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Energy-water-land Nexus in Latin America and the Caribbean: A perspective from the Paris agreement climate mitigation pledges

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Energy-Water-Land Nexus in Latin America and the Caribbean

A Perspective from the Paris Agreement Climate Mitigation Pledges

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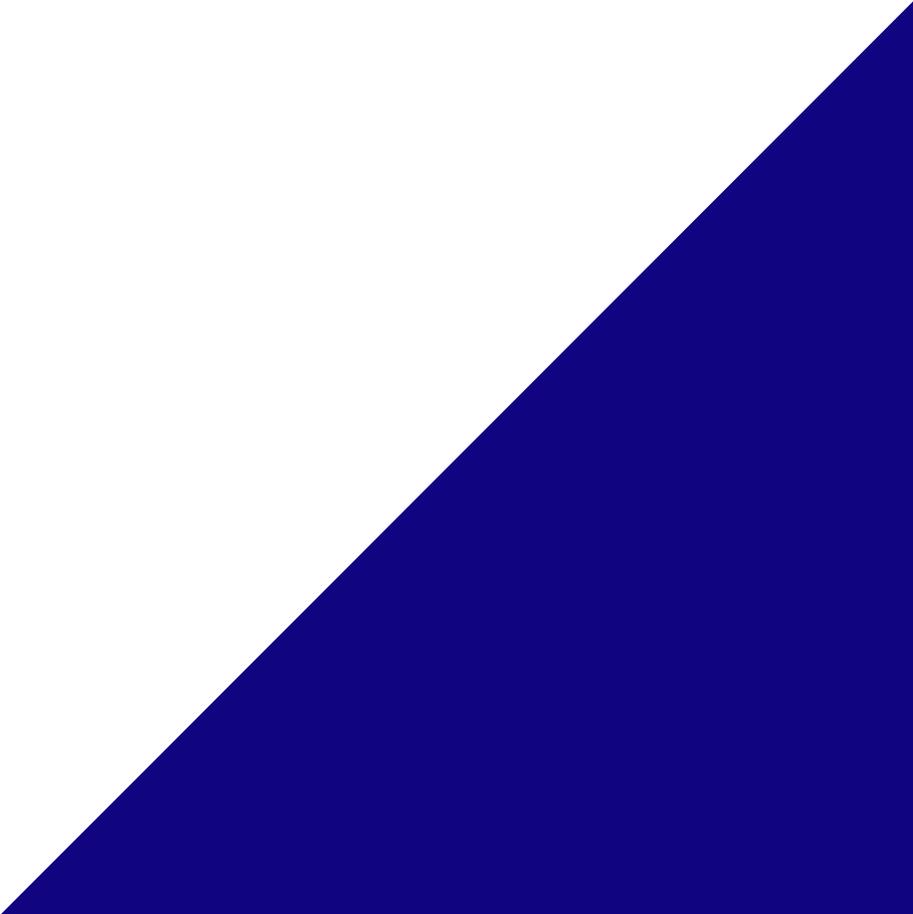
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ENERGY-WATER-LAND NEXUS IN LATIN AMERICA AND THE CARIBBEAN

A PERSPECTIVE FROM THE PARIS AGREEMENT
CLIMATE MITIGATION PLEDGES



Abstract

The concept of the energy, water, and land (EWL) nexus encompasses a growing concern 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 explores how the Paris Agreement Climate Mitigation Pledges might influence the EWL nexus in Latin America and the Caribbean (LAC). In particular, it explores the near-term and long-term implications of the Paris pledges on the EWL nexus in four of the major countries/economies in LAC: Argentina, Brazil, Colombia and Mexico. 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 EWL synergies and tradeoffs and allows understanding of the key drivers of the EWL sectoral interactions and the role of climate policies such as the Nationally Determined Contributions (NDCs) that are included in the Paris pledges.

Our findings indicate that under the emissions mitigation scenarios explicitly modeled to represent the Paris pledges framework, potential conflicts regarding the use of EWL resources in the four focus LAC countries may be exacerbated by the NDC-induced changes in the energy and land sectors that would impinge upon the water sector of those nations. Despite the differential implications of the Paris pledges on each country, increased water demands for crop and biomass irrigation and for electricity generation were identified as the potential sources of nexus conflicts that may emerge under the NDC climate policy scenario. Hence, this study underscores the need to refine national climate policies within a EWL nexus resource planning framework so that a balance between the rational use of the nexus resources and workable climate policies can be found.

Energy-Water-Land Nexus in Latin America and the Caribbean: A Perspective from the Paris Agreement Climate Mitigation Pledges

1. Introduction

The concept of the energy, water, and land (EWL) nexus encompasses growing concerns about the availability of vital resources derived from these intertwined systems and how to manage them in response to the challenges posed by future human demands and climate change. The components of the EWL nexus affect one another in various ways. Water is frequently under stress from the agriculture sector, which is responsible for about 70% of the total global freshwater withdrawals (FAO 2011a). Food production in particular accounts for about 30% of the world's total energy consumption (FAO 2011b). At the same time, water is required in several stages of the process of energy production from the extraction of energy resources to the refining of fuels to electricity generation. Conversely, energy is needed to collect, treat, and distribute water. Constraints in one dimension of the nexus can impact other nexus components with quantifiable consequences to overall societal well being.

In this context, water security, food security, and energy security have been recognized as critical considerations for sustainable growth and social stability (WEF 2011). Given the complex interactions among the EWL sectors, it is imperative to move beyond traditional approaches in which decision-making is focused as if these sectors are independent of each other and towards an integrated (nexus) planning of EWL resource development and use. Apart from promoting economic and resource efficiency, this integrated planning framework is important to avoid unintended consequences and potential conflicts regarding the utilization of the EWL resources in the coming decades (Miralles-Wilhelm 2016; Bazilian et al. 2011).

The EWL nexus in the LAC region is characterized by abundant water in total, but with large spatial and temporal heterogeneities, a critical reliance on agriculture in economic output, and diverse and growing energy sectors. According to estimates from the Food and Agriculture Organization's (FAO) AquaStat database (which incorporates the average annual flow of rivers and recharge of aquifers generated from endogenous precipitation), about 32% of the global renewable water resources can be found in the LAC region. Nevertheless, the large spatial variability in the distribution of these resources results in striking contrasts such as the rainy pattern of the Amazon basin versus the arid or semi-arid climate conditions found in northern Chile, northern and central Mexico, and northeast Brazil. The temporal dimension relates to the natural climate variability of the region, in which strong rainfall anomalies are modulated within a range of temporal scales (Grimm and Saboia 2015; Grimm and Zilli 2009; Mo and Schemm 2008). Substantial challenges to the future water management strategies in the LAC region are imposed by the prospect of climate change with likely shifts in the hydrological cycle, and rising water demands driven by population and economic growth.

At the same time that these EWL interactions are emerging as key societal concerns, countries are also planning and undertaking ambitious efforts to reduce greenhouse gas (GHG) emissions dramatically by mid-century, which also raise a range of societal concerns and linkages to EWL systems. In particular, the Paris Climate Agreement, announced on 12 December 2015 during the 21st Conference of the Parties (COP21) of the United Nations Framework Convention on Climate Change (UNFCCC), aims at limiting the increase in the global mean surface temperature to "well below 2°C above pre-industrial levels", and established that Parties should "pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels" (UNFCCC

2015a). One key aspect of the agreement was an enhanced focus on voluntary commitments made by each country through an instrument known as Intended Nationally Determined Contribution (INDC). By means of the INDC, submitted prior to the COP21 summit, each UNFCCC member nation voluntarily defined its level of intended contribution. After the ratification of the agreement, INDCs were converted into Nationally Determined Contributions (NDCs), which should be updated every 5 years (starting from 2020) so as to achieve the highest possible level of contribution for each country.

Guided by the principle of “common but differentiated responsibilities”, the Paris agreement calls for an immediate global joint effort to deal with the global-scale nature of the climate change problem caused by worldwide human activities. While industrialized countries have produced the largest share of anthropogenic GHG emissions to date, successful achievement of the goals of the agreement will depend in large part on the future path of emissions in emerging economies, such as those in the LAC region. Historically, LAC’s energy-related CO₂ emissions have been relatively low: LAC accounted for about 4% of global energy-related CO₂ emissions in 2014 (IEA 2016). But these emissions are expected to grow over time as LAC economies continue to grow (van Ruijven et al. 2015). At the same time, net emissions from Agriculture, Forestry and Other Land Uses (AFOLU) in the LAC region represented about 24% of global emissions in this sector in 2014 according to the FAOSTAT emission database (Tubiello et al. 2013).

In support of the climate goals of the Paris Agreement, LAC countries submitted their NDCs (UNFCCC 2015b). For example, Brazil has committed to reduce all GHG emissions by 37% in 2025 and 43% in 2030 relative to 2005 levels. Brazil’s NDC is unconditional, which means it is independent of financial and/or technological foreign support. Mexico has committed to an unconditional reduction of 22% in all GHGs below a business-as-usual (BAU) scenario for the year 2030. This NDC also includes a conditional target of reducing GHG emissions by 36% by 2030 relative to the same BAU. Likewise, Argentina has committed to an unconditional target of 18% (37% conditional) reduction in all GHGs below BAU for 2030 whereas Colombia announced an unconditional 20% (30% conditional) reduction in all GHGs below BAU for 2030. These countries also stated goals and/or actions regarding the AFOLU sector, but the reductions generated in this sector are included in the overall national emissions reductions targets. Particularly on land-use, land cover change and forestry, Brazil and Mexico intend to adopt measures to conserve and reforest ecosystems and to reach a rate of zero illegal deforestation by the year 2030. In this respect, Brazil, which is the main driver of AFOLU emissions in the LAC region (41% of the regional AFOLU emissions in 2014 according to the FAOSTAT database), has reduced deforestation considerably. The overall rate of deforestation in the Amazon region declined 76% between 2004 and 2017 (data available at <http://www.obt.inpe.br/OBT/assuntos/programas/amazonia/prodes>). Along similar lines, Colombia’s NDC indicates that the country is committed to reduce deforestation and to preserve important natural ecosystems. Argentina’s NDC states an unconditional target regarding the promotion of sustainable forest management in the country.

In light of the LAC region NDCs, the understanding of regional implications of these climate pledges on the complex interactions among the EWL nexus is essential to better guide future decision making, both for climate policies and EWL planning. This paper explores how the Paris Pledges might influence the EWL nexus in LAC countries. In particular, it explores the near-term (2030) and long-term implications (2050) of the Paris pledges on the EWL nexus in four countries: Argentina, Brazil, Colombia and Mexico. With a total gross domestic product (GDP) of \$3.67 trillion (current US dollars), these four countries represented about 78% of the economy in the LAC region in 2016 (World Bank 2017). The analysis is carried out within the framework of the Global Change Assessment Model (GCAM) (Edmonds and Reilly 1985, Wise et al. 2009), a state-of-the-art Integrated Assessment Model (IAM), specifically developed to incorporate physical

(energy, agriculture, climate, and water), economic and social aspects, and to explore the interactions among sectors. A critical research need related to the nexus is the development and application of appropriate modeling tools that can support the integrated decision-making (Miralles-Wilhelm, 2016; Bazilian et al. 2011). In this sense, the GCAM framework enables the explicit modeling of the Paris pledges, and helps to understand the interdependencies among the EWL sectors, the key drivers of these sectoral interactions as well as the role of the NDC climate policy.

