved understanding of economic and social tradeoffs among competing uses of resources (i.e., water for energy production versus food production, industrial and municipal uses, and environmental benefits of *in situ* water). The results of this research thus aim at helping stakeholders move in the direction of integrated water-energy-food planning and of prioritization of investments.

What are the threats and opportunities posed by climate change on the WEF nexus in the LAC region?

Although understanding of climate change impacts on the water, energy and food sectors has advanced significantly in recent years, little research has been done on the impacts of climate change on the interacting WEF nexus. Potentially, impacts can be compounded or offset each other, posing threats and opportunities, respectively. This research uses climate scenarios and policies such as country-specific Nationally Determined Contributions (NDC) to identify and quantify these impacts.

What are the institutional barriers for the utilization of WEF nexus integrated planning tools?

The water, energy and food sectors are planned today without much integration, e.g., water is allocated without considering energy constraints, energy generation is planned without much consideration of water sources and costs, food production is planned without considering energy and water requirements for the most part. The case needs to be made that planning tools and institutional procedures in place need to evolve towards integrated planning approaches in order to realize synergies and manage tradeoffs identified through this research.

III. METHODOLOGY

Model Description

The scenario results presented in this paper were modeled using the Global Change Assessment Model (GCAM), release version 4.3, a state-of-the-art Integrated Assessment Model(IAM) designed to explore interactions among critical sectors of the economy, the human, and the physical systems, and to support policy-relevant decisions (Miralles-Wilhelm et al. 2017). GCAM has contributed significantly to advance the scientific understanding of climate change as the IAM selected by the Intergovernmental Panel on Climate Change (IPCC) to model the representative concentration pathway (RCP) 4.5 (Thomson et al., 2011). More recently, GCAM became the marker model for the quantification of the Shared Socioeconomic Pathway (SSP) 4 storyline (Calvin et al., 2017).GCAM is freely available as a community model, and can be obtained through a widely used software repository (see https://github.com/JGCRI/gcam-core). The full documentation of the model is also hosted at GitHub (http://jgcri.github.io/gcam-doc/toc.html), and the following description is a summary of the online documentation.The current implementation of GCAM is oriented towards the coupling of five main systems: socioeconomics, energy, agriculture and land, water and climate. Along the first dimension, socioeconomics, assumptions for population and labor productivity are used to derive GDP in each region, which, in turn, drive the regional economic activity, as well as a large chain of interconnected processes and demand responses in the other systems, such as, energy use, land use, and resulting GHG emissions.

Within a partial market equilibrium economic framework, GCAM represents the global economy by disaggregating the world in 32 geopolitical regions. LAC, in particular, is represented as seven distinct regions: Argentina, Brazil, Central America and Caribbean, Colombia, Mexico, northern South America, and southern South America. As a long-term model, GCAM operates in 5-year time steps until 2100. The base year for the model is 2010, based on calibration to historical energy, agricultural, land, and climate data. In terms of solution algorithm, GCAM is a dynamic-recursive model, which solves each period sequentially (based on existing information for the period being solved) through the establishment of market-clearing prices for all existing markets (energy, agriculture, land, GHG emissions). This means that, for each model period, an iterative scheme ensures convergence to final equilibrium prices such that supplies and demands are equal in all markets.

The energy system structure in GCAM contains explicit modeling of the energy supply and demand sectors for each region, and the trading of primary resources among regions. The model includes representations of the availability and extraction of primary energy resources (oil, natural gas, coal, bioenergy, uranium, hydropower, geothermal, solar, and wind energy) as well as the energy transformation processes (e.g., liquid fuel refineries and power generation) that produce the final fuel carriers (refined liquids, refined gas, coal, commercial bioenergy, hydrogen, and electricity) used by the energy end-use sectors (buildings, industry, and transport). GCAM is particularly detailed in the representations of technology options (including technology evolution in the future) with more than 100 different energy supply and conversion technology representations currently available (McJeon et al. 2014).

Another key component of GCAM is the agriculture and land-use system, which allows projections for agricultural supply (crops, livestock, forest products, and bioenergy), prices, and land-use changes, considering also the trading of primary agricultural goods. In this component, each of the 32 geopolitical regions can be disaggregated into up to 18 agro-ecological zones (AEZs) derived from the work of Monfreda et al. (2009), resulting in a total of 283 agriculture and land use regions. Within each of these 283 subregions, land is categorized into approximately a dozen types based on cover and use. Some of these types, such as tundra and desert, are not considered arable. Among arable land types, further divisions are made for lands historically in non-commercial uses such as forests and grasslands as well as commercial forestlands and croplands. Land allocation within any geopolitical region depends on the relative profitability of all possible land uses within each of its land-use regions (Kyle et al., 2014). Land used for any purpose in GCAM competes economically with croplands, commercial forests, pastures, and all lands not involved in commodity production, with the exception of the following land types whose land cover is exogenous (and assumed constant over time): tundra, rock, ice, deserts, and built-up lands. The profitability of any land used for commercial production is derived from the price (value) of the commodity produced, the costs of production, and the yield (Kyle et al., 2014). GCAM models the production of twelve crop categories based on exogenously specified yields that are crop-specific but vary depending on the subregion. The base year demand for food is calibrated using FAO statistics. The future demand for crop and meat is calibrated to match FAO projections up to 2050. Beyond 2050, the per-capita demand is assumed constant. Assumptions regarding technological progress in the agricultural sector is also derived from FAO (Bruinsma, 2009). The model allows specification of different options for future crop management for each crop in each subregion.

The physical atmosphere, oceans and climate are represented in GCAM by the Hector Earth System model (Hartin et al. 2015), which is a reduced-form global climate carbon-cycle model capable of tracking emissions

generated by the energy, agriculture and land systems of 24 GHGs and short-lived species including: CO_2, CH_4, N_2O, halocarbons, carbonaceous aerosols, reactive gases (e.g. CO, NOx, VOCs) and sulfur dioxide.
The water module within GCAM provides estimates of water demands (gross water withdrawals and net consumptive use) for six sectors divided in agricultural water use (irrigation and livestock) and non-agricultural water use (primary energy production and processing, electricity generation, industrial, and municipal). As described by Hejazi et al. (2014ab), the main characteristics of the GCAM water module are: future agricultural water demands are driven by crop production from GCAM and the share of crop production that takes place on irrigated lands in each of the 283 subregions, and by crop type (12 types). Future manufacturing and domestic water demands are driven by socioeconomic assumptions, among other factors (e.g., future changes in efficiency, technological improvements, and water prices); the water demands for primary energy depend on the amount of each fuel produced whereas water demands for secondary energy (electricity, refined liquid products) depend on the specific production technologies used; and the water use in the electric sector depends not only on the generation technology mix, but also on the types of cooling systems used.

