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Sub-national water–food–labour nexus in Colombia

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ABSTRACT

Poorer countries often face a severe trade-off: the need to improve socio-economic conditions is hard to balance with the maintenance of key ecological processes. As a case study, we select Colombia, a Latin American country with almost 10% of its inhabitants living in extreme poverty. We elaborate a water–food–labour (WFL) nexus grounded on a sub-national Environmentally Extended Input–Output (EEIO) analysis to assess the virtual water trade (VWT) and virtual informal labour (VIL) flows across administrative departments and economic sectors related to domestic trade. The main results are the following: high cross-departmental resource interdependence both in terms of VWT and VIL, rich departments highly depend on the resources of their neighbouring trading partners, extreme poverty conditions shown by economically isolated departments, and considerable income inequality in the food production sectors. Moreover, departments that are net exporters of virtual water suffer from water stress that might be exacerbated by future high rainfall variability due to climate change. These results suggest that strategies to attain sustainable development goals (SDGs) must deal with the biophysical constraints and the economic and political feasibility of the proposed solutions. In this vein, we argue that a holistic framework, grounded on quantitative analyses, is necessary to support informed policy decisions for the simultaneous achievement of multiple (possibly contrasting) goals. Moreover, severe spatial imbalances call for local policy responses coordinated at the national level.

1. Introduction

Challenges related to food security, clean energy and poverty reduction are aggravated by climate change, population growth and the deterioration of environmental resources, especially water (Beltran-Peña et al., 2020). Indeed, to achieve such goals in the coming decades, global water demand could well double, as the energy and agricultural sectors should expand their production accordingly (Distefano, 2020). These problems are extremely urgent, especially in the *poorer countries* (hereinafter PCs), where a large fraction of the population is food-energy deficient (FSIN, 2020).[1] A number of PCs experienced a (pre-COVID-19 pandemic) period of rapid economic growth and poverty alleviation, achieved mostly by agricultural intensification at the expense of the degradation of other ecosystem processes. Moreover, such countries are usually less socially regulated (Alsamawi et al., 2017), presenting poor working conditions related to high labour-intensity and low-technology activities (United Nations, 2018). Besides, they are located in areas where climate change would put agricultural production and food security at greater risk (FAO, 2016).

It emerges that PCs face a severe trade-off: the need to rapidly improve material conditions is hard to balance with the maintenance of key ecological processes (Dearing et al., 2014). The pressure on socio-environmental boundaries is exacerbated by the increasing competition for water resources between the agriculture and energy sectors (Rosa et al., 2020) and the expansion of exports mostly toward richer countries (Wiedmann and Lenzen, 2018). This leads us to elaborate a broader framework – that goes beyond one-size-fits-all economic solutions – grounded on complex Nexus by including and connecting sustainable patterns of production and consumption, job security, and justice. We select Colombia as a case study because it is part of the PC group and must tackle several challenges at once such as poverty and famine eradication, labour security, deforestation, contamination of water bodies, etc. As explained below, the methodology applied here

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[1] Note that we avoid labelling the PCs as "developing" countries, but we follow Raworth's argument that "we are all developing countries now" (see https://rb.gy/ss6ias) because, currently, no country meets basic needs for its citizens at a globally sustainable level of resource use (O'Neill et al., 2018). See also other recent debates such as https://rb.gy/5ydkzp and https://rb.gy/ez0ebv.

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and the key messages can be generalized to any other PC. Nevertheless, as this study is based on real data from official statistics, the strength of some connections found here might read differently in other countries. Indeed, any analysis related to complex systems is necessarily contingent.

This paper is structured as follows. Section 2 reviews the literature on the Nexus approach, explains the conceptual framework and provides a brief overview of the Colombian case study. Section 3 describes the data sources and the main terms. Section 4 presents the mathematical structure of the implemented methodology and Section 5 shows the socio-environmental results at the departmental scale. Section 6 provides a broad discussion and interpretation of the results, with a focus on the policy implications, and Section 7 draws the main conclusions.