Recent studies have assessed the NDCs from the point of view of their potential contribution to limit global warming (Fawcett et al. 2015, Rogelj et al. 2016, Salawitch et al. 2017), in terms of their implications on the energy sector (Postic et al. 2017) or on mitigation costs (Iyer et al. 2015, Hof et al. 2017). At the same time, the nexus literature have evolved from theoretical analyses providing the foundations for the nexus concept to studies focused on the development of quantitative approaches to assess the impacts of different policy interventions on water, energy and land/food sectors. These quantitative analyses have utilized problem-specific case studies or developed basic EWL indicators (Giampietro et al. 2013, Flammini et al. 2014). A previous study (Miralles-Wilhelm and Muñoz-Castillo, 2018) focus on the EWL nexus implications of NDC policies at the regional level in LAC (not country-specific). The current study differs from the previous research efforts in that we explore the country level implications of the NDCs in the LAC region within the EWL nexus perspective. More broadly, this study aims at demonstrating the need to explore climate policies fully-integrated within an EWL nexus resource planning framework.

This paper is structured as follows: Section 2 discusses the model and scenarios included in this article, Section 3 presents the analyses of the implications of the Paris Pledges on the EWL nexus in Argentina, Brazil, Colombia and Mexico, and Section 4 provides the concluding remarks.

2. Methods

2.1. Model Description

The scenario results presented in this paper were modeled using the Global Change Assessment Model (GCAM)¹, release version 4.3, a state-of-the-art IAM designed to explore interactions among critical sectors of the economy, the human and physical systems, and to support policy-relevant decisions (Edmonds and Reilly 1985, Wise et al. 2009, Clarke et al. 2014). As a leading IAM, 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) and was implemented regionally in LAC (Miralles-Wilhelm and Muñoz-Castillo, 2018).

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

¹ GCAM is freely available as a community model, and can be obtained through a widely used software repository (<https://github.com/JGCRI/gcam-core>). The full documentation of the model is also hosted at GitHub (<http://jgcri.github.io/gcam-doc>). The description presented in this subsection is a summary of key GCAM characteristics based mostly on the online documentation.

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.

Within a 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 subregions: Argentina, Brazil, Central America and Caribbean, Colombia, Mexico, South America Northern, and South America Southern (Fig. 1).



Fig. 1. GCAM representation of the following 7 LAC subregions: Argentina (red), Brazil (blue), Central America and Caribbean (green), Colombia (purple), Mexico (yellow), South America Northern (brown), and South America Southern (magenta).

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 its 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 feature of GCAM is the agriculture and land-use system, which allows projections for agricultural supply (crops, livestock, forest products, and bioenergy), prices, and changes in land use and cover, considering also the trading of primary agricultural and forest goods. In this component, each of the 32 geopolitical regions can be disaggregated into up to 18 agro-ecological zones resulting in a total of 283 agriculture and land use regions. Within each of these 283 subregions, land is categorized into twelve types based on cover and use. Among the land types considered arable, non-commercial land uses such as forests, shrublands and grasslands are included, 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 the 283 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 land types whose land cover is assumed constant over time such as tundra, deserts, and urban 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. Bioenergy production is derived from various types of dedicated bioenergy crops (e.g., switchgrass, miscanthus, willow, jatropha, and eucalyptus), food crops, residues from forestry and agriculture, municipal solid waste, and traditional bioenergy through a suite of technologies for transforming these biomass feedstocks. For example, the biomass liquids subsector within the energy module includes a number of transforming technologies for biofuels production from agricultural crops such as sugar, corn and oil crops.

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: CO₂, CH₄, N₂O, halocarbons, carbonaceous aerosols, reactive gases (e.g. CO, NO_x, 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 use: primary energy production and processing, electricity generation, industrial, and municipal. As described by Hejazi et al. (2014a, 2014b), the main characteristics of the GCAM water module are: (1) future agricultural water demands are driven by crop production from GCAM, the share of crop production that takes place on irrigated lands in each of the 283 subregions, and by crop type (12 categories of crops plus biomass). The estimates of water withdrawals for biomass includes a number of second-generation biomass crops (purpose-grown bioenergy crops), but crops such as corn, sugar and oil palm used for biofuel production are not included since their water demands are quantified in the irrigation category. (2) Future manufacturing and domestic water demands are driven by socioeconomic assumptions, among other factors (e.g., total industrial output, future changes in efficiency, technological improvements, and water prices); (3) 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 also on the specific production technologies used, which in the case of the electric-sector water use includes the types of cooling systems used during thermal power generation.

2.2. Reference and NDC Implementation Scenarios

In this paper, we focus on three scenarios: the reference scenario and two policy (NDC) scenarios. The two policy scenarios are based upon the implementation of the emissions reductions contained in the NDCs submitted under the Paris Agreement.

The reference scenario is used as a baseline for comparison with the NDC scenarios. It is based upon BAU assumptions about key drivers such as population and economic growth, energy technology, and policies. For the reference scenario, no GHG mitigation action beyond those already in place are implemented beyond 2010. The socioeconomics assumptions in the LAC region used in the reference scenario are shown in Appendix Fig. A1. Both assumptions are consistent with the “Middle of the Road” SSP 2 (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. The reference scenario is characterized by a population growth of 26% and growth in per capita GDP of 167% from 2010 to 2050. Note that these same socioeconomic assumptions will be shared with the policy NDC scenarios.

The two NDC scenarios are based on the same emissions reductions targets derived from the Paris Agreement pledges and share the same general assumptions. However, they differ with respect to the available energy portfolio to address the mitigation targets specified under the NDC policy. The “NDC” scenario assumes a significant expansion of the CO₂ capture and geologic storage (CCS) technology in the energy portfolio. On the other hand, CCS is not available in the “NDC_NOCCS” scenario, which relies on larger deployment of renewable energy derived from wind, solar and biomass. New capacities can include nuclear energy in both scenarios. Each of these scenarios is intended to be purely exploratory, demonstrating the tradeoffs involved with the implementation of the NDCs by two distinct emissions reductions pathways and the evolution of EWL nexus in the LAC region in response to them.

In both policy scenarios, the implementation of the NDCs in GCAM was carried out by means of an economy-wide emissions constraint. This means that the gross GHG emissions (excluding LUC emissions) were specified for each GCAM region and the model internally calculated the carbon prices needed to achieve the constraint. These carbon prices were then applied uniformly across all sectors of the economy (except for the land sector discussed below). The global GHG emission trajectory implemented in this study is based on Fawcett et al. (2015) “Paris-Increased Ambition” scenario with updates on the emissions constraints for the 7 LAC subregions. The emissions constraints used in GCAM were defined in accordance with the countries emissions levels stipulated in their official NDC submissions to the UNFCCC (UNFCCC 2015b). Given the challenge of translating the official NDCs to explicit quantifications of GHG 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. The country-specific assumptions used to represent the 2025-2030 NDC targets (as well as the Copenhagen pledges for 2020) in the LAC region are provided in Appendix Table 1.

It is important to acknowledge that actual climate policy approaches do and will significantly differ from the economy-wide carbon prices approach described above, relying on a range of different policy mechanisms from building standards to automobile fuel efficiency to renewable portfolio standards. The implication for the results in this study is that mitigation is focused more heavily on energy supply adjustments than energy demand changes. Future research will be necessary, and is currently underway, to explore the wide variety of ways that countries will actually implement NDCs.

Consistent with the climate goals set by the Paris agreement, the NDC scenarios in the post-2030 period are anchored on the assumption that the LAC region enhances its overall mitigation effort such that its emissions reduction target represents an ambitious progression over the 2025-2030 period. The post-2030 pathways for the 7 LAC subregions represented by the model were updated from the “Paris-Increased Ambition” scenario based upon sources that included country reports and national communications when available (see sources and overall assumptions listed in Appendix Table 1). Although it is possible to construct alternate scenarios with various post-2030 pathways, our goal here was to achieve enhanced emissions reductions to illustrate the potential implications of the Paris pledges framework on the EWL nexus in the selected LAC countries as a result of two contrasting routes of implementation for this climate policy.

Given the large share of 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 four countries analyzed in the present study accounted for GHG terrestrial emissions by explicitly including the AFOLU sector among the sectors covered by their NDCs. However, there presently exists great uncertainty in the actual magnitude of future land-based emissions reductions in the LAC region derived from the NDCs. Due to the high uncertainties resulting from future land-use change (LUC) emissions, for the NDC scenarios, we imposed an exogenous pathway of regional efforts towards reduced deforestation and forest degradation (REDD). These were implemented by applying a value to carbon in land trajectory. In this regards, it can be argued that LAC countries will possibly implement a range of mitigation actions in the AFOLU sector that are not incorporated in our study. Our approach although straightforward (in the sense that we are assigning carbon prices on LUC emissions as a signal to avoid the loss of forested areas in the model) aims at providing preliminary insights on the interplays between changes in forest cover and the dynamics of the land sector that can affect the nexus as a whole. This is intended to explore whether there are general conclusions that can be drawn at an aggregate level as well as to identify areas for future investigation. Moreover, it is important to mention that GCAM is currently under development of improved modeling capabilities in the land sector that will allow a more comprehensive analysis of land-based mitigation strategies in line with LAC region NDCs in follow-on studies.

The emissions pathways (net emissions including CO₂ LUC emissions) generated by GCAM under the NDC scenario for the 7 LAC subregions are shown in Table I. As expected, these pathways are aligned with the official NDC submissions. For instance, in 2030, the net GHG emissions in Brazil and Mexico resulting from their respective NDCs’ unconditional pledges are 1200 and 759 MtCO₂e, respectively.

GCAM region	2010	2020	2030	2040	2050
Argentina	737	450	505	512	456
Brazil	2174	1476	1242	620	409
Central America and Caribbean	321	313	436	424	414
Colombia	137	205	248	337	293
Mexico	702	717	738	470	208
South America_Northern	307	321	439	487	487
South America_Southern	452	520	628	625	621

^a Global Warming Potentials (GWPs) from the IPCC Fourth Assessment Report (AR). Note that for the computation of the GHGs inventory, each country has specified GWPs from different IPCC ARs. For example, Brazil and Mexico established GWPs from the Fifth AR, whilst Argentina and Colombia defined GWPs from the Second AR.

It should be noted that we are modeling how the energy, water and land systems evolve in the NDC mitigation scenarios but climate change impacts (and adaptation measures) on the nexus sectors were not included. However, a thorough understanding of the national scale EWL system dynamics in the LAC region resulting from the Paris Pledges will require the inclusion of a number of impacts of climate change, for example, on water supplies or through changes in crop yields (that impact bioenergy and agricultural production).