Population and GDP data that are exogenous inputs to GCAM are obtained from the SSP database, and documented in KC and Lutz (2017); Leimbach et al. 2017; Cuaresma, 2017; and Dellink et al. 2017. It is important to consider population and GDP growth trends in the region during this period of analysis, as resource demands are tied to population either directly through consumption or indirectly through consumption of goods and services that require water as input for their production, and to GDP through resources needed for economic output. Figure 1 shows the projected population and GDP in the LAC region over the period of analysis. As is the case globally, in the LAC region population peaks towards midcentury and then decreases mildly towards the end of the century, while the GDP projection shows growththrough the end of the century
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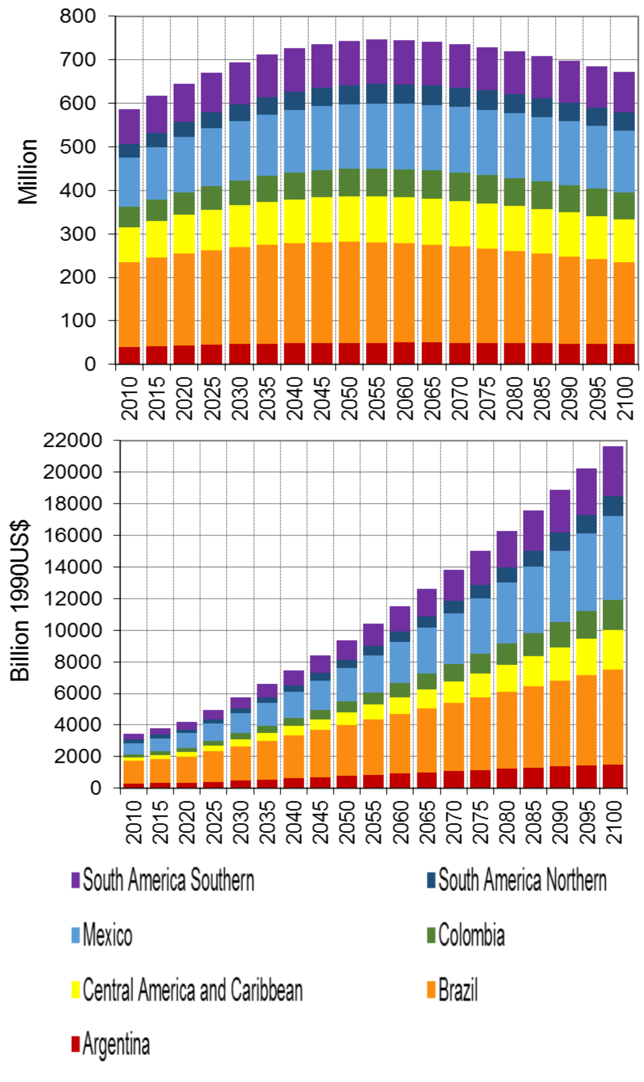

Figure 1*: Population and GDP growth (2010-2100) in the LAC region for the Reference and Policy scenarios.*

Reference Scenario
The reference (no climate policy) scenario to be used as the baseline for comparison with the NDC scenario is based on realistic business-as-usual (BAU) assumptions with regard to population growth, economic growth, energy use, and improvement of technology over time, which, in turn, leads GCAM to generate internally-consistent GHGs emissions. For the reference scenario, no GHG mitigation action is implemented from 2010 throughout the period of the GCAM integration.
The basic socioeconomics assumptions in the LAC region used in the reference scenario are consistent with the "Middle of the Road" shared socioeconomic pathway (SSP) scenario SSP2 (Riahi et al., 2017) with the near-term GDP (up to 2020) harmonized with the projections from the International Monetary Fund (IMF) World Energy outlook database. This process reflects the economic stagnation currently observed in Brazil. The reference scenario is characterized by a population growth of 26% from 2010 to 2050, and per capita Gross Domestic Product (GDP) growth of 167% in the same period. Note that these same socioeconomic assumptions will be shared with the policy scenario.

In the reference scenario, the total primary energy consumption is projected to markedly increase up to 2050 when the percent increase achieves 98% in relation to 2010 levels. In 2010 (calibration year), about 77% of the primary energy in the LAC region came from fossil fuels, predominantly oil (50%) and natural gas (23%). Coal represented a minor contribution of about 4%. Biomass and hydropower constituted important contributors to the regional primary energy in shares of 10% and 8%, respectively. The near-term and medium-term projections indicate that hydrocarbon fuels continue to be the region's dominant energy source with an increasing role of natural gas. In 2050, the primary energy mix is projected to be distributed as follows: fossil fuels in a share of 80% (oil: 37%; natural gas: 35%; and coal: 8%) followed by biomass and hydro with 11% and 5%, respectively. As a result, the share of low-carbon sources (biomass, hydro, nuclear, solar and wind) in total primary energy mix is projected to slightly decline from 23% in 2010 to 20% in 2050. The reference scenario also highlights the substantial expansion of the electricity power sector in the LAC region. Compared to 2010, GCAM projects a threefold increase in the electricity generation for 2050 tied with a larger fossil-fuel based generation. This high reliance on fossil fuels in the energy sector is projected to significantly impact the GHG footprint in the LAC region over the coming decades. In 2050, the gross regional GHGs emissions experience a percent increase of 75% relative to the base-year. In particular, Fossil Fuel and Industrial (FFI) CO_2 emissions grow fast and take a larger proportion of the gross regional GHGs emissions (57% in 2050 versus 51% in 2010). Apart from boosting CO_2 emissions, the projected growth in natural gas and coal usage entails serious additional concerns such as the possibility of fugitive emissions of methane (the major component of the natural gas), which is a potent GHG, as well as increased emissions of sulfur dioxide (SO_2), nitrogen oxides (NOx),particulate matter alongside a series of pollutants associated with the coal combustion with deleterious effects on human health.

In the reference scenario, the regional water withdrawals roughly double from the base-year level until the mid-century, with Brazil and Mexico responsible for the largest shares in water demand. Brazil and Mexico, in this order, represent the two largest population and GDPs in the LAC region, however Mexico is projected to experience higher future water withdrawals than Brazil. In 2010, Mexico and Brazil accounted for 29% and 25%, respectively, of the total regional water withdrawals. However, in 2050, Mexico is projected to experience a percent increase of 83% in the water withdrawals relative to the base-year level, whereas Brazil expects a 69% percent increase. Driven by increasing populations and incomes, and correspondingly increasing demands for food, biomass, and electricity, nearly all sectors exhibit an upward trend in water demand, particularly the irrigation water use, which dominates all other sectors. The shares of irrigation water use relative to the total regional water withdrawals grows from 45% in 2010 to 49% in 2050.