2. The nexus approach

2.1. Literature review

The "Nexus" terminology was first introduced in 1983 under the Food-Energy Nexus Programme,[2] and further extended during the Bonn Nexus Conference in 2011 (Hoff, 2011) to include water resources. The main contribution of this approach is to underline the importance of examining interactions among multiple dimensions to overcome the common practice of addressing each issue in isolation, which might generate the paradox of reducing one problem while exacerbating others (Rasul and Sharma, 2016). Recently, the Water–Food–Energy (WFE) Nexus concept has gained attention among researchers and policymakers who are more prone to embrace a holistic systems-based perspective (Van Vuuren et al., 2019). Indeed, this approach is recognized as a useful conceptual tool to support feasible policy solutions (Gao et al., 2021) because it emphasizes the interlinkages, synergies, and trade-offs amongst the economic sectors involved in the Nexus (Namany et al., 2019). Its importance is particularly evident nowadays due to increasing global interdependence, growing resource scarcities, and failures of sector-specific management strategies (Rasul, 2016).

The literature on the WFE nexus focuses on increasing resource-use efficiency (e.g., Albrecht et al., 2018), balancing different resource users' interests (e.g., Endo et al., 2017), reducing carbon emissions (e.g., Chamas et al., 2021), facing climate change (e.g., Conway et al., 2015), and integrating land use (e.g., Karabulut et al., 2018). However, these studies have traditionally focused on the physical interaction among these systems (Smajgl et al., 2016), with less exploration of the interactions between ecological, economic, and social dimensions (Zhang et al., 2018) and their social side-effects (Rasul et al., 2020). A few studies have considered the interconnection of the water-food nexus with some aspects of the social dimension, such as the labour system (e.g., Wang et al., 2020), population growth (e.g., Tamea et al., 2014), or poverty (e.g., Hameed et al., 2019). It is worth pointing out that, although some research has been carried out on the WFE nexus in Latin America (Mahlknecht and González-Bravo, 2018) considering social dimensions (e.g., Lazaro et al., 2021), this approach has not yet been used to implement policies that might help to tackle climate change (Mahlknecht et al., 2020).

Among the various methodologies applied to study the WFE nexus, the Environmentally Extend Input–Output (EEIO) approach seems the most promising because it accounts for inter-sectoral trade, including direct and indirect linkages. Although most studies rely on the country scale (Xiao et al., 2019), the role of sub-national trade has recently been investigated (e.g., Chen et al., 2019), while only Wang et al. (2020) extended the above approach to the social dimension (employment). To the best of our knowledge, most of this literature is based on China, perhaps due to the availability of data. Although we follow this strand of literature, we aim to provide further contributions by: i) recovering and reconstructing missing data, ii) including a detailed disaggregation of the food production sectors, besides agriculture, together with the food processing industry, iii) computing so-called "virtual" flows, viz. the amount of resources (water and labour) required throughout the entire supply chain at a low spatial scale, and (iv) focusing on informal labour (viz. with no legal protection), which is widespread in the PCs, as a key social variable strictly related to poverty (Galvis and Meisel-Roca, 2010). Our goal is to provide a quantitative analysis to ascertain to what extent the Colombian departments are reciprocally dependent, how spatial imbalances are related to the economic structure, and how these issues might be challenging in achieving sustainable development goals (SDGs) at both the national and sub-national scales.

2.2. The conceptual framework

A macro-view summarizing the conceptual framework of the current study is shown in Fig. 1. We elaborate a water–food–labour (WFL) Nexus[3] grounded on a sub-national EEIO matrix that allows quantification of their connection strength via trade. This methodology allows us to quantify the direct and indirect linkages due to inter-sectoral and cross-departmental exchanges and then to assess spatial distribution and imbalances. The main premise can be summarized in a nutshell: water resources are used to produce raw food products which, in turn, are either processed or sold for final consumption. Food productive sectors (FPSs) also need energy and labour. We add other possible indirect issues to these WFL connections: i) how future climate conditions might alter current water availability, and (ii) the social implications, namely poverty and income inequality, related to working status.