3. Results and Discussion

3.1 Greenhouse Gas Emissions

Under the NDC climate policy implemented in this study, total emissions across the LAC region drop by about 9% and 21% in 2025 and 2030 relative to the reference, respectively. They peak by 2025 (Fig. 2) and are reduced by 54% relative to the reference scenario in 2050. The results vary substantially across countries (Fig. 3). Overall, the share of non-CO₂ emissions relative to the total gross emissions in the region is projected to be kept high under the policy. This is because sectoral policies were not explicitly modeled in the NDC scenarios and, consequently, emissions reductions are derived mainly from the energy system.

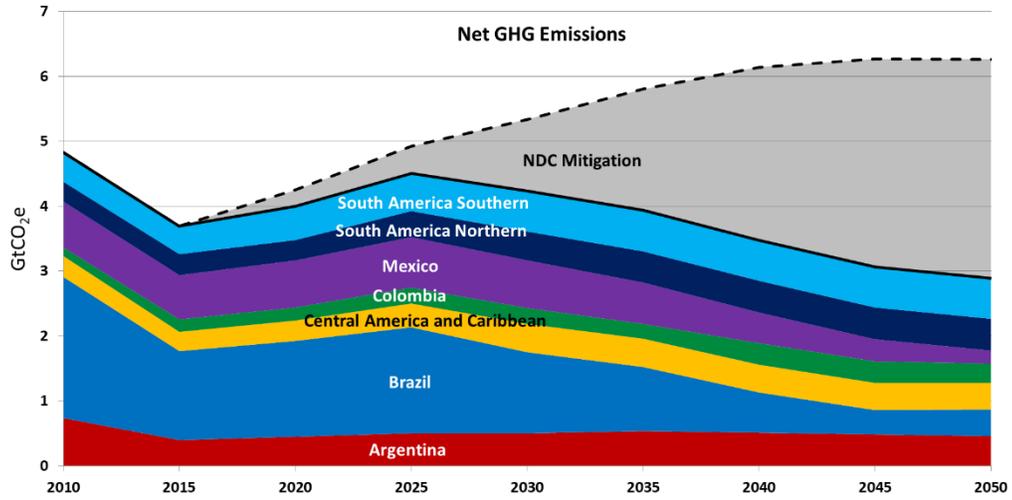


Fig. 2. Net GHG emissions (GtCO₂e) in the LAC region for the reference (dashed line) and NDC scenario (includes (1) CO₂ emissions from fossil fuel production and use and industrial processes such as cement manufacture that also produce CO₂ as a byproduct; (2) CO₂ emissions from land-use changes; and (3) Non-CO₂ emissions).

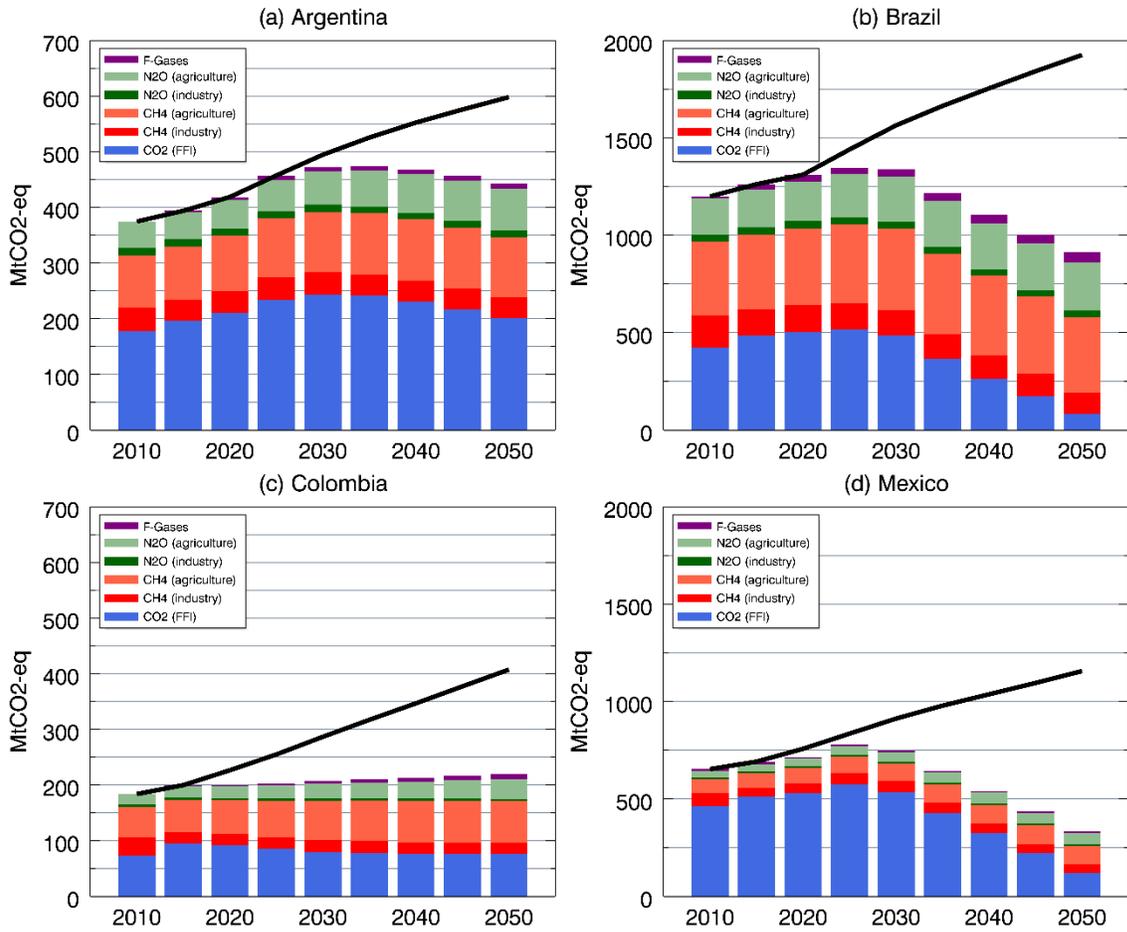


Fig. 3. Gross greenhouse gases emissions (MtCO₂e) for the reference (solid line) and NDC scenario. (a) Argentina, (b) Brazil, (c) Colombia, and (d) Mexico.

3.2. Energy

The LAC region is expected to face increasing demands for energy as population and GDP grow. In the absence of mitigation interventions, the reference scenario projects a 98% increase in primary energy consumption and a threefold increase in electricity generation for 2050 relative to 2010, with predominance of fossil fuels and a larger role of natural gas (Appendix Figs. A2(a)-(d)). Thus, gross GHG emissions follow a marked upward trend, in particular, the Fossil Fuel and Industrial (FFI) CO₂ emissions, which take larger proportions of the regional emissions up to 2050 (Appendix Figs. A2(e)-(f)). In this context, the fulfillment of the climate goals of the Paris Agreement requires contribution from LAC countries towards substantial reductions in the energy-related emissions produced in the region. To achieve such reductions, the NDC policy scenarios implemented in this study follow two contrasting low-carbon development pathways. Due to the interconnected nature of the EWL nexus, it is expected that each potential energy mitigating pathway could lead to key implications on the land and water sectors through a number of ways. Before discussing specific results, it is informative to introduce some of these important EWL nexus interplays.

A first pathway in which the energy system impacts both the land and water sectors is through the demand for bioenergy (energy from biomass that is mainly supplied as heat, liquid fuels, and electricity). This energy option is well established in the literature as a crucial strategy to meet part of the future global energy demand while limiting energy-related GHG emissions. The mitigation potential largely increases when bioenergy is employed in combination with CCS technologies (BioCCS), allowing the possibility of deep carbon removals from the atmosphere and net negative emissions (Azar et al. 2010, Vuuren et al. 2013, Kriegler et al. 2013). Given the large-scale of bioenergy production required to achieve deep emissions reductions, the LAC region grows in importance owing to its potential for substantial increases in bioenergy production from various feedstock categories (Dallemand et al. 2015). In response to future domestic and global demands, bioenergy production and net exports, mainly through biofuels, are expected to grow in LAC throughout the upcoming decades (Bauen et al. 2009).

Another pathway for key nexus interactions between energy and water systems stems from a larger reliance on wind and photovoltaic (PV) solar technologies that can reduce water requirements in the power sector in comparison to the water-intensive thermal (fossil fuels or nuclear) energy with substantial water demands depending on the type of cooling system (Liu et al. 2015). On the other hand, mitigation through CCS considerably impacts the water sector given that CCS-based power plants generally have higher water requirements than the non-CCS systems (Klapperich et al. 2014; Grubert and Kitasei 2010).

Given the design of our climate mitigation (NDC) scenarios, substantial differences from the reference case can be observed in the evolution of the primary energy system (Fig. 4). Overall, both NDC scenarios involve the use of less fossil fuel sources, increased nuclear capacity and biomass consumption, with larger reliance on solar and wind technologies or CCS depending on the NDC pathway. Carbon prices propagating through energy markets along with the expansion of the higher-cost, lower-carbon technologies stimulate improvements in the efficiency of energy conversion and the reduction in energy demand in all countries up to 2050. In the near-term (2030), changes are relatively small, however, as countries strengthen their mitigation efforts larger transformations occur over the long-term (2050).