Policy Scenario
The Policy (NDC implementation) Scenario in GCAM was carried out by means of an economy-wide emissions constraint. This means that the gross GHGs emissions were specified for each country/region and the model internally calculated the carbon prices needed to achieve the constraint. These carbon prices were, then, applied uniformly across all sectors. The global GHG emission trajectory is predicated on Fawcett et al. (2015) "Paris-Increased Ambition" scenario with updates on the emissions constraints for the 7 LAC regions (Table 1). The official NDC submissions to the UNFCCC (UNFCCC, 2015ab) guided the definition of the emission constraints used in GCAM. For example, Brazil has committed to reduce all GHG emissions (including LUC) by 43%below 2005 levels in 2030. Mexico has committed to a reduction of 22% in all GHGs (including LUC) below BAU for the year 2030. Likewise, Argentina has committed to a 15% reduction in all GHGs (including LUC) below BAU for 2030 whereas Colombia announced a 20% reduction in all GHGs (including LUC) below BAU for 2030. Given the challenge of translating the official NDCs to explicit quantifications of GHGs

emissions (see Damassa et al. (2015) for an in-depth discussion about the critical transparency gaps contained in the NDCs that affect their understanding), specific assumptions for each country had to be implemented.
Consistent with the climate goals set by the Paris agreement, the NDC scenario in the post-2030 period is anchored on the assumption that countries enhance their mitigation efforts such that their emission reduction targets represent an ambitious progression over the 2025-2030 period. The stringent post-2030 mitigation assumptions in our NDC scenario were designed to illustrate the implications of the Paris pledge framework on the EWL nexus in the LAC region as well as the potential conflicts within the nexus that may be exacerbated as a result of this climate policy.

Table 1: Regional gross GHG emissions (MtCO$_2$e) in the NDC scenario

GCAM region	2010	2020	2030	2040	2050
Argentina	375	449	472	468	443
Brazil	1199	1566	1339	1104	915
Central American and Caribbean	309	313	437	437	437
Colombia	184	200	207	213	219.5
Mexico	654	725	759	551	343
South America_Northern	317	390	488	488	488
South America_Southern	414	520	629	629	629

Table 2: Value of Carbon in Land (2010$/tC)

GCAM region	2010	2020	2030	2040	2050
Argentina	0.0	0.0	1.0	7.0	21.0
Brazil	0.0	0.2	1.5	8.3	22.0
Central American and Caribbean	0.0	2.6	9.9	91.3	163.5
Colombia	0.0	0.1	5.0	50.0	120.0
Mexico	0.0	1.0	7.0	30.0	70.0
South America_Northern	0.0	0.0	0.0	17.0	45.0
South America_Southern	0.0	0.0	1.9	23.5	64.9

Given the large share of agriculture, forestry and other land use (AFOLU) emissions in the LAC region as compared to the rest of world, the successful achievement of the climate goals contained in the NDCs from LAC will greatly depend on the strategies to manage anthropogenic carbon emissions from terrestrial systems. The analysis in this study accounted for GHG terrestrial emissions by explicitly including the AFOLU sector among the sectors covered by their NDCs. However, their emission reduction targets should be achieved by several means of implementation throughout the economy, covering sectors such as energy, transport, industry, waste, etc., apart from the AFOLU sector. Thus, there is great uncertainty on the extent of future land-based emissions reductions in the LAC region derived from the NDCs. Due to the high uncertainties resulting from future indirect land-use change (LUC) emissions, for the NDC scenario, we assumed overall regional efforts towards reduced deforestation and forest degradation (REDD) through exogenous values of carbon in land trajectory (as shown in Table 2). The value of land carbon is assumed to increase over time to avoid widespread deforestation driven by rapid increase in biomass production. This would result in a substantial increase in LUC emissions (Wise et al., 2009), that is in strong disagreement with the intended mitigation goals for the land sector contained in the Paris pledges of the four focus countries of this study. In particular, Brazil and Mexico specified a goal of reaching a rate of 0% deforestation by the year 2030.

IV. RESULTS AND DISCUSSION

WEF Nexus in the LAC Region under the Reference Scenario

Figure 2 shows total water demands in the reference scenario. It is important to note that while results are presented for each of the sectors (water, energy and food), the developed GCAM-LAC model calculates sectoral results that are internally consistent through its partial market equilibrium approach that matches supply and demand for each sector simultaneously. These results show Mexico as a major water user in the region, followed by Brazil. In the case of Mexico, major water withdrawals occur to produce both energy and food, while in Brazil the major use of water is agricultural production, as the country relies on hydropower (which consumes significantly less water than other sources) for a large measure of its electricity generation needs. The regional picture of water demand in LAC is illustrated in Figure 3. The major demand for water in the region is food production (~65 percent on average over the period 2010-2100), which encompasses agricultural crops, livestock and livestock feed. This is followed by water for energy (~20 percent), which includes electricity generation and extractives (industry). Domestic water use (municipal and rural) accounts for the remaining 15 percent over the period of analysis.Primary energy produced in the LAC region is illustrated in Figure 4 and Figure 5. These figures include energy demand not only within the region itself, but also include energy imported/exported to/from other regions of the world. These results for primary energy are reflective of the growth of energy demand due to population growth, as well as increase in energy demand per capita as economic growth occurs worldwide. Figure 14 shows that this projected growth in primary energy will occur across countries in the region. Figure 15 suggests the LAC region will continue to rely on extractives (e.g., oil, natural gas, coal), while several renewable energy options (wind, solar, biomass) which have relatively small footprints at present will grow rapidly over time. This growth in renewables will contribute to the growth in overall primary energy produced, particularly in countries with scarce extractive resources (e.g., Central America and Caribbean).The results for agricultural production in the region are shown in Figure 6 and Figure 7. The overall picture in the region is one of growth through 2050, then stabilization and mild growth towards the end of the century. This is consistent with population growth trends, both globally and in the region, with agricultural production closely tied to per capita consumption of crops. These results also suggest that these temporal trends will occur across countries in the region, particularly in Brazil where production grows rapidly through midcentury (Figure 15); and across crops, with sugar and corn experiencing a higher rate of growth than other crops (Figure 16). The growth in sugar and corn is partially driven by their use in the production of biofuels to mitigate climate change.

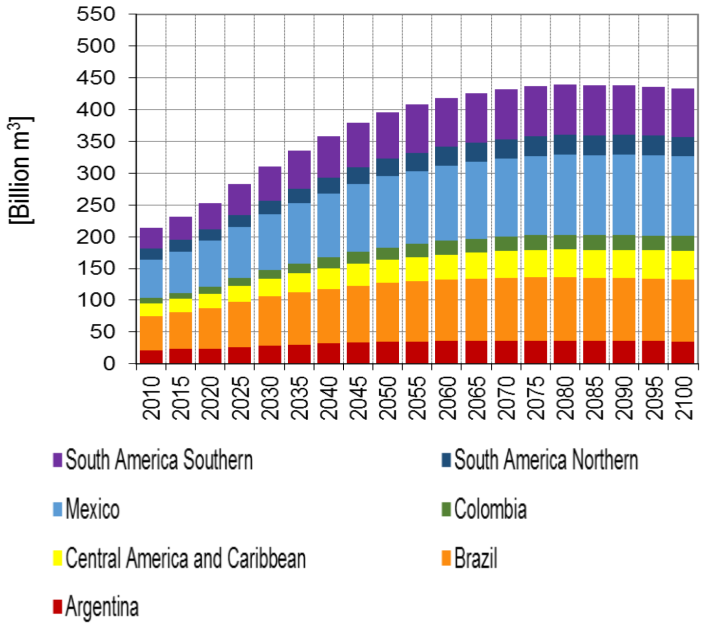

Figure 2: *Total water demand in the LAC region, broken down by subregion; reference scenario.*

