Integrated energy-water-land nexus planning to guide national policy: an example from Uruguay

Zarrar Khan1,7, Thomas B Wild1,2, Maria Eugenia Silva Carrazzone3, Rossana Gaudioso3, Maria Pia Mascari4, Fabiana Bianchi5, Federico W einstein3, Federico Pérez5, Fernando Miralles-Wilhelm1, Leon Clarke1, Mohamad Hejazi1, Chris R Vernon1, Page Kyle7, Jae Edmonds1 and Raul Muñoz Castillo6

1 Joint Global Change Research institute, Pacific Northwest National Laboratory (PNNL), College Park, MD 20740, United States of America
2 Earth System Science Interdisciplinary Center (ESSIC), University of Maryland, College Park, MD 20740, United States of America
3 National Secretary of the Environment, Water and Climate Change, Presidencia República Oriental, Uruguay
4 National Planning Directorate, Planning and Budget Office, Presidencia República Oriental, Uruguay
5 Universidad de la Republica, Montevideo, Uruguay
6 Inter-American Development Bank (IDB), Washington DC, United States of America
7 Author to whom any correspondence should be addressed.
E-mail: zarrar.khan@pnnl.gov

Keywords: energy, water, land, integrated, nexus

Abstract
Despite broad consensus on the benefits of a nexus approach to multi-sector planning, actual implementation in government and other decision-making institutions is still rare. This study presents an approach to conducting integrated energy–water–land (EWL) planning, using Uruguay as an example. This stakeholder-driven study focuses on assessing the EWL nexus implications of actual planned policies aimed at strengthening three of Uruguay’s key exports (beef, soy, and rice), which account for more than 40% of total national export revenue. Five scenarios are analyzed in the study: a reference scenario, a climate impacts scenario, and three policy scenarios. The three policy scenarios include measures such as increasing the intensity of beef production while simultaneously decreasing emissions, increasing irrigated soybean production, and improving rice yields. This study supplements previous sector-specific planning efforts in Uruguay by conducting the first stakeholder-driven integrated multi-sector assessment of planned policies in Uruguay using a suite of integrated modeling tools. Key insights from the study are: as compared to a reference scenario, improving beef productivity could lead to cropland expansion (+30%) and significant indirect increases in water requirements (+20%); improving rice yields could lead to increases in total emissions (+3%), which may partially offset emissions reductions from other policies; expanding irrigated soy could have the least EWL impacts amongst the policies studied; and climate-driven changes could have significantly less impact on EWL systems as compared to human actions. The generalizable insights derived from this analysis are readily applicable to other countries facing similar multi-sector planning challenges. In particular, the study’s results reinforce the fact that policies often have multi-sector consequences, and thus policies can impact one another’s efficacy. Thus, policy design and implementation can benefit from coordination across sectors and decision-making institutions.

1. Introduction
Uruguay (figure 1(a)) is one of the smallest countries in Latin America, both by population (3.5 million in 2018) and land area (176 000 km²). About 96% of the population is concentrated in urban areas, and more than half of the population lives in the capital city of Montevideo [1] (figure 1(b)). Uruguay’s relatively small, export-oriented economy is tightly connected to international markets. This strong dependency...
became strikingly clear when the economic crisis of 2002 in neighboring Argentina reduced Uruguay’s GDP by 10.8%, exchange rate by 90%, and average household income by 20% relative to 1998 levels [2]. In the nearly two decades following this crisis, Uruguay has become a regional economic power with the highest per capita Gross National Income in Latin America [3] as a result of prudent macroeconomic policies in combination with a diversification of its markets. Uruguay reduced its regional trade with other Latin American countries from 45% of total trade to 26% between 2000 and 2017, and increased trade with China and Europe to make up the difference [4, 5].

However, while it expanded its markets, Uruguay’s mix of export products has become increasingly concentrated in a few key products over the years [6, 7]. From 2000 to 2017, beef-related exports increased from 15% of total export revenue to greater than 25%, soybean exports increased from 0.06% to 7%, and rice exports have remained at about 5% (figure 1(c)). Together these three products (beef, soybeans, and rice) accounted for about 40% of all export revenue in 2017. At the same time, all three products are heavily dependent on the availability of accessible and affordable water and land resources, together accounting for more than 75% of the country’s land use [8], water use [9], and greenhouse gas (GHG) emissions [10, 11]. On a national scale Uruguay has more than sufficient water resources (170 km³ yr⁻¹) to meet demands (4.5 km³ yr⁻¹ in 2015) [9, 12], with a large reservoir storage capacity of 17.3 km³ concentrated in four main reservoirs [13]. However, the uneven spatial distribution of water [9] and its quality [14] pose infrastructure planning and management challenges. Thus far, Uruguay has not faced serious challenges meeting energy demands. Hydropower generation from Uruguay’s large multipurpose reservoirs have traditionally accounted for the largest share (>75%) of electricity generation [15]. In recent years Uruguay has made strong efforts to increase non-hydropower renewables in its electricity mix. With 30% of electricity generated from wind in 2017, Uruguay is now ranked along with Denmark as a world leader in wind energy generation. Land in Uruguay is dominated by natural pastures, which cater to Uruguay’s large grass-fed livestock sector and account for about 70% of total land [8]. Agriculture, forests, and other non-pasture natural land occupy about 10% each of total land, with urban land-use accounting for less than 1%.