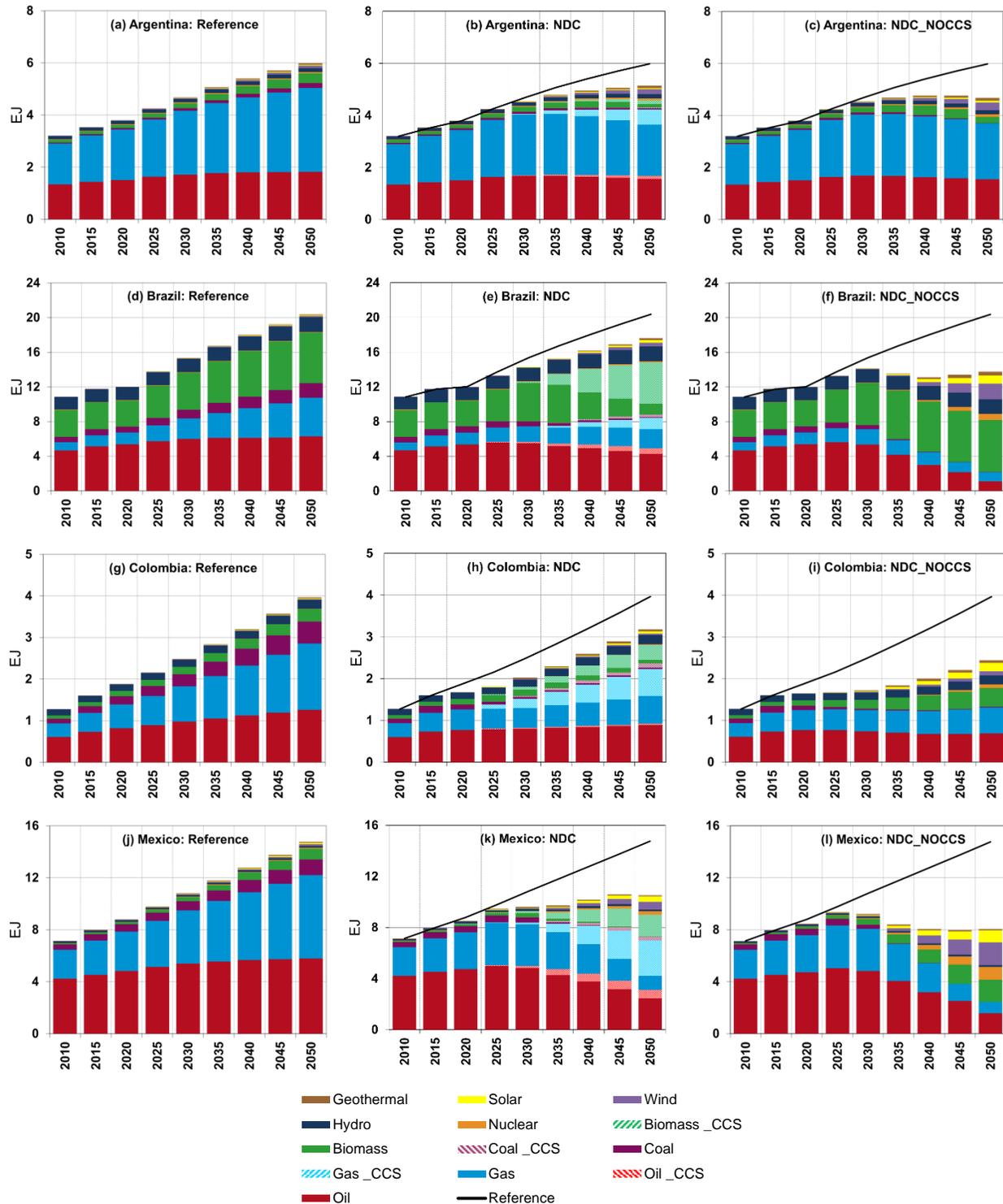


Fig. 4. Distribution of the primary energy consumption (EJ) for the Reference ((a), (d), (g), and (h)), NDC ((b), (e), (h), and (k)) and NDC_NOCCS ((c), (f), (i), and (l)) scenarios in Argentina, Brazil, Colombia, and Mexico, respectively.

Except for Argentina, when CCS is unavailable (NDC_NOCCS scenario), biomass plays a larger role in the primary energy mix relative to the reference scenario. In this scenario, although Brazil has the largest participation of biomass in the primary mix (34% and 44% in 2030 and 2050,

respectively), Mexico experiences the largest expansion of biomass consumption relative to the reference with percent increases of 52% and 104% (versus 13% and 3% in Brazil) in 2030 and 2050, respectively. With regards to solar, wind and nuclear energy, the differences between both NDC scenarios are small in the near term, and, overall, these low-carbon sources represent less than 2% of the total primary mix in all countries. Over the long term, the NDC_ NOCCS scenario induces a strong expansion of solar, wind and nuclear energy, particularly in Mexico where these sources represent about 46% of the primary energy mix (versus 10 to 25% in the other countries). On the other hand, the contribution of these low-carbon options to the primary mix is much lower in the NDC scenario (shares of about 12% in Mexico and 4 to 6% in the remaining countries in 2050) because CCS systems allow the larger use of fossil fuels.

Under the NDC scenario, the larger expansion of CCS occurs for natural gas combined with CCS and BioCCS albeit with differing magnitudes depending on the country. BioCCS significantly expands in Brazil over the long term whereas the remaining countries develop more natural gas with CCS than BioCCS. Although the large-scale deployment of CCS is acknowledged as a potential approach to achieve deep CO₂ emissions reductions over the long-term, great uncertainties exist regarding the viability of such approach. Barriers to the large-scale implementation of CCS include the significant research & development (R&D) investment required to overcome the technological challenges involved in a safe and cost-efficient utilization of CCS systems, or even the lack of political and policy support (Lipponen et al. 2017). In this sense, it is also crucial to understand the implications and potential conflicts within the EWL nexus stemming from abatement strategies that largely rely on CCS systems.

The previously shown transformations in the energy system are accompanied by germane changes in the land and water sectors explored in the upcoming sections.

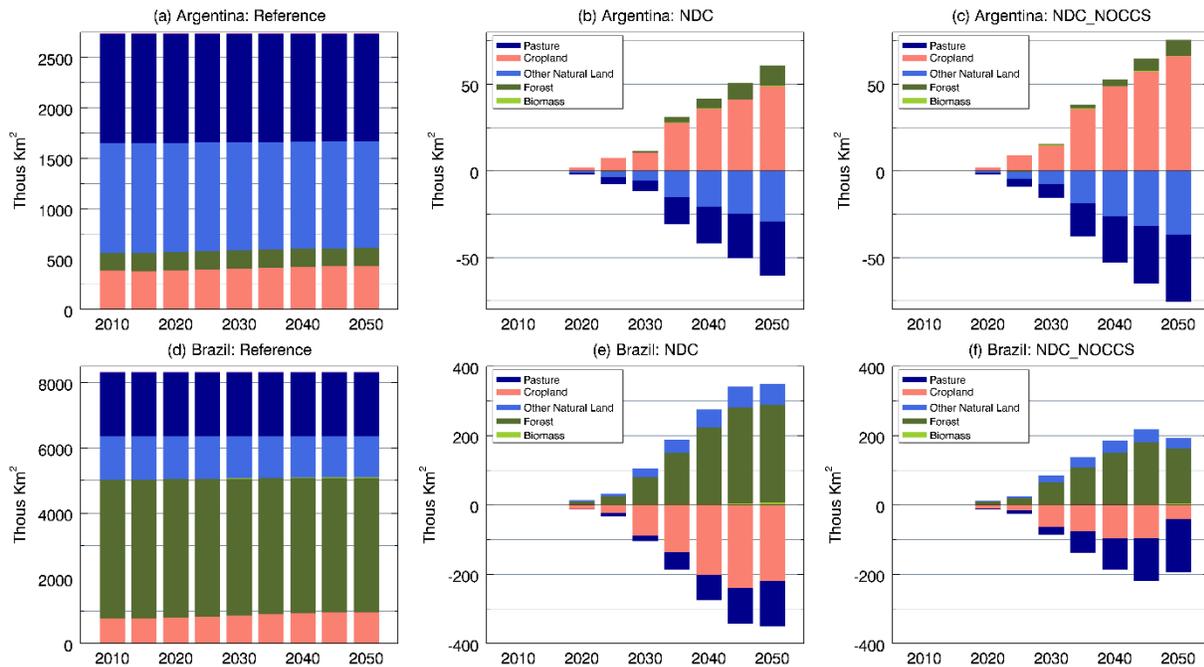
3.3. Land

The LAC region is endowed with ample land resources and freshwater resources that sustain large-scale agricultural production. From its total land surface, 52% has potential for growing rainfed crops at yields minimally acceptable, although part of this potential may remain untapped including forests, protected or urban zones, areas suitable for growing a few categories of crops (not necessarily the highest demand crops), or that suffer from constraints (chemical, physical, lack of infrastructure, etc.) possibly unfeasible to overcome (Bruinsma 2009). As a whole, LAC is currently positioned as a net exporter of agricultural commodities (ECLAC/FAO/IICA 2012), and the region is expected to play an increasingly role in the global agricultural trade over the coming decades with profound implications on global food security.

Within this context, it is important to understand the extent to which a decarbonizing energy pathway induced by the NDC policy can affect the land sector in LAC. One way is through increased bioenergy production. Due to its favorable potential, the LAC region may follow a path towards increased bioenergy production and consumption as a strategy to fulfil its Paris Agreement pledges. In addition, the region may be led to increase its bioenergy exports to regions with limited land and/or feedstock resources in need to intensify their bioenergy imports to achieve their emissions reductions pledges. Despite the benefits in terms of GHGs mitigation, it has been generally argued that a large-scale deployment of bioenergy could exacerbate land competition with potential loss of: (1) natural ecosystems (with subsequent increase in LUC emissions) and biodiversity, and (2) cropland and/or pastureland that might impact food production and costs (Wise et al. 2009, Calvin et al. 2014). Hence, a mitigation strategy relying on large-scale bioenergy production from dedicated bioenergy crops poses challenges owing to the large land requirements to grow the feedstocks.

It should also be considered that additional expansion of arable land is thought to represent an important source for future crop production growth in the LAC region (Bruinsma 2009). Nevertheless, intense deforestation in the region has been historically driven by agricultural expansion for crops cultivation and cattle pastures (Houghton 2012). In this sense, many NDCs in LAC countries are directed towards land conservation and avoided deforestation efforts in order to reduce LUC emissions and sequester carbon in terrestrial systems (e.g., through reforestation and afforestation activities). In this case, depending on the level of stringency of the land protection enforced, there may be important implications on land availability requiring proper management actions to accommodate the large-scale production of biomass, food, fiber and livestock needed to satisfy the increasing demands in domestic and international markets up to midcentury.

The complete distribution of land use in the four selected LAC countries under the reference scenario are presented in Fig. 5 (left panels). Focusing on the differences between the reference and the NDC scenarios (Fig. 5 – center and right panels), it can be noted that changes in land cover associated with biomass production are pronounced in Mexico, where substantial deployment of bioenergy is needed to decarbonize its baseline energy system largely dominated by fossil fuels. Hence, land allocated to bioenergy crops expands considerably in both NDC scenarios in that country. It is important to note that the representation of land allocation decisions in GCAM respond to the expected profitability among competing land uses. Hence, biomass expands where the value of the energy provided and the carbon mitigated in the energy system are more profitable than using that land for other purposes.



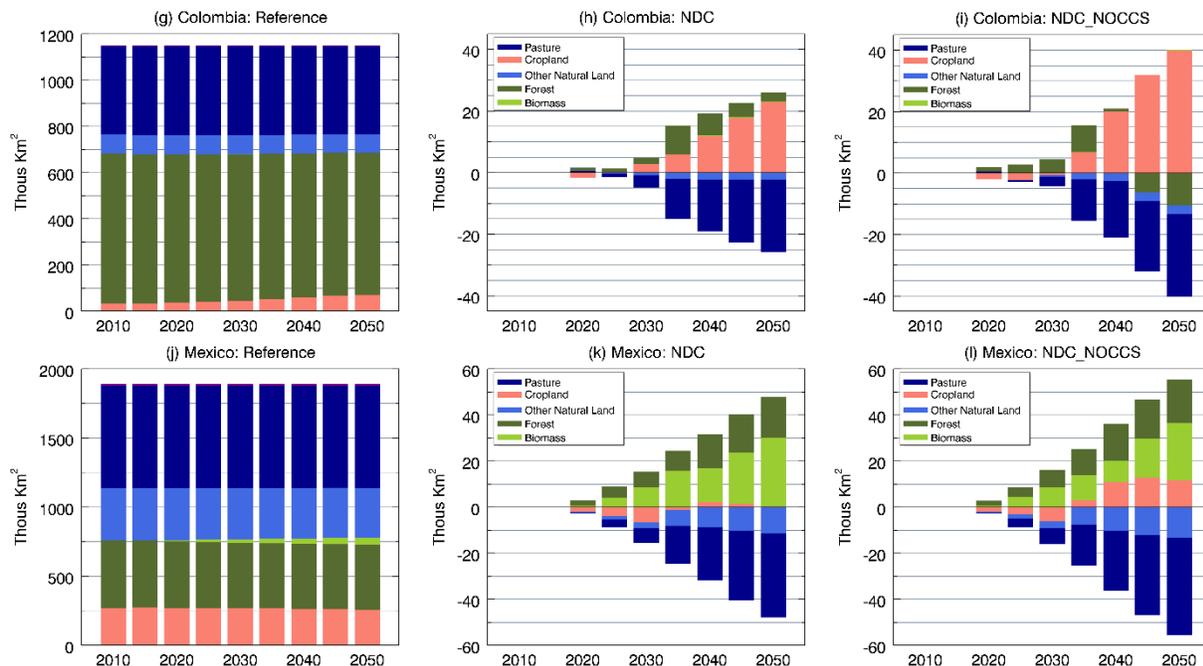


Fig. 5. Land allocation (thous. Km²) under the Reference ((a), (d), (g), and (j)). Difference in land allocation between the NDC and the reference pathways in (b) Argentina, (e) Brazil, (h) Colombia, and (k) Mexico. Difference in land allocation between the NDC_NOCCS and the reference pathways in (c) Argentina, (f) Brazil, (i) Colombia, and (l) Mexico.