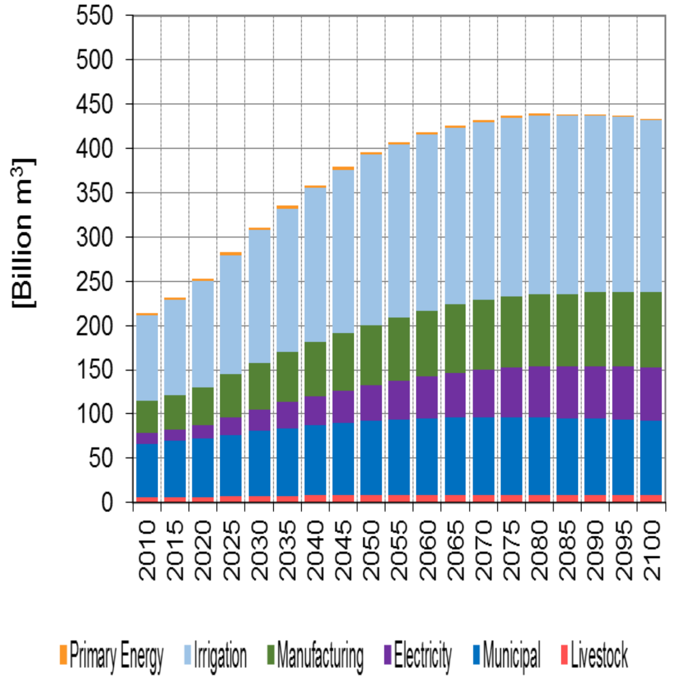

Figure 3: *Total water demand in the LAC region, broken down by sectors; reference scenario.*

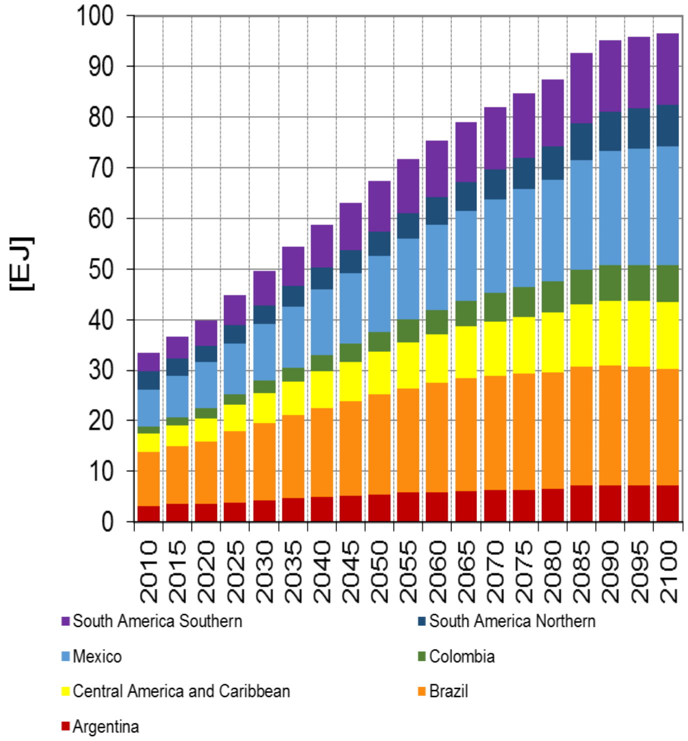

Figure 4: *Primary energy(EJ) producedin the LAC region, by subregion; reference scenario.*

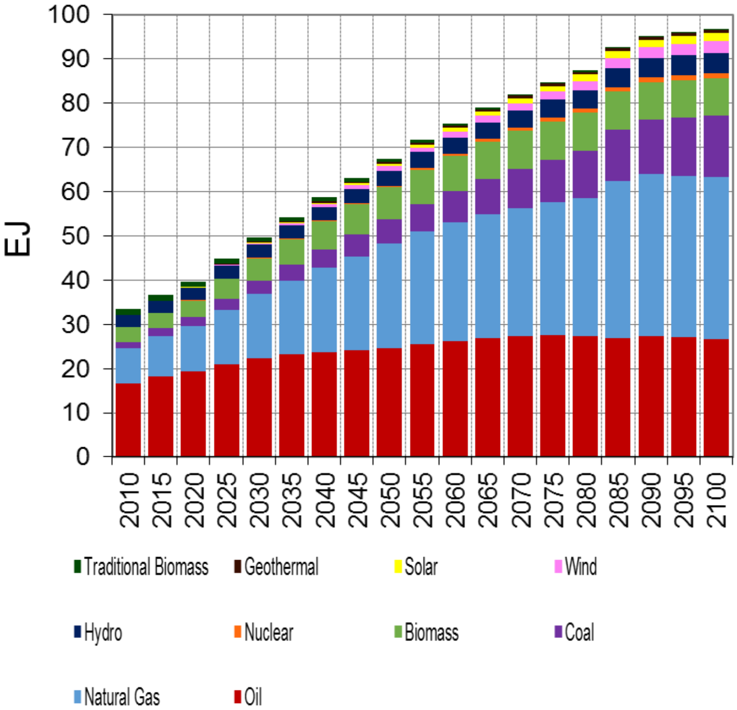

Figure 5*: Primary energy(EJ) produced in the LAC region, by source; reference scenario.*

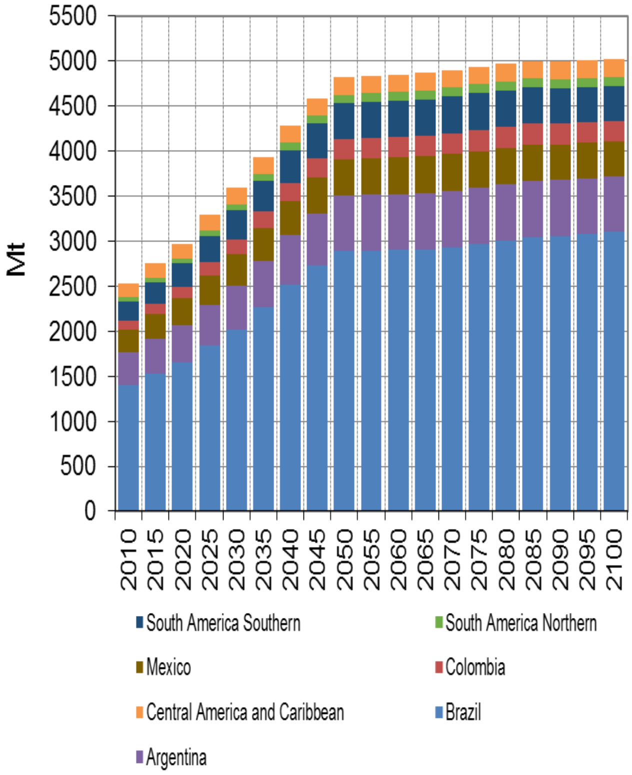

Figure 6*: Agricultural production (MT) in the LAC region, by subregion; reference scenario.*