Although traditionally managed independently, there is a growing consensus on the benefits of holistically planning EWL resources together in order to better account for linkages and trade-offs between sectors that evolve in response to a range of possible socio-economic, climatic, and technological drivers [16, 17]. These linkages include water competition for residential, agricultural, and energy use; changing crop mixes in response to global food, agriculture, and bioenergy markets; and subsequent impacts on forest, pasture, and other land-use changes [18–28]. Numerous studies have holistically analyzed EWL interactions, from regional to global scales [29–36]. Together these studies highlight several key issues that we seek to address in this analysis. Land has been pointed out as a critical factor that is often ignored in nexus analysis, despite the land sector’s critical interconnections with water and energy, as well as the rapid degradation of land resources currently taking place in many regions [32]. Capturing global dynamics in international commodity markets is also highlighted as essential to better understand socioeconomically-driven EWL resource demands, as well as the transfer of interconnected virtual EWL resources [29, 33, 37]. Some studies call for the need to address EWL nexus issues at decision-relevant scales, which can require both co-developing insights with stakeholders and flexibly conducting analysis at variable spatial resolution [35, 38]. Finally, several studies project that climate change mitigation strategies aimed at energy decarbonization may result in unexpected impacts on water and land that require further evaluation [31, 39, 40]. Our study addresses these key elements by analyzing the implications of relevant national policies across multiple economic sectors (including land) and spatial scales (from sub-regional to national), while at the same time capturing global dynamics.

The LAC region in particular bears further investigation with respect to the factors described above because it faces strong EWL nexus challenges as a result of its abundant but often unevenly distributed resources, strong connection to the global economy through agricultural trade, and potential for climate change impacts on EWL systems. Willaarts et al (2014) [41] describe the links between water and food security in LAC, finding that globalization and expanding international trade could greatly intensify water and food security challenges, which must be addressed by rapidly evolving governance of the region’s complex, inter-connected natural and human capital. Muñoz-Castillo et al (2019) [42] investigate broader EWL and climate impacts in the LAC region and find that water-scarcity will evolve unevenly across LAC, and is heavily driven by water withdrawal pathways, which are in turn determined by shifting socio-economic, agricultural, and energy trends. Santos Da Silva et al (2019) [36] evaluate the EWL nexus implications of the Paris climate accord pledges in Argentina, Colombia, Brazil, and Mexico, and point to areas of concern such as the increased pressure that decarbonization efforts will place on land and water resources for biomass and electricity production. This paper expands on these studies and explores EWL dynamics in Uruguay’s key export sectors, which drive its economy, while at the same time weighing the relative implications of climate change.
impacts versus socio-economic drivers, all in a local governance context led by in-country stakeholders.

Building on all these previous efforts in LAC and elsewhere, our study is the first we are aware of that analyzes EWL nexus interactions and implications in Uruguay. We believe this study can serve as a valuable example, not just in LAC but in other regions globally, for how to conduct a stakeholder-driven study of the multi-scale EWL nexus implications of policies and investments being planned in a particular region, while also embedding the analysis of that region within the context of broader (i.e. global) EWL dynamics. Our stakeholder-driven study begins with a baseline model that captures national and global EWL dynamics, but supplements these global data sets with local data, models, and sector-specific expert knowledge in evaluating the implications of specific policies [38].

Given Uruguay’s small economy and relatively concentrated export mix, the indirect multi-sector feedbacks that occur through shared EWL resources cannot be ignored in national plans seeking to strengthen Uruguay’s position in global markets. Additionally, Uruguay is well-positioned to undertake integrated multi-sector planning precisely because of the country’s relatively small population coupled with its coordinated government structure [43, 44]. Along with traditional sector-specific ministries, an active overarching planning department (Oficina de Planeamiento y Presupuesto [45]) is capable of facilitating the implementation of cross-sector nexus insights across its various sectors. In this stakeholder-driven study, we evaluate policies in the livestock, soybean, and rice sectors from an integrated perspective, considering the implications of long-term global and regional socio-economic, climatic, water, energy and land related changes. We seek to answer the following three research questions: (1) To what degree are the energy, water, and land systems in Uruguay interconnected? (2) How do existing policy plans made in one of these sectors impact the availability and consumption of resources in the other sectors? (3) How do these human-driven impacts compare to changes driven by the climate?

The remainder of this paper is organized as follows. Section 2 describes the novel methodology used to analyze policies related to livestock, soybean, and rice production. Section 3 presents model outputs together with an analysis of the results. Section 4 provides a summary of the paper, addresses the study’s limitations and lessons for other planning contexts, and describes planned future extensions of the work.

2. Methodology

Over the course of two years, in collaboration with Uruguay’s National Planning Directorate, the Inter-American Development Bank, and local stakeholders representing multiple sectors, we designed several representative scenarios. Each scenario was investigated using an integrated assessment modeling (IAM) framework comprised of a suite of tools, with a global IAM at its core, and a constellation of interconnected downscaling models that interact with the IAM to capture finer-resolution EWL dynamics.

A conceptual schematic of the modeling framework used in this study is shown in figure 2. The Global Change Analysis Model (GCAM) [47] is a dynamic-recursive IAM that combines representations and interactions of the global economy, energy, climate, agriculture, water, and land use systems. GCAM has been used extensively for stakeholder-driven exploration of technology investments, national and international policy approaches, and the implications of changes in key driving forces such as technology and economic growth [48–53]. The standard version of GCAM represents the global economy by disaggregating the world into 32 geopolitical-economic regions, 235 river basins, and 384 land-use regions. In this particular study, Uruguay is broken out as a distinct (i.e. 33rd) energy-economy region. GCAM operates as a market equilibrium model with representative agents from various aggregated representations of economic sectors making resource allocation decisions based on relevant information such as prices and elasticities. Sectors interact via regional and global markets (e.g. electricity, agricultural goods, land), and GCAM iteratively searches for equilibrium between supply and demand across the markets for all goods and services.

The model is calibrated based on historical EWL system behavior using a discrete choice formulation that takes into account both price information and preferences. This calibrated model is then carried into the future. The discrete choice methodology limits winner-take-all behavior (e.g. cost minimization in energy, or profit maximization in land management). Further details are available in the extensive online documentation for GCAM [54].