Brazil, in particular, is acknowledged as having a prominent bioenergy sector. The country is the world's largest sugarcane ethanol producer, and counts with a well-developed biofuels program. Among all LAC countries, bioenergy in Brazil has the largest contribution on the energy sector accounting for 17% of the domestic energy supply in 2015 (EPE 2016). In this context, it seems counter-intuitive that Brazil does not expand land dedicated to biomass production to a great extent. Unlike the Mexican case, biomass consumption in the Brazilian primary energy mix under both NDC runs is not projected to substantially increase in comparison with the reference case (that already relies on large bioenergy usage). Because the NDC scenarios include pricing of terrestrial carbon and the large amount of carbon stored in forest systems, there is a high economic cost for the large-scale clearing of forested lands to grow dedicated bioenergy crops. Hence, the NDC scenarios are able to achieve the emissions reductions required by the Brazilian NDC by other available energy mitigation options such as wind and solar energy or CCS.

As noted above, the carbon prices applied to LUC emissions place an economic incentive on forests. As a result, forested lands are projected to expand throughout the 2030-2050 horizon in nearly all countries under both NDC scenarios albeit at different levels. The largest increases are projected over Brazil at the expense of cropland and pasture that have lower carbon density. An exception is Colombia under the NDC scenario from 2045-2050. In this case, despite the pricing on terrestrial carbon, land shifts in Colombia responded to higher cropland profitability that led to main losses in pastureland and, to a lesser extent, in forests and "other natural lands" (e.g., scrublands, grasslands, etc.) over the long term. As crops become more profitable, GCAM projects the expansion of croplands into pasturelands and lands dedicated to other natural systems in both NDC runs in Argentina and Colombia, particularly in the NDC_NOCCS scenario. In Mexico, the long-term expansion of cropland is less pronounced given the pressure for land to increase bioenergy production.

It is also important to underscore the fact that the overall dynamics discussed above is largely dependent on the countries' needs to increase the production of agricultural goods to satisfy their internal and external markets. Then, various interplays among shifting land uses, changing levels of domestic agricultural production and demands and trade volumes across LAC in response to the NDC climate policy can be expected, with differing consequences depending on the country. The GCAM responses to this complex dynamic can be appreciated in Fig. 6, which shows the agricultural commodity trade volumes for the selected LAC countries. GCAM allows the tracking of trade of major crop commodities through the global and regional markets for agricultural products that are represented in the model. The amount of agricultural goods available for trade in each region is computed as the difference between regional production and consumption. The consumption of agricultural commodities in GCAM includes demands for food, feed, biofuel production, among other uses. It can be noted that the overall impact of both NDC pathways on trade volumes is to increase net exports (or reduce net imports in the case of Mexico) relative to the reference case, which occurs predominantly over the long run. This pattern is more pronounced for the NDC_NOCCS scenario. In particular, Brazil and Colombia are projected to substantially increase their net exports relative to 2010 levels up to the mid-century. In general, these results imply that the NDC policy could lead to upward pressure on trade volumes in LAC countries in response to changes in domestic production and consumption and larger demands for agricultural products in the global markets.

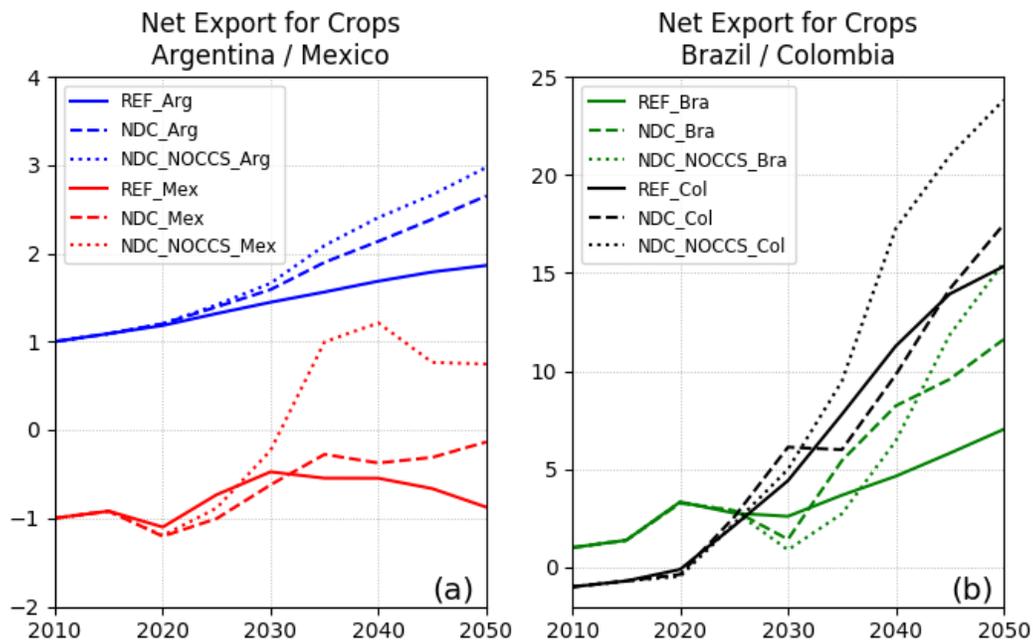


Fig. 6. Indexed crop trade volumes by country as an aggregate of 10 major crop categories: corn, fiber crop, miscellaneous crops, oil crops, grains, palm fruit, rice, root_tuber, sugar crops and wheat (for each scenario: 2010=|1|).

3.4. Water

As mentioned before, the present-day context of freshwater resources in LAC is overall abundance albeit with critical regional differences. Mexico and Argentina, for example, currently experience water deficits, particularly in northern Mexico and some parts of Argentina where moderate to severe water scarcity conditions last more than six months (Mekonnen and Hoekstra

2016). In this regards, one fundamental concern is the growing pressure from socioeconomic trends whose signal may outweigh the effects of climate change on water supplies in the near future (Vörösmarty et al. 2000). Under the BAU assumptions from our reference scenario, the water demand for different uses, particularly agricultural irrigation, is expected to largely increase in the region over the coming decades (Appendix Figs. A3(a) and (b)). Among all LAC countries, Mexico is the main water user, followed by Brazil (see Figs. 7(d) and (j)). Presently, Mexico has the largest area of irrigated land in LAC (about 6.4 million ha) with an infrastructure mostly based on water-inefficient surface (flood) irrigation techniques. Brazil and Argentina also maintain sizable areas of land equipped for irrigation with 5.4 and 2.4 million ha, respectively (Bellfield 2015). In general, irrigation in LAC is characterized by poor efficiency with an average of 39% contrasting to the global average of 56% (Bellfield 2015). In this case, Brazil has the highest irrigation efficiency with about 41%. Within this context, we explored potential directions in which the water component of the EWL nexus in LAC can evolve under the two alternative NDC implementation scenarios discussed above.

Results from the prior sections highlighted that potential NDC implications on land cover can result from a substantial increase in participation of bioenergy in the energy system since more land can be allocated to grow bioenergy crops. This, in turn, could drive larger demands for irrigation. Indeed, bioenergy derived from purpose-grown agricultural feedstocks is significantly more water intensive than fossil fuels, particularly when biomass is used to produce biofuels, the main strategy in LAC, rather than bioelectricity (Gerbens-Leenes 2009, Hoff 2011).

Another impact of the NDC policy could be experienced in the water demand for crop irrigation associated with changes in agricultural production. These potential increments or reductions in crop production would be a reflection of shifts in the demand-side sector that could be induced by various factors (e.g., increased demand for conventional food crops for biofuels production, shifts in crops used for feeding purposes in livestock production to reduce methane emissions, etc.) that interact with the overall dynamic of the land sector. One relevant aspect in this dynamic refers to the potential land cover shifts affecting the availability of croplands.

Lastly, water requirements in the electricity generation sector can also be impacted by the NDC mitigation policy depending on the portfolio of energy sources and technology implementations. In this sector, the LAC as a whole is characterized by heavy use of hydropower generation (see Appendix Fig. A2(d)) that entails significantly lower water consumption (basically due to evaporation although large land-requirements and environmental impacts are associated with the construction of the reservoirs) than other energy sources. Although some growth is expected through mid-century, the share of hydropower in the electricity mix should decrease over time due to limitations on natural resources availability. Hence, other power generation sources will have to increase participation in the electricity mix to account for the fast growing electricity demand in the region (see Appendix Fig. A2(c)). The water management sector in LAC is then expected to deal with the challenge posed by the larger water requirements of conventional thermal power plants, particularly if CCS largely expands over the long-term horizon. In the case of CCS-based power plants, there are additional water demands for cooling and other processes and indirect increases in the water intensity of generation through extra fuel needs that increase water consumption by 37-95% depending on the power plant type (Grubert and Kitasei, 2010). Liu et al. (2015) show that climate mitigation strategies focusing on CCS and nuclear power are associated with unfavorable water consumption effects in the US relative to strategies relying on renewable energy. On the other hand, solar PV and wind technologies have the lowest water demands among the power generation sources ranging from 4-15 liters MWh⁻¹ (Grubert and

Kitasei, 2010). Operational water requirements in solar facilities include water to clean the mirrors/panels. However, concentrating solar power (CSP) systems have water requirements similar to that of traditional thermoelectric power plants due to the additional water usage for cooling processes that is maximized if wet-cooling methods are employed (Bukhary et al. 2018).

To clarify the potential implications of the Paris Agreement pledges on water demands in the selected LAC countries as well as their interplays with the EWL nexus, we compute the differences by sector in water withdrawal estimates between each NDC scenario and the reference case (Fig. 7). Note that the water demands estimated by GCAM are not constrained in terms of water availability, and that climate change impacts are not included. Under both NDC scenarios, the overall picture across the countries, except for Brazil, is one of larger water footprint in a growing pattern over the long term. Fig. 7 brings out the fact that crop irrigation accounts for a great part of the changes in total water withdrawals. In the near term, there is some variability with Argentina and Mexico showing larger irrigation demands in both NDC scenarios, while in Colombia the opposite is noted. Brazil is the only country where the near and long-term total water withdrawals are projected to decrease under the NDC scenarios, as well as the water demands for irrigation when compared with the reference scenario (Figs. 7(d)-(f)).