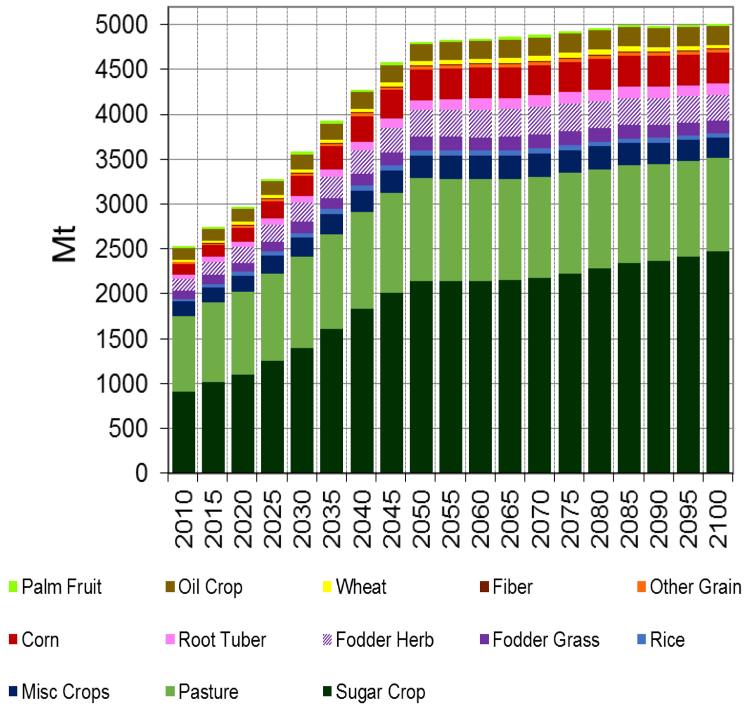

***Figure 7**: Agricultural production (MT) in the LAC region, by crop; reference scenario.*

WEF Nexus in the LAC Region under the Policy (NDC Implementation) Scenario

Under the Policy scenario, Figure 8 shows the total water demand for the LAC region during the period of analysis, broken down by subregion. Comparing these figures with those shown in Figure 2 (reference or business-as-usual scenario), this policy scenario that makes efforts to both mitigate and adapt to climate change, results in an increase in water demands of over 35 percent. Figure 9 shows the water demand broken down into water consuming sectors. This significant increase in regional water demand, although may appear to be counterintuitive, can be explained precisely because of nexus considerations.

An increased focus on climate change, mitigation in particular, places emphasis on an overall reduction of energy demands, and a"decarbonization" of the economy. This moves the energy sources from traditional primary energy (see Figure 5) to an energy matrix like that shown in Figure 10, consisting of a larger mix of more carbon-efficient technologies, particularly biomass andCCS: carbon capture and sequestration.These technologies, although carbon-efficient, are also more demanding of water. This overall trend of reduction in energy demand and decrease in demand of traditional primary energy sources, accompanied by increased water demands occurs across the region as shown in Figure 11.

Also along these lines, demand scenarios that focus on increasing resiliency and sustainability (such as NDC) result in increased usage of land for forest conservation activities for climate mitigation. This results in an overall increase in land used for cultivation of forests in lieu of agricultural crop production, which is slightly reduced as shown in Figure 12 (also, see Figure 7 for comparison). This shift in land use towards forests coupled with increased biomass production occurs particularly in Brazil and southern South American countries (see Figure 13, and Figure 6 for comparison).

The overall increase in water demand under scenarios that focus on climate mitigation and decarbonization is a clear tradeoff that emerges as a result of nexus analysis of the water, energy and food sectors. This result has also been documented in other recent research focused on climate change mitigation and increased water consumption in the US (Hejazi et al. 2013). Because water is a relatively inexpensive resource for users in these sectors, as water supply is relatively abundant but also heavily subsidized in the region, this tradeoff has important implications for areas of the region that are water scarce. In these regions, a more realistic consideration of water supply costs in analysis such as this can result in different results in allocation of investment resources in water, energy and food infrastructure. A recent study (World Bank, 2017) in South Africa, a widely water scarce country, shows how considering water supply costs in energy infrastructure planning can dramatically change the resulting demands of energy (primary energy matrix) and water (total demand and allocation) over time.This is an important area for future nexus work in the LAC region.

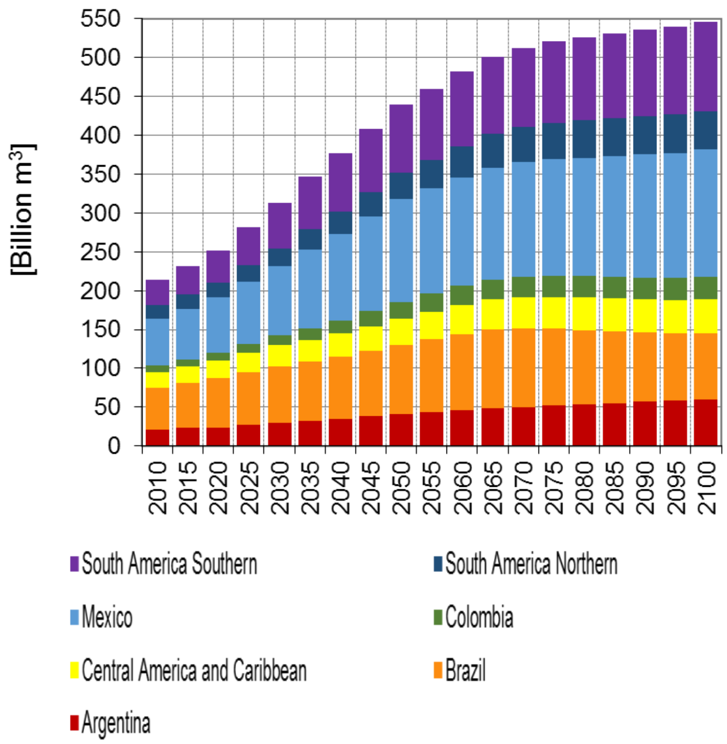

Figure 8: *Total water demand in the LAC region, broken down by subregion; policy scenario.*

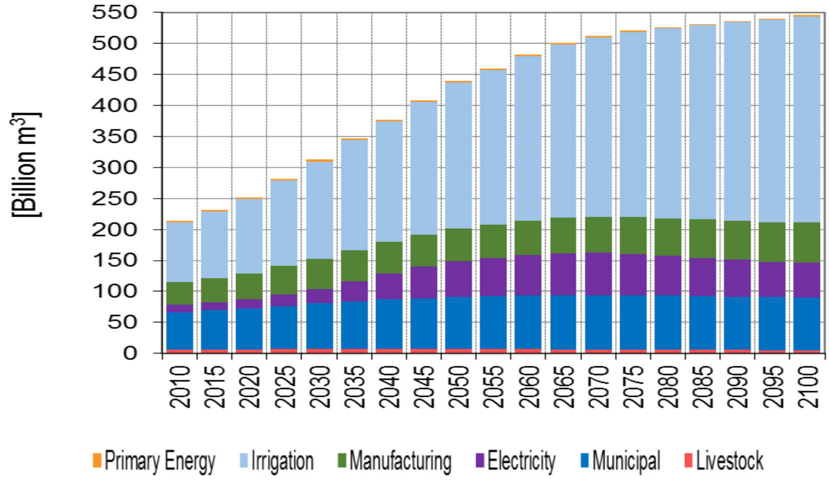

Figure 9: *Total water demand in the LAC region, broken down by sector; policy scenario.*