A constellation of other tools designed to interact with GCAM provide insight into EWL dynamics at more detailed spatiotemporal resolution. We use a global hydrologic model (Xanthos) and a gridded crop model (PDSSAT) to provide information to GCAM, while we use downscaling tools (Tethys and Demeter) to downscale GCAM EWL dynamics for visualization at finer spatiotemporal resolution. The Xanthos global hydrologic model [55, 56] supplies GCAM with information regarding water availability and hydropower production at the scale of 235 large river basins globally. Xanthos simulates the impacts of climate change by receiving temperature, precipitation, and other climate inputs from Global Climate Models (GCMs). Xanthos is a computationally efficient hydrologic emulator that is calibrated to perform similarly to the physically-based
Variable Infiltration Capacity (VIC) model globally [57]. The gridded crop model PDSSAT [58], one of seven crop models that participated in the Agricultural Model Inter-comparison Project (AGMIP) [59], is used to supply GCAM with estimates of changes in global crop yields in response to the same climate drivers (e.g. temperature and precipitation) to which Xanthos is exposed. PDSSAT produces annual changes in agricultural productivity (% change relative to the previous time step), which we smooth before feeding these exogenous values into GCAM at 5-year intervals. GCAM in turn applies these rates to crop yields, which changes the relative profit rates across each of GCAM’s 14 crops and 235 global basins. Uruguay is covered by portions of two of these 235 large river basins. Across these climate impacts categories (runoff, hydropower, and agricultural yields), we evaluate impacts on a global scale, not just in Uruguay. This captures important global dynamics. For example, reduced availability of water...
Table 1. Summary of scenarios used in study.

| Scenario   | Description |
|------------|-------------|
| Reference  | Uses an agreed upon set of assumptions for key drivers such as population and GDP growth in Uruguay. For the rest of the world, the scenario is roughly consistent with the Shared Socioeconomic Pathway 2 (SSP2). The SSP2 scenario represents costs, prices, elasticities and preferences in a “middle-of-the-road” narrative in which social, economic, and technological trends do not shift markedly from historical patterns [64–66]. The Climate and policy scenarios below employ the same basic socioeconomic assumptions built into the Reference scenario. |
| Climate    | Evaluates the impacts of climate change on three key parameters: hydro-electric power production, agricultural yields, and water availability (i.e. runoff) for five bias-corrected Global Climate Models (GCMs) from the Inter-Sectoral Impacts Model Intercomparison Project (ISI-MIP) [67] and four Representative Concentration Pathways (RCP) [68]. This range of models and climate forcing scenarios are used to explore uncertainty surrounding future climate conditions. From among this range of Climate scenarios, we selected one to be used in the Climate scenario, which consists of the GFDL GCM run with the RCP8.5 climate forcing trajectory. This results in the following outcomes, which are fed into GCAM:  
• Hydropower increases by 20% by 2050 from the Reference scenario  
• Runoff increases by 3% by 2050 from the Reference scenario  
• Irrigated Soy yield increases by about 4% by 2050 from the Reference scenario within Uruguay, though significant changes also take place in global markets  
• Irrigated Rice yield fluctuates between ± 4% by 2050 from the Reference scenario within Uruguay, though significant changes also take place in global markets. |
| Beef       | Increases the productivity by weight of beef production, and decreases the CH₄ and N₂O emissions intensity of beef production in line with the National Adaptation Plan for Agriculture (NAP-Ag) [8, 69] and the Nationally Determined Contributions (NDCs) of emissions outlined in Uruguay’s commitment as part of the Paris Agreement [70].  
• Increase production (kg beef/kg feed) by 40% by 2030 relative to 2015 values, then hold this production efficiency constant through 2050  
• Decrease emission intensity (emissions/kg) of CH₄ by 40% by 2030 relative to 1990 values, then hold this production efficiency constant through 2050  
• Decrease emission intensity (emissions/kg) of N₂O by 40% by 2030 relative to 1990 values, then this production efficiency hold constant through 2050. |
| Soy        | Increases irrigated area of soybean crops to gain higher yields in line with the National Plan to Improve Irrigated Agriculture [71, 72].  
• Increases share of irrigated soybean area as compared to rainfed soybean area, so that irrigated soybean area is 600% of the 2015 values in 2030. Shares of irrigated vs rainfed soybean area are then held constant through 2050. |
| Rice       | Improves the yield of rice based on recommended best-practices from Uruguay’s Ministry of Agriculture to close the national rice yield gap [73, 74].  
• Adjusts annual rice yield growth to increase yields (tons/ha) by 20% by 2030 relative to 2015 values, and then maintain reference growth in yields through 2050. |

or production of crops in other parts of the world can affect Uruguay through shifting agricultural trade patterns.

Tethys [60] is used to downscale GCAM water demands (onto a 0.5-degree grid globally) using gridded irrigated area and population datasets. The Demeter model [61] is used to downscale GCAM land use (onto a 0.25-degree grid globally) using Demeter’s base MODIS global gridded landcover data sets. Dowscaled gridded data is re-aggregated to relevant spatial boundaries using the Metis model [38]. We employ a gridded Water Scarcity Index (WSI) in this study that is calculated as the ratio of total water withdrawals (produced by Tethys) to total water supply (produced by Xanthos), divided into four categories [62, 63]: no scarcity (WSI < 0.1), low scarcity (0.1 ≤ WSI < 0.2), moderate scarcity (0.2 ≤ WSI < 0.4), and severe scarcity (WSI ≥ 0.4).

A summary of the five scenarios chosen for this study is provided in table 1, with further descriptions of each provided in SI1. The five scenarios include: a reference scenario (Reference), a climate impacts scenario (Climate), and three policy scenarios (Beef, Rice, and Soy). The Beef policy seeks to increase the intensity of beef production while simultaneously decreasing emissions. The Soy and Rice policies seek to increase irrigated soybean production, and improve rice yields, respectively. The policy scenarios we explore in this study are ‘stylized’, in that they provide simplified but strategy-relevant representations of real policies. Real policies often consist of numerous components, some of which can
be difficult to account for in the modeling framework described earlier. For example, in Uruguay this includes rotating crops to improve soil management, optimizing irrigation and drainage patterns, improving seed cultivation, and protecting harvested grain. Through an extensive and iterative process, local stakeholders involved in the design and implementation of the policies explored in this study guided the selection of: GCAM model parameters to implement the stylized policy representations, GCAM output metrics used to evaluate policy outcomes across multiple sectors, and the spatial scale of analysis. The policies explored here are closely tied to the water sector, so hydrological units (i.e. river sub-basins) were selected as a common spatial analysis unit.