The previous results point to germane interactions between the water and land sectors in which the NDC policy may have an influence upon. Without changes in agricultural practices, the growth in crop production is affected by the expansion in the physical area allocated to crops (Bruinsma 2009). As a consequence of this interaction between land shifts and agricultural production, there is a reflection in the total irrigation demand. This signal is more clearly shown in the results from Argentina and Brazil where the expansion of croplands (compared with the reference case) in both NDC scenarios (see Figs. 5(a)-(f)) is followed by an increase in crop production (Fig. 8) and in irrigation demand (see Figs. 7(a)-(f)), and viceversa.

For understanding of results in Mexico (under the NDC scenario) and Colombia, it is also important to consider a substitution effect in which land allocated to certain crops (and hence their production) decreases since other categories (that become more profitable within the land sector dynamic of GCAM) expand. This affects the net irrigation estimates because of the differences in irrigation requirements among crops, as illustrated by the case of Colombia (Fig. 9). Despite the fact that the Colombian crop production under the NDC scenario was lower than the reference over the 2040-2050 period (see Fig. 8b), larger net irrigation demands were projected (see Fig. 7(h)) due to a shift away from sugar crops towards other crop categories (Figs 9(a)-(b)) in this period. In particular, the increased share (despite modest as compared with the reference) of the water-intensive rice production played an important role in the irrigation demand (Figs 9d-e). The same effect albeit in the opposite direction is seen under the NDC_NOCCS scenario in 2030 (see Fig. 8(b)), in which a reduction in the share of rice production (Figs. 9(c) and (f)) relative to the reference case (Figs. 9(a) and (d)) contributes to determine the overall decline in the total water irrigation demand (see Fig. 7(i)). Although this crop substitution effect is subject to modeling assumptions as well as a range of uncertainties, the fact that the linkage between the land-sector dynamic and irrigation demands in LAC could be potentially affected by the NDC policy, particularly under the more stringent emissions constraints, is a key insight gained through this analysis.

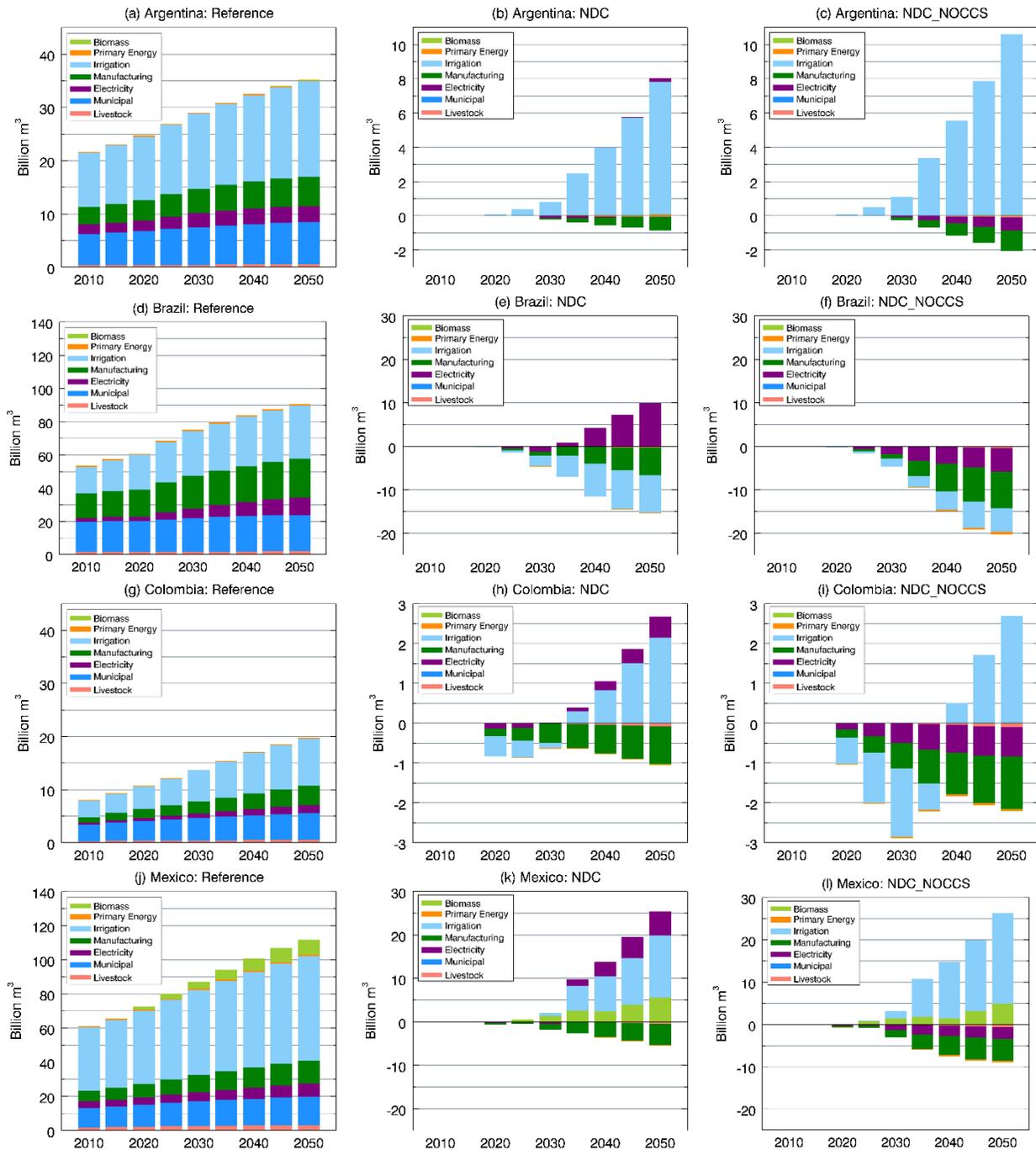


Fig. 7. Total water withdrawals by sector (billion m³) under the Reference ((a), (d), (g), and (j)). Differences in water withdrawals between the NDC and the reference pathways in (b) Argentina, (e) Brazil, (h) Colombia, and (k) Mexico. Differences in water withdrawals between the NDC_NOCCS and the reference pathways in (c) Argentina, (f) Brazil, (i) Colombia, and (l) Mexico.

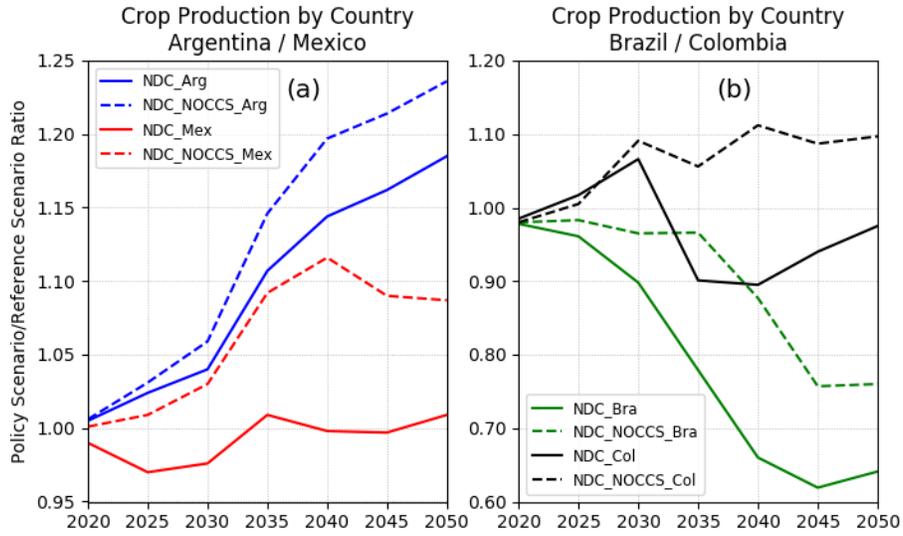


Fig. 8. Crop production by country expressed as the ratio between each NDC scenario and the reference scenario. For each country, the amount of agricultural production only includes those crop categories in which a share of their total production is under irrigation. This means that the amount of crop production accounted in this figure does not reflect the total crop production calculated by GCAM for each country.

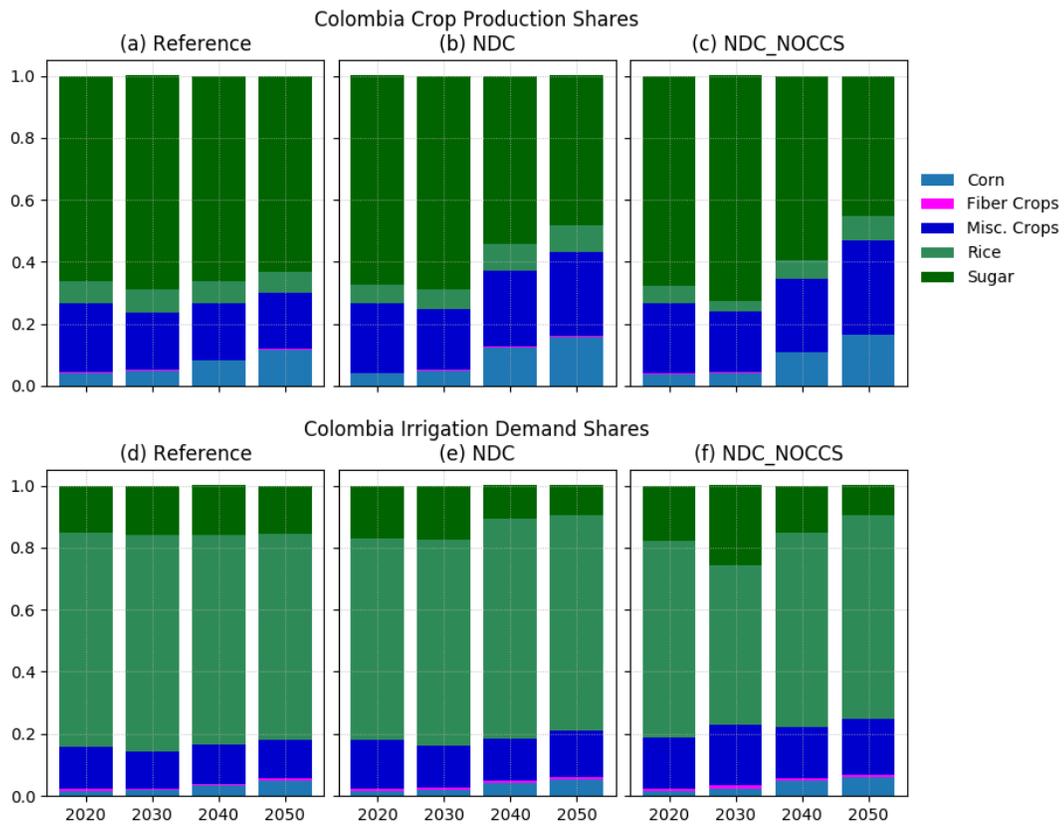


Fig. 9. Production shares of crops categories in Colombia under the Reference, NDC and NDC_NOCCS scenarios (a-c). Irrigation shares of crops categories in Colombia under the Reference, NDC and NDC_NOCCS scenarios (d-f).