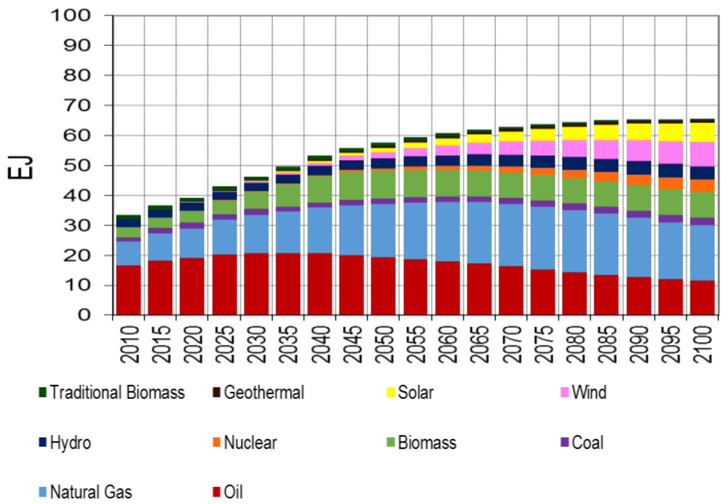

Figure 10*: Primary energy (EJ) produced in the LAC region, by source; policy scenario.*

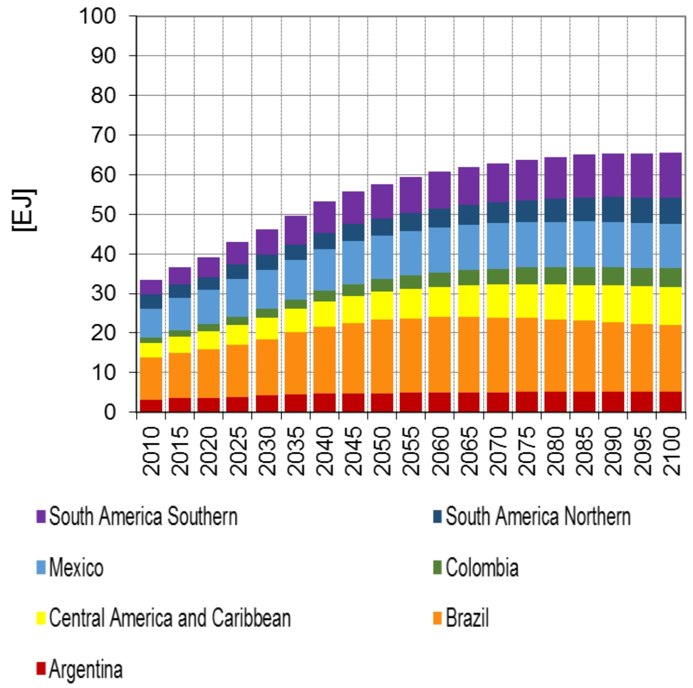

Figure 11*: Primary energy (EJ) produced in the LAC region, by subregion; policy scenario.*

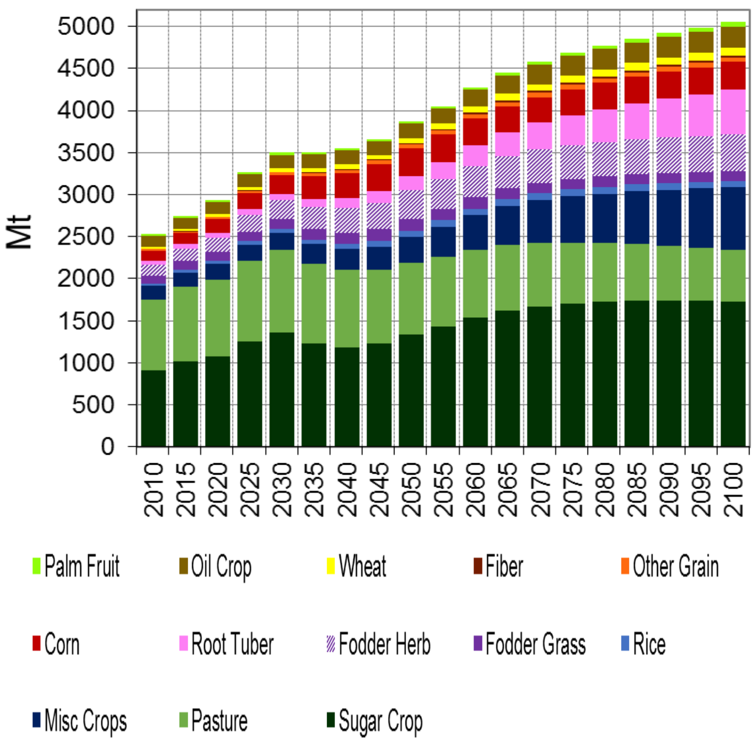

Figure 12: *Agricultural production (MT) in the LAC region, by crop; policy scenario.*

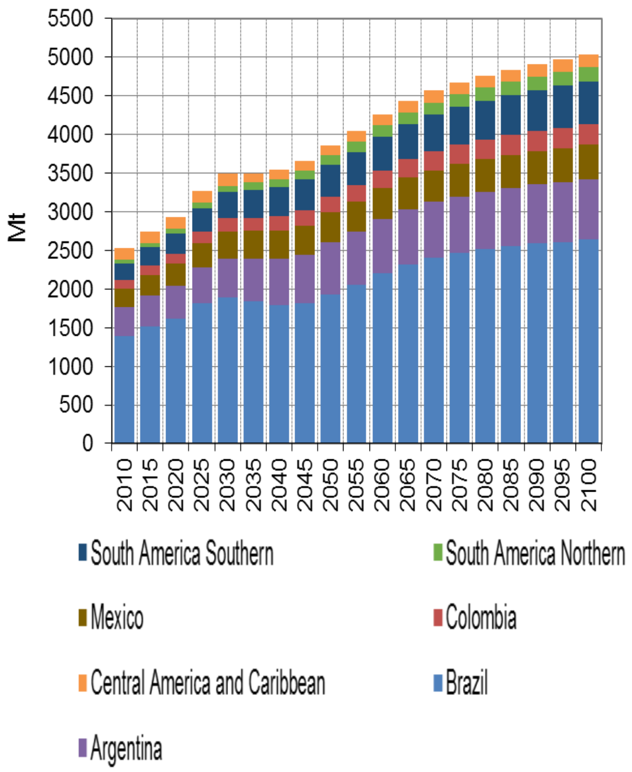

Figure 13: *Agricultural production (MT) in the LAC region, by subregion; policy scenario.*

Towards Metrics of Performance for the WEF Nexus in the LAC Region

Because the WEF nexus involves multiple sectors with linkages and feedbacks among them, a useful way to understanding the implications of policy interventions is through the development of indicators of performance.Such indicators can be used to compare results from the GCAM model under different scenarios of related to climate change, socioeconomic development, or different policy interventions. While such indicators or measures of performance have yet to be developed for WEF nexus specific applications, this section briefly discusses some potential indicators and the results obtained for the LAC region with respect to these.