3. Results & discussion

3.1. Reference scenario

A nexus overview of projected developments across EWL sectors in the Reference scenario is provided in figure 3. Uruguay sees considerable growth across the EWL sectors in response to population and GDP growth. Details regarding the baseline socioeconomic drivers that set the scale of economic activity across all scenarios (including the Reference) is provided in SI2. Pasture land remains the largest land-use type in Uruguay through 2050 to support the country’s large livestock and beef industry (figure 3(a)). Crops occupy about 10% of national land area (figure 3(a)), with a slight increase through 2050 in response to agricultural production growth. Agricultural production increases by 40% by 2050 (relative to 2015) as a result of increased cropland area and crop yields. Wheat, rice, and soy account for the largest crop shares by production and land area in 2010, with rice showing the largest increases in production, almost doubling by 2050 (relative to 2015), in line with national plans and projections [8, 69, 71] (figure 3(b)). The evolution of the agricultural system has important implications for the water sector.

The agricultural sector is currently the largest user of water (75%) (figure 3(c)), for purposes of irrigation, demanding about 3.2 km$^3$ of total water in 2010, and more than doubling that usage by 2050 (6.5 km$^3$ of the total 8.5 km$^3$). Figure 3(d) shows the distribution of agricultural water withdrawals (i.e. the green bars in figure 3(c)) by crop. Rice accounts for almost all of the water withdrawals in the agricultural sector (figure 3(d)), with its share of total water withdrawals steadily increasing through 2050. This underscores the potential value of policies...
focused on increasing rice yields without increased water requirements (table 1).

In the energy sector (figure 3(f)), total final energy demand is projected to more than double from 2010 to 2050. The fuel mix shifts toward more electricity and oil, and less biomass. (From 2010 to 2050, the share (%) of electricity, biomass, and oil in final energy shift from 22% to 26%, 42% to 49%, and 36% to 22%, respectively). This shifting energy fuel mix has limited implications for total water withdrawals, particularly given the electricity mix is dominated by non-water intensive renewables (e.g. wind power). Electricity increases threefold from 2015 to 2050. Hydropower currently accounts for the majority of electricity generation (figure 3(e)), with Uruguay already using 85% of total national hydropower potential, the highest national usage of hydropower capacity in Latin America [75]. With limited growth potential in hydropower, planned wind energy expansion is projected to supply the majority of new electricity demand (60% in 2050). This expansion will reduce the percentage of fossil fuel-based power generation from 8% in 2015 to about 1% in 2050. The Reference scenario for Uruguay in figure 3(e) projects about 5 TWh of solar production annually in Uruguay, which would amount to as much as 120 km$^2$ of land required (using the land use requirements of about 3–6 acres per GWh/yr from Ong et al (2013) [76]). This represents a relatively small percentage of the national total land area of 176,000 km$^2$ shown in figure 3(a).

Total GHG emissions in Uruguay in 2015 were about 42 Mega Tons of CO$_2$ equivalent (MTCO$_2$ eq.), which amounts to < 0.07% of global emissions and 0.8% of Latin American emissions [10, 11] when considering the 100 year Global Warming Potential (GWP). (Total GHG emissions are only about 20 MTCO$_2$ eq. when considering the Global Temperature change Potential (GTP). Further details on the GWP and GTP metrics are provided in SI3)). The majority of emissions resulted from CH$_4$ emissions from livestock, as seen in figure 3(g). CO$_2$ emissions come mostly from the transport sector and show considerable growth, doubling from 2010 to 2050 in response to transportation demand growth.

Our integrated modeling framework allows us to investigate the distribution of water and land resources at flexible and stakeholder-relevant spatial scales, in this case by river sub-basins (figure 4(a)) given the focus on agriculture and water resources. Figure 4 displays the spatial distribution of land and water availability and usage in Uruguay for the Reference scenario, using downscaled GCAM outputs. Figure 4(a) demarcates the eight sub-basins used for spatial analysis in this study. Each land allocation sub-figure within figure 4(b) shows the fraction of land in each of the eight sub-basins that corresponds to each of five dominant land use types. Water supplies and demands in figures 4(c) and (d) are reported in units of depth (mm) to facilitate comparison across unequally sized regions. The majority of Uruguay’s land is currently (in 2015) dedicated to pasture land.
with agriculture concentrated in the south (figure 4(b)). Agriculture, particularly rice, accounts for the large water demand in the south east (figure 4(d)). Despite low water scarcity (ratio of water demands to runoff) at the national level in 2010, moderate water stress may develop in several basins across the country by 2050 (figure 4(e)) in response to the socio-economic and human-driven evolution of global EWL dynamics explored in the Reference scenario.

3.2. Climate impact scenarios and policy scenarios
In this section, a climate impact scenario (GCM: GFDL, RCP: 8.5) and three policy scenarios (Beef, Soy, and Rice) described in section 2 are explored to understand their broad EWL nexus implications. Figure 5 shows the results of climate impacts analysis on water and agriculture run externally to GCAM. Figure 5(a) is a map of climate impacts on runoff (mm), as measured by the difference between the Climate and Reference scenarios. Figure 5(b) shows the change (%) in hydropower production, relative to 2010 production, that is projected to occur in Uruguay across 20 simulations which are combinations of four RCPs and five GCMs. We smoothed out the variability in hydropower production projections from Xanthos to generate long-term trends useful in the context of GCAM. The projected relative changes in figure 5(b) are entirely a result of altered runoff patterns resulting from future climate change. The twenty GCM/RCP scenarios are shown in gray, while a single selected scenario from among those 20 scenarios is shown in blue to reflect the Climate scenario. Both runoff and potential hydropower are projected to increase as a result of climate change across the suite of GCM and RCP scenarios. In this paper we select one of the 20 climate scenarios to serve as the Climate scenario, GFDL-RCP 8.5. This scenario represents a relatively smaller increase in runoff compared to the reference long-term mean (figures 5(a)) and a median increase in potential hydropower (figure 5(b)) as compared to the other climate scenarios.