The main novelty concerning the available literature is the explicit inclusion of a socially vulnerable category, i.e. informal workers. This choice is justified by the fact that social well-being depends, among other things, on the workers' status of affiliation and access to social security. Indeed, this category suffers from a lack of legal protection, low earnings, and high income volatility. These issues, together with the economic structure, determine the level of poverty and (unequal) income distribution in each department. Moreover, informal workers are highly employed in sectors that are more labour intensive, i.e. FPSs. The issue of informal labour is particularly relevant within the PCs whose economies are strongly based on rural activities.

In this vein, we select Colombia as a representative case study to assess the WFL Nexus in a Latin American PC. This country is seeking political stability after the recent peace agreement to end the internal conflict between the state and illegal armies (Andrián, 2018). One of the main features of this post-conflict policy is support for agricultural activities to foster the development of those poor rural areas most affected by the armed conflict. Colombia's territory is also characterized by a considerable spatial variability, mainly in terms of social well-being and resource endowment. Indeed, previous studies pointed to sub-national disparities in terms of production (Haddad et al., 2016), poverty (Galvis and Meisel-Roca, 2010), water use (Distefano et al., 2020a), and economic growth (Pacheco Flórez and Saldarriaga Isaza, 2019). The success of national action plans and strategies must therefore address the reduction of such regional disparities (Pineda-Escobar, 2019). While the country seems to be moving in the right direction, it is still unclear how actions at the national level will translate to sub-national levels (DNP, 2015).

[2] https://rb.gy/j78pab.

[3] For the sake of clarity, we exclude "Energy" in the title because we consider it at a high aggregated level without distinguishing among the various energy power plants related to water or food, such as hydro-power, bio-fuel, etc. However, the "Energy" sector was included in the study, as indicated in Table B.2 in Appendix B.

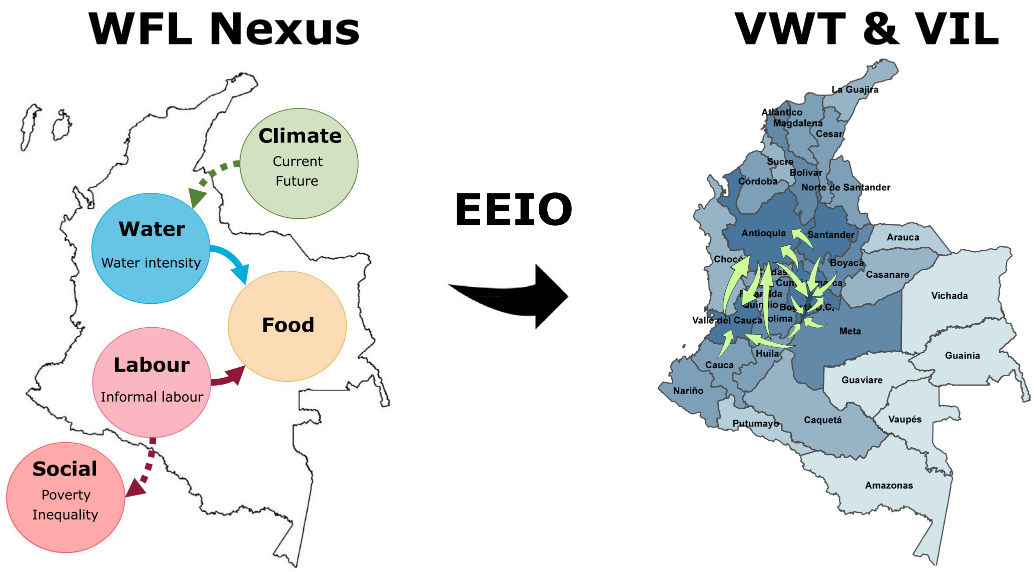

Fig. 1. Macroview. Graphical representation of the main connections in the Water–Food–Labour (WFL) nexus through the Environmentally Extended Input–Output (EEIO) table, and their indirect linkages with climate change, poverty, and income inequality. Each of these variables is spatially connected across the 33 administrative departments. The right-hand side of the figure shows the interactions between the departments in terms of virtual water trade (VWT) and virtual informal labour (VIL) flows associated to the domestic monetary trade through the supply chain.