The following are some illustrative examples of indicators of WEF nexus performance that can be quantified for the LAC region using the GCAM model results. In the results that follow, these indicators are used to compare the reference (no efforts to mitigate climate change) and policy intervention scenarios (with efforts to mitigate climate change, such as NDC).

[1]. *Water demand per capita* (e.g., m^3 per person): This indicator provides a measure of water use at the regional level. It can also be broken down into sectors, subregions, to get some insight at those levels.

[2]. *Electricity generated per unit water demand for generation* (e.g., EJ/m^3): this can also be done by subregion to look at differences.

[3]. *Agricultural production per unit water demand for irrigation* (e.g., MT/m^3): this can also be done by subregion to look at differences.

[4]. *Water intensity of the economy* (e.g., m^3 per unit GDP): This indicator provides a measure of the demand for water by the aggregated economy.

Figure 14 shows the water demand per capita under the reference and policy scenarios for the LAC region. As discussed in the results for the reference and policy scenarios, actions oriented towards climate mitigation in the region tend to have a larger water demand for two reasons. First, there is a shift to low carbon energy technologies that are more water consuming. Second, there is a shift towards biomass which increases irrigation water requirements. The results for this indicator imply an overall larger water footprint for the region under a climate mitigation policy scenario relative to a reference business-as-usual scenario.

These two separate effects are shown in the next two indicators. Figure 15 shows the amount of electricity generated per unit water demand used for generation. When comparing the reference and policy scenarios, this indicator shows a decrease towards 2050, as technologies for electricity generation are slowly introduced in the region and water demand continues to grow due to population increase. After 2050 and towards the end of the century, the implementation of these technologies that are more water efficient, result in an increase in the power generated per unit water demand.

Figure 16 shows the relative reduction in agricultural production per unit of irrigation water demand. Because of the shift to biomass in the policy scenario, and biomass is a water intensive crop, there is a decrease in overall efficiency in irrigation water used for agricultural production. This shift to biomass in the region to mitigate climate change and meet international targets needs to receive special consideration in those parts of the region that are water scarce, and these policies need to be devised accordingly.

A measure of water intensity of the economy is shown on Figure 17. The increase in water demand under the policy scenario causes this indicator to decrease in comparison to the reference scenario. The decrease is found to emphasize reductions in GDP per unit water demand for Brazil, Argentina and other southern cone countries, which is where this increase in water demand is concentrated the most in shifting to more water-intensive crops (e.g., biomass) and power generation (e.g., CCS).

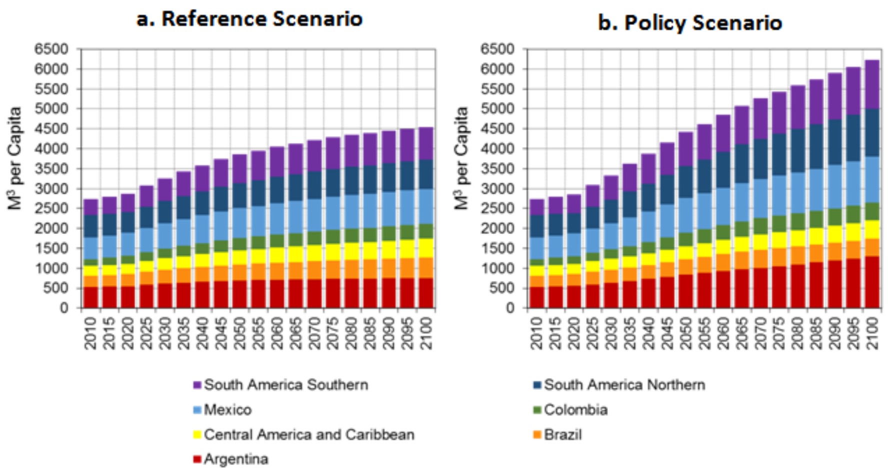

Figure 14*: Water demand per capita for the LAC region under the reference and policy scenarios.*

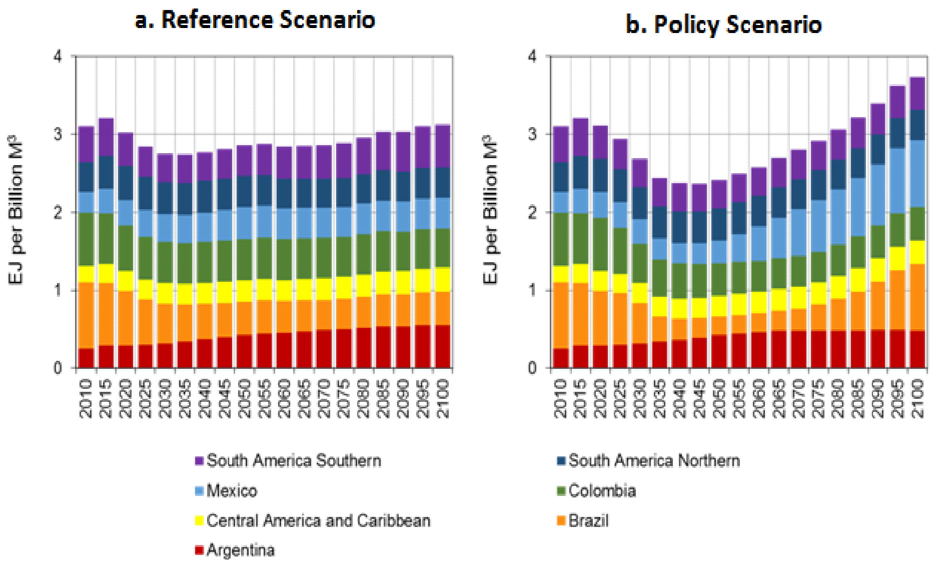

Figure 15:*Electricity generated per unit of water demand for generation in the LAC region under the reference and policy scenarios.*

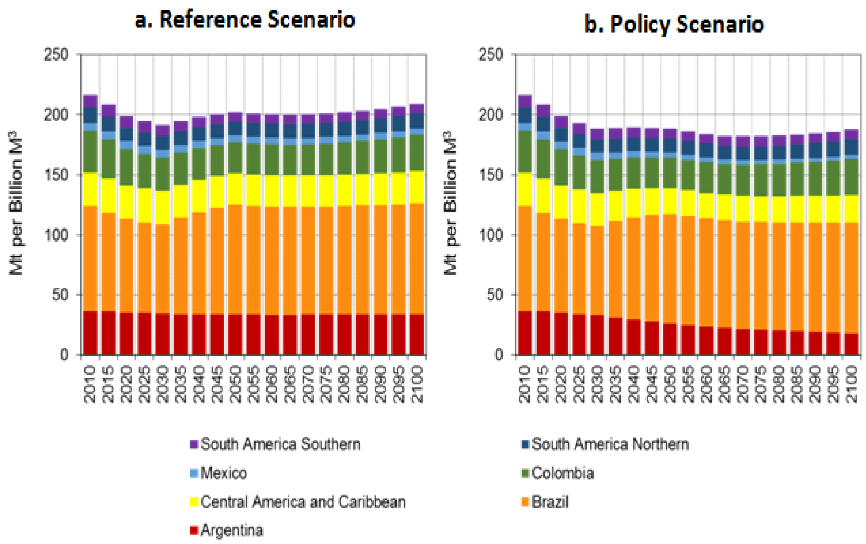

Figure 16: *Agricultural production per unit irrigation water demand in the LAC region under the reference and policy scenarios.*