Figure 5. Climate scenario inputs. Projected changes for combinations of five different GCMs and four RCPs for (a) absolute difference between 2050 and reference runoff (mm) (b) % change in hydropower (c) change in yield of soy (Million tons per thousand square kilometers) (d) change in yield of rice (Million tons per thousand square kilometers). For illustration: black lines correspond to the Reference scenario, blue lines correspond to the chosen climate scenario for this study (GFDL_RCP8p5), while the grey lines show all other GCM/RCP combinations. Note: 1 Mt/thous km² = 10 ton/hectare.
Figures 5(c) and (d) show the evolution of crop yields, as estimated by the gridded crop model PDSSAT. Yields differ across Uruguay’s two large river basins and 14 GCAM crops, each of which can be either irrigated or rainfed. Thus, to provide a representative sample of crop yield trends, we focus discussion here on two crops (rice and soy) important in the context of the policies considered in this study. Crop yields are increasing for all crops in the Reference scenario, including the sample of crops shown in figure 5, to reflect increased access to technology, cultivar improvements, etc, along the lines of Shared Socioeconomic Pathway 2 (SSP2) [66]. The impacts of climate change on crop yields within Uruguay are projected to be relatively smaller than the changes seen in runoff and hydropower across the different climate scenarios. Importantly, the global connectivity established through agricultural trade in GCAM means that factors such as altered crop yields posed by climate change could affect Uruguay both directly and indirectly [77]. For example, increased soy and rice production in other regions globally as a result of climate change-induced crop yield effects could affect global prices and demands for these commodity exports from Uruguay. Multiple factors can interact in complex and nonlinear ways in the context of GCAM. Thus, the absence of clear climate impacts on crop yields for rice and soy within Uruguay does not indicate the absence of global crop yield impacts on Uruguay.

The policy scenarios, which were run independently of the Climate scenario, were designed to address particular aspects of each chosen export sector. Figure 6 shows a scenario comparison of the evolution of a set of EWL metrics through 2050, while figure 7 shows the sub-sector details for the values from figure 6. The following paragraphs summarize key nexus insights from these two figures.
Figure 7. Nexus comparison across scenarios. First column shows sub-sector details for the Reference scenario, and the second through fifth columns show the differences between the Reference scenario and the Climate, Rice, Beef, and Soy scenarios, respectively. (a) Land allocation (1000 km$^2$), (b) Agricultural Production (Mt), (c) Water withdrawals (km$^3$), (d) Final energy (Mtoe), (e) Electricity (TWh), and (f) GHG emissions GWP (MTCO$_2$eq).

Nexus insight 1: Improving beef production efficiency and emissions intensity could indirectly impact land, crops, and water. The Beef policy is designed to increase the efficiency of beef production (i.e. to produce larger cattle (kg/head) with the same amount of feed), as well as to lower the emissions intensity of beef production (i.e. emission/kg) (section 2) (figure 6(f)). Emissions as a result of the policy decrease relative to the reference by about 6% in 2050. Despite the policy’s confinement to the beef sector, it significantly increases crop land area (25% increase) (figure 6(a)) and agricultural production (a 30% increase) (figure 6(b)) relative to the Reference scenario. This occurs because improving the productivity of livestock results in less need for pasture land to produce the same amount of beef. Land previously used for pasture then becomes available for other uses such as forests and crops. This substitution is seen figure 7(a) and is driven by the profitability of each type of land-use. The new crops, in particular rice, demand additional water, resulting in a 22% increase in total water withdrawals relative to
the Reference scenario. While other studies such as Ran et al [78] serve an important purpose by focusing in detail on particular sectoral interactions, our modeling approach allows stakeholders to see new effects by capturing a broad range of sectoral interconnections. Thus, we see that a policy targeted at improving the productivity of beef can have significant impacts on water, agriculture, and land resources.

**Nexus Insight 2: Increased emissions from rice yields could offset decreased emissions from enhancing beef production efficiency and emissions intensity.** The Rice policy is designed to close the wide gap in rice yields across Uruguay by improving rice growing practices. An important consideration in rice irrigation is the associated CH$_4$ emissions from rice paddies, which conflicts with national climate mitigation and adaptation goals [73, 74]. Globally, rice paddies account for 20% of total agricultural CH$_4$ [79]. Improving the yield of rice makes it more profitable, thus slightly expanding the production of rice and its land footprint (figure 7(a)). Given the water-intensity of rice irrigation, a corresponding increase in water withdrawals (about 25%) (figure 6(c), figures 7(b) and (c)) is expected. In addition, the policy also results in a significant increase in GHG emissions (about a 5% increase relative to the Reference scenario in 2050) (figures 6(f) and 7(f)). This has the potential to offset emission reductions gained by other climate-related policies, including efforts to increase beef production efficiency and emissions intensity. This result highlights the benefits of jointly evaluating multiple policies that may interact and conflict in unintentionally ways.

**Nexus insight 3: Soy irrigation expansion policy is the least disruptive to EWL systems.** The purpose of the Soy policy is to increase soy yields. This improves the economic competitiveness of soy, which increases total soy production by about 4%. Since almost all soy cultivation in Uruguay is rain-fed, a shift to irrigating 600% more land for soy production also increases water-withdrawals, as shown in figures 6(c) and 7(c). The increase is about 15% by 2050 relative to the Reference scenario. (By comparison, the Beef and Rice scenarios individually increased water demands by over 20%). Apart from these expected increases, the Soy policy has minimal impacts on other EWL sectors. This lack of unintended nexus conflicts makes the Soy policy an attractive potential area for future investment.