Regarding the specific case of irrigation for biomass, relevant changes are seen in Mexico where larger demands are associated with both NDC runs in the near and long term compared to the reference scenario (Fig. 7(j)-(l)). This is in line with previous results from the energy and land sectors that point out Mexico as the country with the largest proportional increase in biomass share in the energy mix followed by larger land requirements to grow the bioenergy crops.

Across all countries, changes in the electric sector water withdrawals can be noted in both NDC scenarios in response to the availability of CCS in the energy system (Fig. 7). When CCS is available (NDC scenario), all countries show larger water withdrawals over the long term, consistent with the timeframe when CCS is substantially deployed. The magnitudes of these increases are the largest in Brazil and Mexico, reflecting the scale of their energy systems and the substantial expansion of CCS needed to account for the emissions constraints in each country. Contrary to Argentina that shows the lowest level of CCS deployment, the expansion of CCS in Colombia achieves considerable levels over the long term. These patterns are then reflected in the large changes in electric sector water demands observed in Colombia in comparison to Argentina. Overall, in the near term, both NDC scenarios signal lower water withdrawals relative to the reference, which is mostly due to the energy reduction demands across countries and the consequent less use of water for energy.

In the case of the NDC_NOCCS scenario, the water demands for electricity are consistently lower than the reference in all countries over the long-term. Even considering that the water-intensive nuclear energy also increase participation in this scenario relative to the reference, the overall net reduction in water withdrawal volumes result from the larger expansion of wind generation and solar-powered electricity (Fig. 10). Note that the long-term expansion of solar energy displayed in Fig. 10 also includes CSP systems that respond for most of the water withdrawal volumes associated with solar energy in 2050. The magnitudes of the negative changes shown in Fig. 7 are compounded by the size of the energy system, the stringency of the mitigation target and the expansion of solar and wind energies relative to the other sources.

In general, both NDC scenarios are associated with less water being demanded by the manufacturing sector in the near and, particularly in the long run. This is attributable to commensurate declines in the total industrial output in the NDC scenarios that is the main driver for future water demands in the GCAM manufacturing sector (Hejazi et al. 2014a).

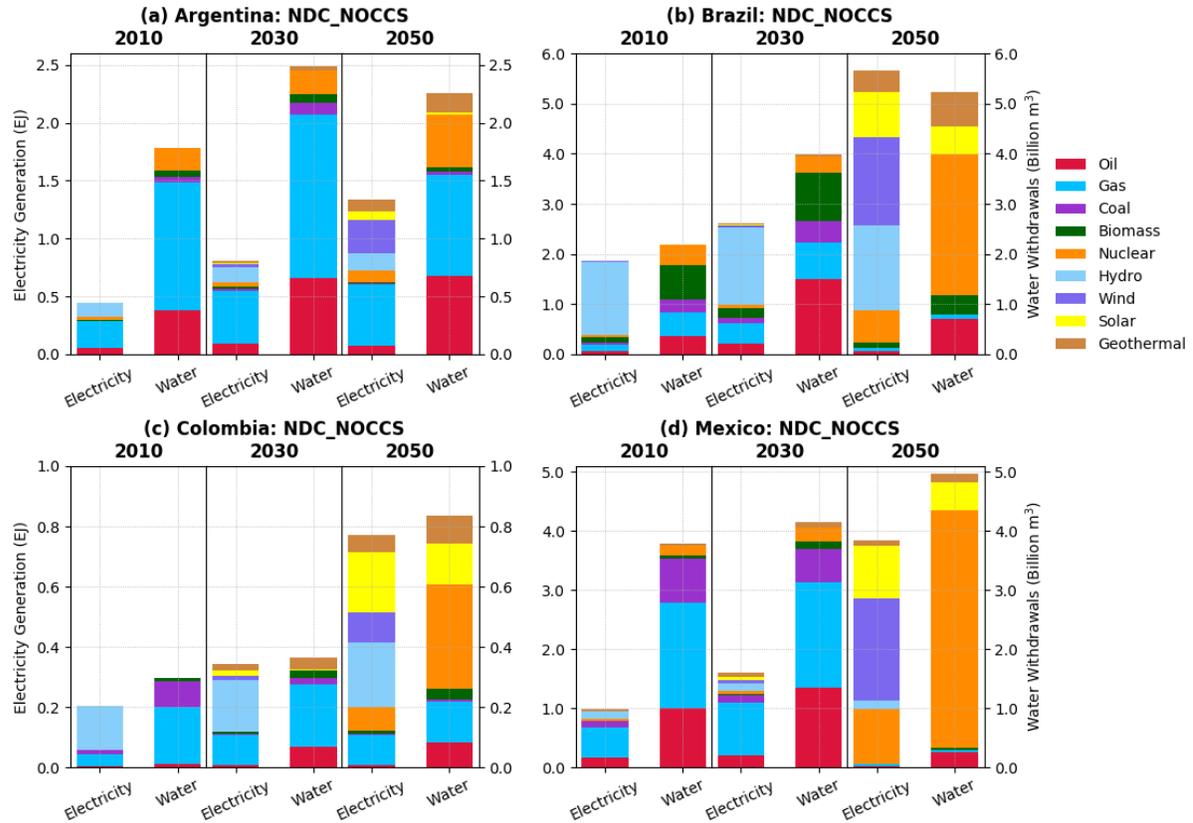


Fig. 10. Water withdrawals (right bars) by power generation source (left bars) under the NDC_NOCCS scenario for (a) Argentina, (b) Brazil, (c) Colombia and (d) Mexico.

4. Concluding Remarks

We employed the GCAM model, driven by emissions constraints consistent with the official NDCs submitted by Argentina, Brazil, Colombia and Mexico to conduct an initial study focused on the near-term and long-term implications of the Paris Agreement climate mitigation pledges on the EWL nexus under two distinct climate mitigation (NDC) pathways. By taking advantage of GCAM's capability of incorporating socioeconomic changes and future technological transitions, this study provides preliminary insights into key potential competing demands within the nexus at national scales that may emerge under each NDC pathway. This analysis led to the identification of differentiated directions of changes in the nexus variables shaped by the level of mitigation ambition of each NDC as well as by the national circumstances. Some countries may have to face more challenging impacts on their EWL nexus variables than others while implementing the sectoral transformation processes required to achieve the mitigation goals established in their Paris Agreement pledges. One example is Mexico, owing to its unfavorable water footprint that might be exacerbated under climate change that may lead to precipitation declines in the sub-tropics (Cook et al. 2014).

A key message that follows from our results is that relevant implications on national water resources could be produced depending on the pathways followed by LAC countries to enforce emissions reductions in their energy systems and their interplays with the land sector. When compared to a reference case with BAU emissions assumptions, these implications were

manifested in both NDC scenarios mainly through: (1) larger irrigation demands in all countries over the long term, except for Brazil (where forested areas were projected to expand, inducing reduction in croplands with consequent lower levels of irrigated crop production); (2) larger irrigation demand for bioenergy crops in Mexico; and (3) larger water withdrawals in the power sector across all countries associated with the long-term CCS deployment in the energy system versus reduced electric-sector water demands when CCS is unavailable.

The understanding gained through this analysis is expected to serve as a first step towards improved knowledge concerning mitigation constraints posed by the mutual interaction and competing demands among the EWL sectors in LAC. This process should help to drive better-informed decisions in business and government sectors regarding policy, infrastructure and logistics investments for the proper management of the EWL resources in line with the NDC climate policy. Particularly relevant in this context is the direction of investments in infrastructure and R&D in low-carbon sources in LAC's power sector over the coming decade given their effects on midcentury infrastructure. As previously noted, there are water use tradeoffs with a larger deployment of the water-intensive CCS versus wind and solar PV technologies.

With a view towards the climate mitigation goals of the Paris Agreement, a clear necessity in LAC is to decouple agricultural growth from deforestation. This could be achieved by a range of measures that inevitably include the expansion of irrigated land area and improvements in irrigation efficiency. Moreover, the fact that almost 90% of all arable land and permanent crops in LAC is rainfed greatly increases vulnerability to droughts with further implications on local economies and food security (Bellfield 2015). Hence, a paramount challenge to the nexus in LAC is the adequacy of the irrigation infrastructure to cope with the future irrigation demand while keeping pace with the growing water requirements from the other sectors and the prospects of climate change. Apart from the investments needed, expanding irrigation in conjunction with the use of more water-efficient techniques, such as drip and sprinkler systems, has tradeoffs in terms of higher energy requirements.

Another nexus challenge germane to the context of climate mitigation in LAC stems from the expansion of bioenergy production given the land and water requirements of conventional food and dedicated energy crops. In this case, a nexus approach would require, for example, careful consideration of the feedstocks to be employed since the water footprint of the main types of crops used for bioenergy production largely varies from about 50 to 400 m³/gigajoule (Gerbens-Leenes 2009). Moreover, the selection of novel feedstocks could be benefitted from research that has demonstrated that a number of energy crops are tolerant to drought conditions and might be employed in marginal lands that are unsuitable for traditional crop production (Quinn et al. 2015). Finally, bioenergy feedstocks consisting of forest and agricultural residues or organic wastes do not entail substantial additional water and land requirements.

All of the aforementioned challenges do not exhaust the wide range of synergies within the EWL nexus in LAC. Nevertheless, they were identified as important nexus issues at the national-level context treated here. More importantly, these issues underscore the need for detailed consideration of the impacts of the Paris Agreement pledges on the EWL nexus. In the context of the agreement, which established a framework in which the NDCs should be regularly updated, the revised climate mitigation pledges would need to incorporate a nexus approach such that a balance between the rational use of the nexus resources and the necessity of achieving NDC goals can be achieved over time.