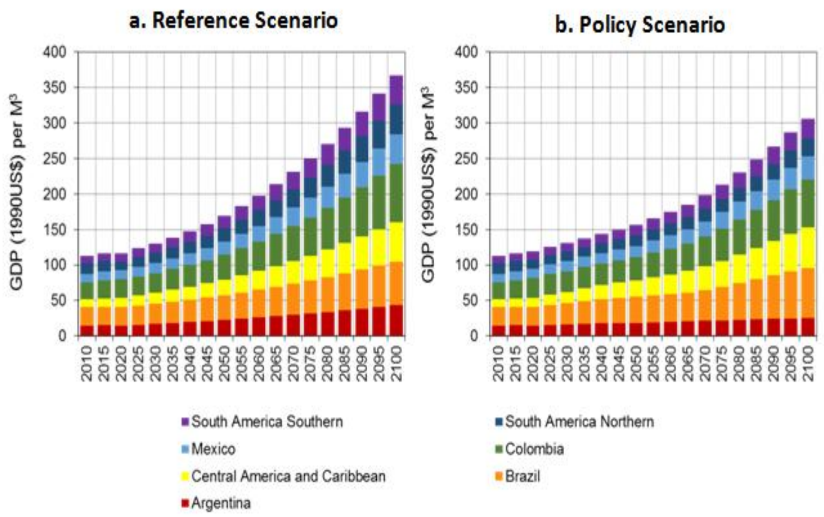

Figure 17:*Water intensity of the economy in the LAC region under the reference and policy scenarios.*

V. CONCLUDING REMARKS

This paper presents a prospective assessment of the nexus between water, energy and food in the LAC region. Focus is placed on developing tools and insight for strategic thinking towards planning and management in nexus sectors, specifically such as water supply and sanitation, energy and agriculture, and quantifying infrastructure needs in the case of water. This assessment is grounded on a physically-based analysis of water supply and demand, highlights the synergies and tradeoffs posed by the mutual interaction and interdependency of WEF, and addresses different possible nexus futures and their implications through a variety of potential future scenarios of climate change and socioeconomic development in the region.

The analytical work supporting the finding documented in this white paper is based on the application of an *Integrated Assessment Model* (GCAM: Global Change Assessment Model) to quantify these impacts for a range of scenarios: physical and socioeconomic that present a mix of possible futures for the availability, use and management of the water, energy and food sectors in an integrated (nexus) way. The understanding gained through this analysis is expected to contribute to the ongoing dialog on sustainability among multiple human activities and their trajectories towards global development pathways. Through this research and analysis, this research provides an integrated qualitative and quantitative understanding of the implications of several selected potential future scenarios for water, energy and food, including climate change and mitigation, socioeconomic and technological developments, and water demand for water-energy-food interactions at the country level and within a regional context in LAC.

An increased focus on climate change, mitigation in particular, places emphasis on an overall reduction of energy demands, and a decarbonization of the economy. This moves the energy sources from traditional primary energy sources to an energy matrix consisting of a larger mix of more carbon-efficient technologies. These technologies, although carbon-efficient, are also more demanding of water. This overall trend of reduction in overall energy demand and decrease in demand of traditional primary energy sources is accompanied by significantly increased water demands across the region; this may appear to be counterintuitive, butis explained precisely because of nexus considerations.Land use changes associated with afforestation to mitigate climate change result in increased water demand as well.

The overall increase in water demand under scenarios that focus on climate mitigation and decarbonization is a clear tradeoff that emerges as a result of nexus analysis of the water, energy and food sectors. Because water is a relatively inexpensive resource for users in these sectors, as water supply is relatively abundant but also heavily subsidized in the region, this tradeoff has important implications for areas of the region that are water scarce. In these regions, a more realistic consideration of water supply costs in analysis such as this can result in different results in allocation of investment resources in water, energy and food infrastructure. This is an important area for future nexus work in the LAC region.

Also along these lines, demand scenarios that focus on increasing resiliency and sustainability result in increased usage of land for forest conservation activities for climate mitigation. This results in an overall increase in land used for cultivation of forests in lieu of agricultural crop production, which is slightly reduced in the region as a whole. This shift in land use towards forests coupled with increased biomass production occurs particularly in Brazil and southern cone countries. This is accompanied by an increase in water demand which increases the water intensity of the LAC economy over the next decades. This increase is found to emphasize reductions in GDP per unit water demand particularly for Brazil, Argentina and other southern cone countries, which is where this increase in water demand is concentrated the most in shifting to more water-intensive crops (e.g., biomass) and power generation (e.g., CCS).

Data on future projections of water supply and demand for different climate and socioeconomic development scenarios generated through this analytical work need to be validated at the regional and country levels so they can provide reliable intelligence for water security assessment, planning and management purposes, particularly for the purposes of prioritizing investments in water infrastructure throughout the region.

By providing an economic quantitative framework for integrated analysis of water supply and demand, multiple demand sectors, climate inputs, and other forcing factors such as land use change, policy interventions and technological developments, IAMs such as GCAM provide a viable tool to explore additional issues related to water security such as the water-energy-food nexus. Further research along these lines can be focused on such issues as: (i) the implications of groundwater availability and changes in pumping costs on future water supply and its effect on urban services, energy and food security; (ii) the repercussions of removing existing distortions (i.e., subsidies) in water availability and distribution in the future; (iii) the economic costs (of inaction) of non-cooperation across basins/countries/regions and the potential benefits of cooperation; (iv) governance issues, particularly as they relate to institutional arrangements necessary to manage water, energy and food using more integrated (nexus) approaches (e.g., CEPAL, 2017); (v) define effective adaptation strategies/investments that

are necessary to mitigate the impact of climate change on water scarcity and stress; (vi) identify and plan key investments at regional and country levels to address economic water scarcity.
As highlighted in this work, the WEF nexus encapsulates complex and interconnected challenges and highlights the importance of integrated assessment in achieving a larger sense of integration of sectoral issues in the region. Many factors contribute to improved management of these sectors, ranging from biophysical to infrastructural, institutional, political, social and financial, many of which lie outside the scope treated in this investigation. In this respect, nexus approaches can be applied to increasingly complex areas, that are linked to water, energy, and food. For instance, post-2015 processes in the development community (e.g., SDGs) and the climate community (e.g., NDCs) already incorporate goals and related targets for achieving WEF security to address other multiple priority development areas such as conflict and fragility, environmental sustainability, growth and employment, health, hunger, nutrition, inequities, and others.

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