**Nexus insight 4: The human dimension of change may exceed climate change with respect to EWL nexus impacts.** Climate change is often the focus of numerous nexus assessments and planning efforts in the literature [80–83]. However, a growing body of literature is suggesting that the human dimension of change can rival or exceed physical change factors in some sectors [50]. In our study, the electricity sector is the only one in which the Climate scenario had a bigger impact than any of the other policies examined. The Climate scenario increased electricity production by 4% relative to the Reference scenario (figure 6(e), figure 7(e)) as a result of increased hydropower potential. Crop yield impacts resulting from climate change also had effects, reducing total agricultural production by about 6% by 2050 (figure 6(b), figure 7(b)), with corresponding decreases in cropland area (figure 6(a), figure 7(a)). These EWL climate-induced changes are comparable in magnitude to the changes resulting from the policies explored in this paper, and are significantly less impactful than the overall changes across the EWL systems as a result of socio-economic drivers (figure 3). As governments make plans to adapt to the potentially devastating impacts of climate change [84, 85], studies such as this one can help planners understand the relative importance of key human (e.g. socioeconomic) and natural (e.g. climatic) drivers of change.

**4. Conclusions**

Uruguay has made steady progress since recovering from the regional economic crisis in 2002, rising to the status of a ‘high income’ nation by 2012. To improve resiliency to economic shocks, Uruguay diversified its export markets to Europe and China. However, its export products have remained concentrated in a few key sectors such as beef, soy, and rice, which accounted for a combined 40% of total exports in 2017 [6, 7]. The process of designing and evaluating policies to improve Uruguay’s performance in these key sectors has traditionally focused on a limited set of sector-specific parameters directly related to each commodity, without consideration of broader multi-sector implications. This study presented the first energy-water-land (EWL) nexus study in Uruguay that analyzes multiple policies from a holistic perspective using a suite of integrated human-earth system modeling tools. The project was conducted over the course of two years in collaboration with Uruguay’s National Planning Directorate, the Inter-American Development Bank, and local stakeholders representing multiple sectors to guide the development of the research in line with local needs.

Results from the Reference scenario showed that socio-economic change in Uruguay could drive growth across all sectors, with the greatest increases projected in electricity generation (three-fold from 2010 to 2050), followed by total final energy and water withdrawals (increasing about two-fold each), and finally agricultural production and emissions (increasing by about 50%). While traditionally the electricity sector has been predominantly fueled by hydropower (>75%), Uruguay has made concentrated efforts to expand wind generation (30% in 2017), making Uruguay a recognized world leader in renewable power supply. Future projections reflect continued growth of wind and solar generation.
to meet new demands since existing hydropower potential has already been almost completely tapped. Agriculture is dominated by rice, soy, and wheat, with rice accounting for the majority of total water demands, other crops being predominantly rain-fed. While water resources in Uruguay are sufficient at a national scale today, certain regions of Uruguay are projected to develop moderate water stress in future years in response to increased agricultural activity.

In collaboration with local stakeholders, several key policies were identified for analysis in the rice, soy, and beef sectors. Rice yields in Uruguay are uneven across the country, with policy measures aimed at closing the yield gap; Soy policy measures encourage shifting from rain-fed to irrigated practices to expand growing seasons and improve yields; and several methods have been identified for simultaneously improving the productivity and lowering the emissions intensity of the beef industry. An integrated analysis of these policies showed several insights across multiple sectors. Emissions in the beef industry are a substantial concern in Uruguay since the sector accounts for the largest share of sectoral GHG emissions. Beef policies were seen to have multiple benefits, including allowing expansion of forests and crops into pasture land that was previously used for cattle grazing. However, as a result, Beef policies could create unintended consequences, such as a 22% increase in total water withdrawals relative to the Reference scenario. Similarly, the Rice policy, while successfully increasing production, also results in increased emissions from the associated water-logging practices, which could offset savings made by improving beef sector emissions. Thus, it could be strategically advantageous for Uruguay to design and evaluate multiple policies jointly in a nexus context, as policies may interact and conflict in unintentionally ways. The Soy policy was the least impactful of the three policies, as switching to irrigated soy cultivation had the least comparative impacts on water demands and emissions.

Climate scenarios explored in this study projected increased runoff and hydropower potential in Uruguay, with smaller climate-induced changes in agricultural yields within Uruguay. Changes in hydropower directly impacted the electricity mix with corresponding shifts in wind and solar. Results show that impacts of climate change were comparable to those resulting from the Beef, Soy, and Rice policies, and were significantly less impactful than the changes resulting from socio-economic drivers such as population, income, and GDP growth. This underscores the importance of accounting for the human dimensions of change in EWL nexus-focused planning efforts. In other regions, such as the Indus Basin, Spain or the Western United States, where climate-driven changes are projected to have more severe impacts on water availability, temperature-driven peak electricity demands, and agricultural yields, this modeling framework would highlight the need for more adaptive planning to optimize the use of limited shared resources across sectors[86–89]. Multiple interacting and conflicting stressors may be worth considering in integrated planning efforts such as the one undertaken here.

Feedback from the extensive interaction with local stakeholders helped identify key areas to address in future work. These include analyzing the wood pulp industry, which is also one of Uruguay’s major exports; tracking the impacts of pollution from agriculture and livestock activities and corresponding deterioration of water quality; climate policies; shifts in international diets away from meat; investigating droughts, which have had a major impact on the agriculture and livestock industry in recent years; and understanding the implications of monoculture agriculture as Soy continues to expand. Additionally, the land-use implications of the extensive wind and solar expansion projected in this study’s Reference scenario should be further explored.