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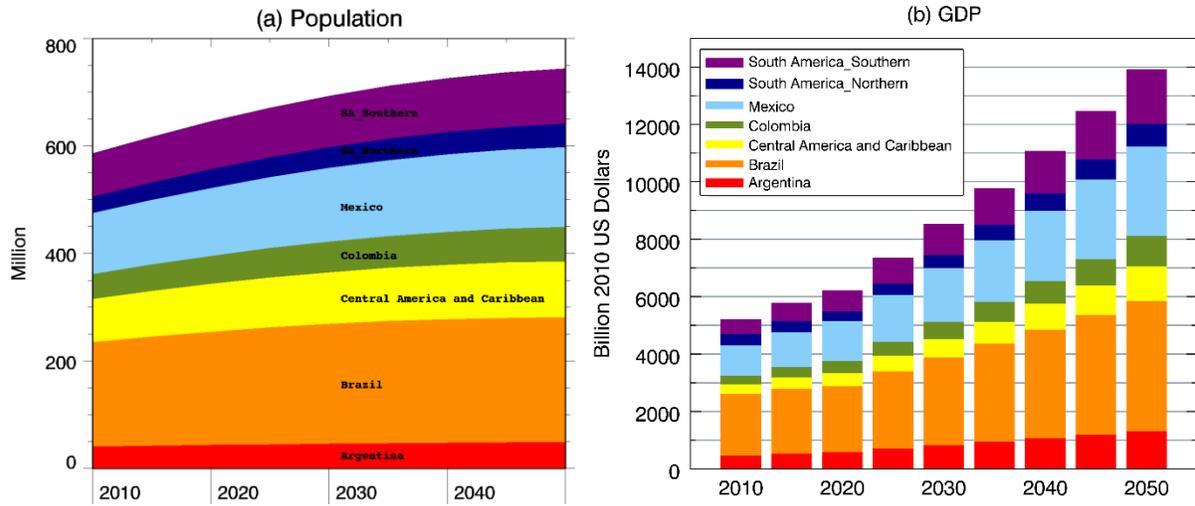
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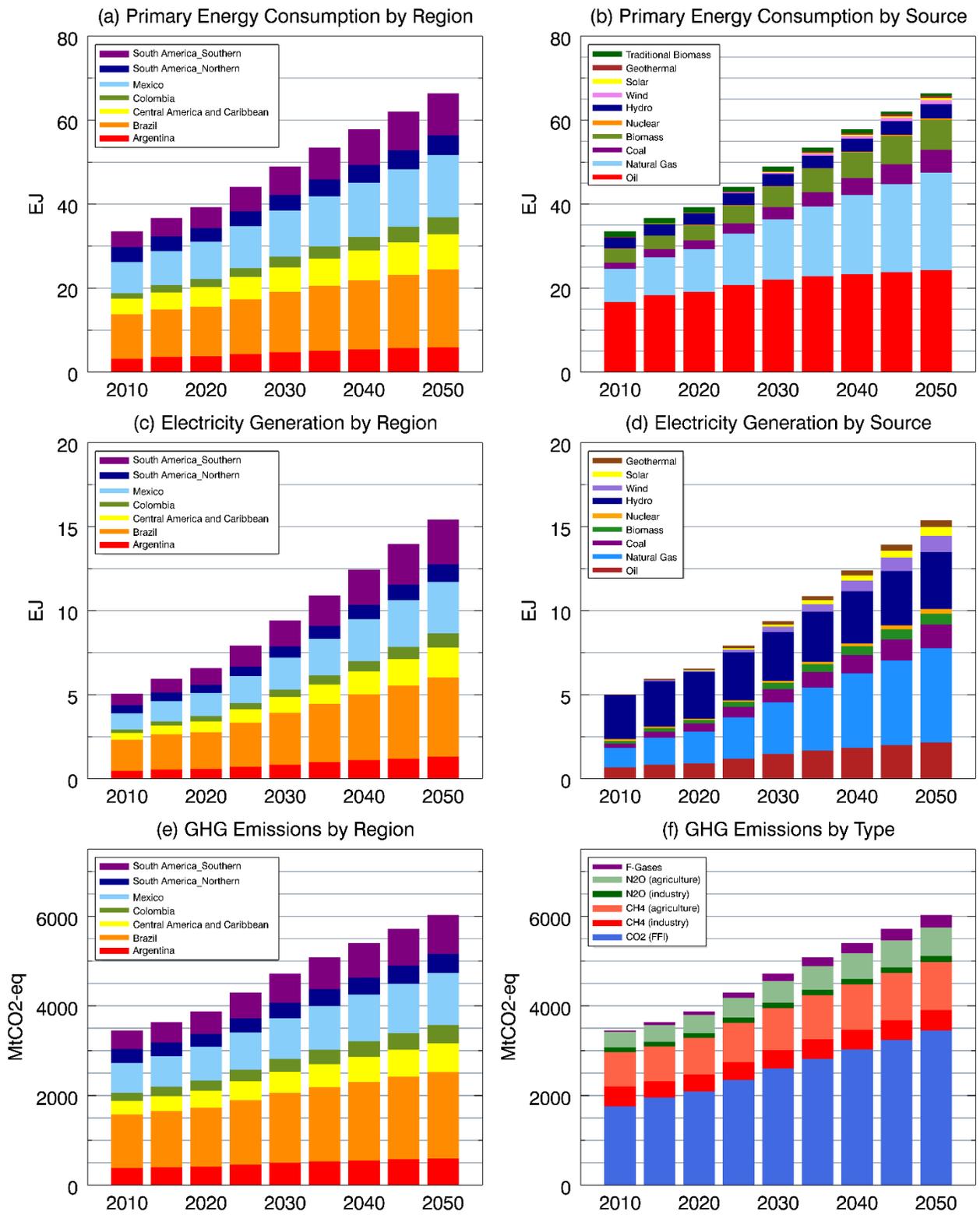
Appendices



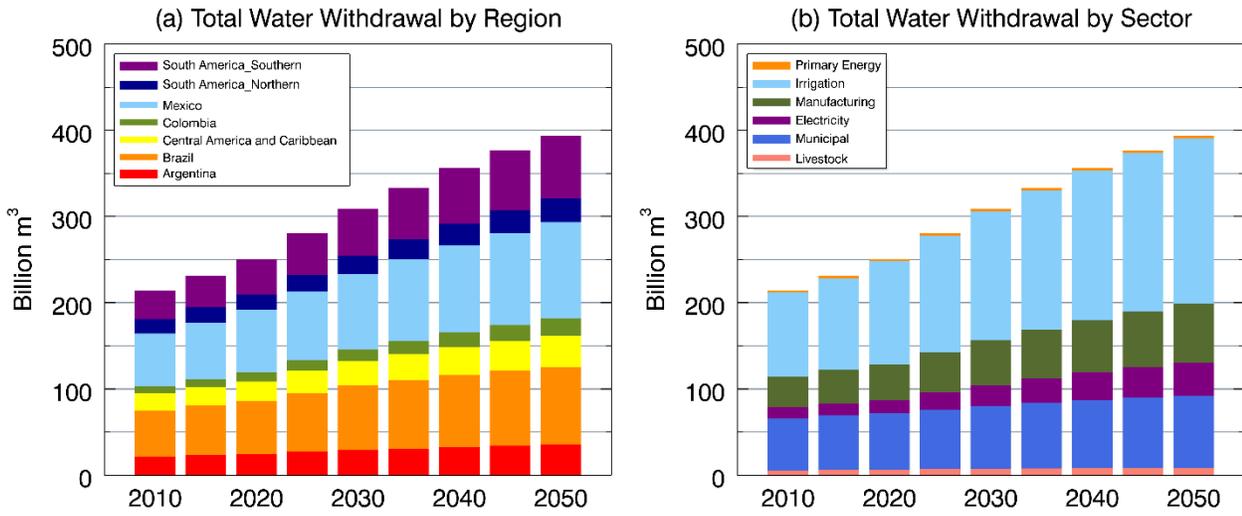
Appendix Fig. A1. Socioeconomics assumptions used in this study: (a) Population and (b) Gross Domestic Product (GDP).

Short-term GDP: IMF World Energy outlook database.

Long-term GDP and population: Shared Socioeconomic Pathways database (SSP2).



Appendix Fig. A2. GCAM outputs for the Reference (no policy) scenario: (a) primary energy consumption by region and (b) by source; (c) electricity generation by region and (d) by source; and (e) gross greenhouse gases emissions by region and (f) by type.



Appendix Fig. A3. GCAM outputs of water demand for the Reference (no policy) scenario: (a) total water withdrawals by region and (b) total water withdrawals by sector.

Appendix Table 1. Assumptions by GCAM Region in LAC for the reduction targets under Copenhagen pledges, NDCs and the post-2030 period.

GCAM Region	Country	Interpretation of Copenhagen Pledges ⁱ	Interpretation of INDCs ⁱⁱ		Source for History/BAU emissions	Long-term goal	Notes
		2020	2025	2030			
Argentina	Argentina		Linear interpolation between 2020 BAU and 2030 emissions constraint	15% reduction in all GHG (including LUC) below BAU ³	BAU based on INDC submission [2]	The conditional NDC target is assumed to be achieved by 2050	Emissions target based on the initial INDC submission from Oct. 2015 (see [2]). Note that in Nov. 2016, Argentina submitted a revised NDC [3].
Brazil	Brazil	37.5% (average of 36.1-38.9%) reduction in all GHG (including LUC) below BAU	37% reduction in all GHG (including LUC) below 2005	43% reduction in all GHG (including LUC) below 2005	Historical emissions and 2020 BAU based on INDC submission [4]	Emissions constraints extrapolated from 2025-2030 rate of emissions reduction until 2050	Revised emissions constraints based on [5]
Central America and Caribbean	Grenada		30% reduction in all GHG (including LUC) below 2010		Historical emissions based on INDC submission [6]	Emissions targets assumed to be constant beyond 2030	
	Dominica		39% reduction in all GHG (including LUC) below 2014	45% reduction in all GHG (including LUC) below 2014	Historical emissions based on INDC submission [6]		
	Guatemala		Linear interpolation between 2020 and 2030 emissions constraints	11.2% reduction in all GHG (including LUC) below BAU	BAU based on INDC submission [6]		
	Haiti			5% reduction in all GHG (including LUC) below BAU	BAU based on INDC submission [6]		
	Barbados			44% reduction in all GHG (excluding LUC) below BAU	BAU based on INDC submission [6]		
	Trinidad and Tobago			30% reduction in CO ₂ from fossil fuels and industry below BAU	BAU based on INDC submission [6]		
Colombia	Colombia		Linear interpolation between 2020 BAU and 2030 emissions constraint	20% reduction in all GHG (including LUC) below BAU	BAU based on INDC submission [7]	2050 long-term target (30% reduction in all GHG below BAU) based on [8]	Revised emissions constraints based on [8]
Mexico	Mexico	30% reduction in all GHG (including LUC) below BAU	Linear interpolation between 2020 and 2030 emissions constraints	22% reduction in all GHG (including LUC) below BAU	BAU based on INDC submission [9]	Emissions extrapolated from 2030 NDC emissions level towards the 2050 target stipulated in Mexico's Climate Change Mid-Century Strategy [10]	Revised emissions constraints based on [11]
South America_Southern	Peru		Linear interpolation between 2020 BAU and 2030 emissions constraint	20% reduction in all GHG (including LUC) below BAU	BAU based on INDC submission [6]	Emissions targets assumed to be constant beyond 2030 ⁱⁱ	
	Uruguay			Reduction of 1.4 MtCO ₂ in all GHG (including LUC) below BAU	Emissions reductions from BAU based on INDC submission [6]		
	Paraguay			10% reduction in all GHG (including LUC) below BAU	BAU based on INDC submission [6]		

General Observations

ⁱ Following [1]. Only quantifiable Copenhagen commitments that have not been formally rescinded are represented. Countries that have both a Copenhagen pledge for 2020 as well as a NDC for the 2025 or 2030 timeframe are assumed to achieve both. Emissions constraints based on [1] with revisions where noted (see ii and Notes).

ⁱⁱ Following the "Paris Increased Ambition" scenario taken from [1] with emissions constraints revised where indicated (see Notes). NDCs represented: unconditional pledges. Note that those countries with INDCs not represented in [1] (e.g., for not having submitted INDCs or with no unconditional pledges – see details in [1]) are not listed in Table S1.

ⁱⁱⁱ Similarly for South America_Northern.

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