In conclusion, this study presented a holistic assessment of multiple scenarios and sectors in a single, consistent modeling framework. This approach allows planners to both understand inter-sectoral dynamics as well as identify key areas of conflict and synergies at multiple spatial scales, while at the same time readily weighing the impacts of environmental factors versus policy decisions to guide long-term strategies. While the benefits of integrated analysis have been demonstrated in many studies [18, 19, 22, 23], applications of nexus analysis in practice remain scarce as a result of continuing sectoral independence and lack of facilitating bodies to oversee holistic development across sectors. This study provides an example of how to overcome some of these challenges by combining integrated multi-sector analysis with extensive stakeholder interactions to guide identification of relevant scenarios and solutions to explore. Such studies can be particularly useful in other regions that may be more exposed to both local and transboundary resource conflicts, higher vulnerability to climate-driven changes, and areas with a strong dependence on international markets. This work opens the door to future opportunities for similar analysis across sectors and scales to identify unique regional, national and sub-national conflicts and synergies across the globe.

Acknowledgments

The authors wish to thank the Inter-American Development Bank for sponsoring this effort under contract C0260-16. Additionally, this material is based upon work supported by the National Science Foundation under Grant No. 1855982.
Data availability statement

All data that support the findings of this study are included as part of the supplementary information.

ORCID iDs

Zarrar Khan  https://orcid.org/0000-0002-8147-8553
Thomas B Wild  https://orcid.org/0000-0002-6045-7729
Page Kyle  https://orcid.org/0000-0002-1257-8358

References

[1] CIA 2019 South America: Uruguay — The World Factbook - Central Intelligence Agency  https://www.cia.gov/library/publications/the-world-factbook/geos/ur.html (Accessed 18 December 2019)
[2] World Bank 2004 Uruguay poverty update 2003 http://documents.worldbank.org/en/publication/documents-reports/publication/1821414687/61674646/Uruguay-Poverty-Update-2003 (Accessed 18 December 2019)
[3] World Bank 2019 GNI per capita, atlas method (current US$) - Uruguay, Argentina, Chile Data https://data.worldbank.org/indicator/NY.GNP.PCAP.CD?locations=UY-AR-CL (Accessed 18 December 2019)
[4] CEPII 2019 CEPII - BACI – presentation http://www.cepii.fr/CEPII/en/bdd_modele/presentation.asp?id=37 (Accessed 18 December 2019)
[5] OECD 2019 OECD - (URY) exports, imports, and trade partners, observatory of economic complexity (OECD) https://oec.world/en/profile/country/ury/ (Accessed 18 December 2019)
[6] World Bank 2015 Uruguay Systematic Country Diagnostic - June 2015 (Washington, DC: World Bank Group) http://documents.worldbank.org/en/publication/documents-reports/publication/914791468187801159/Uruguay-SysCountry-Diagnostic (Accessed 18 December 2019)
[7] Alberto P, Jose-Daniel R and Gonzalo V 2015 Uruguay - Trade Competitiveness Diagnostic (Washington, DC: World Bank Group) http://documents.worldbank.org/curated/en/336461486179662552/Main-report
[8] MGAP 2019 Plan nacional de adaptación a la variabilidad y el cambio climático para el sector agropecuario http://www.mgap.gub.uy/sites/default/files/pma-agro-digital_0.pdf
[9] MVOTMA 2017 Plan nacional de aguas http://www.mvotma.gub.uy/politica-nacional-de-aguas/pln-nacional-de-aguas
[10] MVOTMA 2016 Uruguay’s fourth national communication to the conference of the parties in the United Nations framework convention on climate change - executive summary https://www.mvotma.gub.uy/component/k2/item/download/7051_b5707195e3c3b28e48889cf0c24074
[11] MVOTMA 2016 Primera contribución determinada a nivel nacional de Uruguay al acuerdo de París http://www.mvotma.gub.uy/politica-planes-y-proyectos/contribucion-determinada-a-nivel-nacional/item/download/11506_e92380420bca0df6e4a877c166f30d
[12] FAO 2019 Water resources - country profile - Uruguay - AQUASTAT https://storage.googleapis.com/fao-aquastat.appspot.com/countries_regions/factsheets/water_resources/en/URY-WRS.pdf (Accessed 20 December 2019)
[13] FAO 2015 AQUASTAT Perfil De País – Uruguay, Organización De Las Naciones Unidas Para La Alimentación Y La Agricultura (Roma, Italia) (Accessed 20 December 2019) http://www.fao.org/3/ca0442es/CA0442ES.pdf
[14] Modernell P, Rossing W A H, Corbeels M, Dogliotti S, Picasso V and Tittone P 2016 Land use change and ecosystem service provision in Pampas and Campos grasslands of southern South America Environ. Res. Lett. 11 113002
[15] IEA 2019 Electricity Generation by Source, Uruguay 1990-2017 - Data and Statistics IEA https://www.iea.org/data-and-statistics/country=URY&fuel=Electricity%20supply&indicator=Electricity%20generation%20by%20source (Accessed 20 December 2019)
[16] Bazilian M et al 2011 Considering the energy, water and food nexus: towards an integrated modelling approach Energy Policy 39 7896–906
[17] Miralles-Wilhelm F and Muñoz R 2017 An analysis of the water-energy-food nexus in Latin America and the Caribbean Region: identifying synergies and tradeoffs through integrated assessment modeling Int. J. Eng. Sci. 7 8–24
[18] Cremades R et al 2016 Ten principles to integrate the water-energy-land nexus with climate services for co-producing local and regional integrated assessments Sci. Total Environ. 693 133662
[19] Johnson N et al 2019 Integrated solutions for the water-energy-land nexus: are global models rising to the challenge? Water 11 2223
[20] Simpson G B and Jewitt G P W 2019 The development of the water-energy-food nexus as a framework for achieving resource security: a review Front. Environ. Sci. 7 8
[21] Nauditt A 2018 Discussion of “Challenges in operationalizing the water–energy–food nexus” Hydrob. Sci. J. 63 1866–7
[22] Albrecht T R, Crootof A and Scott C A 2018 The water-energy-food nexus: A systematic review of methods for nexus assessment Environ. Res. Lett. 13 043002
[23] Endo A, Tsurita I, Burnett K and Orencio P M 2017 A review of the current state of research on the water, energy, and food nexus J. Hydrol.: Reg. Stud. 11 20–30
[24] Wallington K and Cali X 2017 The food–energy–water nexus: a framework to address sustainable development in the tropics Trop. Conserv. Sci. 10 194008291772066
[25] de Strasser L, Lipponen A, Howells M, Stec S and Bréthaut C 2016 A methodology to assess the water energy food ecosystems nexus in transboundary river basins Water 8 59
[26] Scott C A, Kurian M and Wescott J L 2015 The water-energy-food nexus: enhancing adaptive capacity to complex global challenges Governing the Nexus ed M Kurian and R Ardakanian (Berlin: Springer) pp 15–38
[27] Ringer C, Bhaduri A and Lawford R 2013 The nexus across water, energy, land and food (WELF): potential for improved resource use efficiency? Curr. Opin. Environ. Sustainability 5 617–24
[28] Khan Z, Linares P and García-González J 2017 Integrating water and energy models for policy driven applications. A review of contemporary work and recommendations for future developments Renewable Sustainable Energy Rev. 67 1123–38
[29] Ibrahim M D, Ferreira D C, Daneshvar S and Marques R C 2019 Transnational resource generativity: efficiency analysis and target setting of water, energy, land, and food nexus for OECD countries Sci. Total Environ. 675 134017
[30] Kahil T et al 2017 A continental-scale hydroeconomic model for integrating water-energy-land nexus solutions Water Resour. Res. 53 1–33
[31] Lechón Y, De La Rúa C and Cabal H 2018 Impacts of decarbonisation on the water-energy-land (WEL) nexus: a case study of the spanish electricity sector Energies 11 1203
[32] Gober P 2018 Hidden vulnerabilities in the water-energy-land-food (WELF) nexus Building Resilience for Uncertain Water Futures ed P Gober (Berlin: Springer) pp 61–89
[33] White D J, Hubacek K, Feng K, Sun L and Meng B 2018 The water-energy-food nexus in east Asia: A tele-connected value chain analysis using inter-regional input-output analysis Appl. Energy 210 550–67
[72] Montoya F and Otero Á 2019 Is irrigating soybean profitable in Uruguay? A modeling approach Agron J. 111 749
[73] MGAP 2018 Guía de buenas prácticas en el cultivo de arroz en Uruguay http://www.aca.com.uy/wp-content/uploads/2019/04/GIPA-17-de-octubre.pdf
[74] INIA 2017 Rompiendo el techo de rendimiento del cultivo de arroz http://www.inia.uy/Publicaciones/Documentos%20compartidos/ST-251-2019.pdf
[75] Yépez-García R A, Johnson T M and Alberto L 2010 Meeting the electricity supply/demand balance in Latin America & the Caribbean (Washington, DC: The World Bank)
[76] Ong S, Campbell C, Denholm P, Margolis R and Heath G 2013 Land-use Requirements for Solar Power Plants in the United States, National Renewable Energy Lab (Golden, CO: NREL)
[77] Baker J S, Havlík P, Beach R, Leclère D, Schmid E, Schmid E, Valin H, Cole J, Creason J, Ohrel S and McFarland J 2018 Evaluating the effects of climate change on US agricultural systems: sensitivity to regional impact and trade expansion scenarios Environ. Res. Lett. 13 064019
[78] Ran Y, Deutsch L, Lannerstad M and Heinke J 2013 Rapidly intensified beef production in uruguay: impacts on water-related ecosystem services Aquat. Procedia 1 77–87
[79] van Groenigen K J, van Kessel C and Hungate B A 2013 Increased greenhouse-gas intensity of rice production under future atmospheric conditions Nat. Clim. Change 3 288–91
[80] Zhu X 2020 Climate Impacts on the Water-Food Nexus PhD Thesis https://preserve.lehigh.edu/etd/5625
[81] Zhang X, Li H-Y, Deng Z D, Ringler C, Gao Y, Hejazi M I and Leuning L R 2018 Impacts of climate change, policy and Water-Energy-Food nexus on hydropower development Renewable Energy 116 827–34
[82] Rasul G and Sharma B 2016 The nexus approach to water–energy–food security: an option for adaptation to climate change Clim. Policy 16 682–702
[83] Nhamo L, Ndlela B, Nhemachena C, Mabhauhiti T, Mpandeli S and Matchaya G 2018 The water–energy–food nexus: climate risks and opportunities in Southern Africa Water 10 567
[84] Masson-Delmotte V, Zhai P, Pörtner H-O, Roberts D, Skea J, Shukla P R, Pirani A, Moufouma-Okia W, Péan C and Pidcock R 2018 Global warming of 1.5 °C IPCC Report
[85] Hoegh-Guldberg O et al 2019 The human imperative of stabilizing global climate change at 1.5°C Science 365 977–980
[86] Aufhammer M, Baylis P and Hausman C H 1886–1891 Climate change is projected to have severe impacts on the frequency and intensity of peak electricity demand across the United States PNAS 114 1886–91
[87] Byers E et al 2018 Global exposure and vulnerability to multi-sector development and climate change hotspots Environ. Res. Lett. 13 053012
[88] Kahil T, Albiac J, Fischer G, Strokal M, Tramberend S, Greve P, Tang T, Burek P, Burtscher R and Wada Y 2019 A nexus modeling framework for assessing water scarcity solutions Curr. Opin. In Environ. Sustainability 40 72–80
[89] Vogel E, Donat M G, Alexander L V, Meinshausen M, Ray D K, Karoly D, Meinshausen N and Frieler K 2019 The effects of climate extremes on global agricultural yields Environ. Res. Lett. 14 054010