3. Data and definitions

Haddad et al. (2019) provided data on the Colombian monetary input–output (IO) matrix for 2015, based on the National Administrative Department of Statistics (DANE) and the National Planning Department (DNP) data sources. This IO table includes 56 economic sectors and tracks both international and sub-national trade. The latter is defined at a low spatial scale because it includes 32 administrative departments plus the capital city Bogotá. In order to provide a detailed overview of the environmental (water) and social impacts along the entire supply chain, we aggregate specific sectors to define eight macro-sectors.[4] We maintain all five sectors related to raw food production (agriculture, fish, livestock, forestry and wood, and coffee) – as presented in the original data – and add the food processing sector, which contains all industries involved in the production of processed food. To these, we add the energy sector (electricity, gas and water) and sum up the remaining sectors under the label “Others”. Data on water resources, informal labour, inequality, and poverty by sector and department are collected from several data sources (see Table B.1 for detailed references).

We retrieve data on sectoral water intensity coefficients (ω_s, in m^3/COP), from DANE (2015) following the guidelines of the environmental and economic accounting system. These coefficients are used to calculate the virtual water trade (VWT), which refers to the volume of water ‘embodied’ in traded goods within and across national borders (Allan, 2003), including direct and indirect uses along the whole supply chain (Acquaye et al., 2017). We use the aridity index (AI) as a proxy for current water scarcity because it identifies the degree of sufficiency or insufficiency of precipitation to sustain the ecosystems (IDEAM, 2015). Moreover, we consider the impact of future climate conditions on water availability using data on projected precipitation changes during 2011–2040 compared to 1976–2005. These are calculated using the mean of four RCPs scenarios (RCP2.6, RCP4.5, RCP6.0, and RCP8.5)[5] (IPCC, 2019). Data on AI and precipitation changes are collected from IDEAM (2015), IDEAM et al. (2015), respectively.

We depart from the data of the Household Survey provided by DANE (“Gran Encuesta Integrada de Hogares”, GEIH 2015), to recover the number of informal workers in small firms (less than 5 employees) in metropolitan areas.[6] In general, informal labour refers to self-employment with low income and poor job quality, marked by instability, insecurity, and lack of social protection (Sánchez Torres, 2020). Virtual informal labour (VIL) refers to the number of informal workers indirectly employed to produce the goods or services traded within national borders along the whole supply chain. As a measure of inequality, we use the Gini index that considers the distance from an even distribution of income and ranges between 0 (in case of no inequality) and 100 (maximum of inequality). The Gini coefficient is calculated by comparing the cumulative proportions of the population with the cumulative proportions of the income they receive. To provide a deeper understanding of the issue of poverty, we distinguish between monetary (PI) and multidimensional poverty (MPI) indexes. The monetary approach to poverty uses income per capita to calculate the incidence, depth, and severity of poverty. The PI measures the share of people under a relative poverty line that defines the minimum income necessary to consume an acceptable level of goods and services. The MPI is an indicator that reflects the degree of deprivation of people in a set of dimensions (education, living standards, and health).

We use Matlab for the calculation of the VIL and VWT; R, IDL, and ArcGIS for creating the figures; and R and Stata to process data from the household survey. See the “Data Availability” declaration and Table B.1 in Appendix B for a detailed description of the data sources. Moreover, Appendix A shows the procedure to recover missing data related to specific indicators and departments as well as the procedure to allocate national aggregated values, i.e. water use and number of informal workers by sector, to each department.

[4] See Table B.2 in Appendix B for the correspondence with the classification used by the National Accounts.

[5] RCP2.6 describes a peak in radioactive forcing at ~3 W/m^2 before 2100; RCP4.5 and RCP6.0 stabilization without overshoot pathway to 4.5 and 6.0 W/m^2, respectively, at stabilization after 2100; and RCP8.5 rising radiative forcing pathway leading to 8.5 W/m^2 in 2100 (IPCC, 2019).

[6] See Appendix A.3 in Appendix A

4. Method

The Environmental Extended Input–Output (EEIO) approach is widely used to calculate both the environmental and social effects of economic processes by considering the entire supply chain (Sherwood et al., 2017). This methodology offers a complementary approach to what is done in most studies that focus on the international food trade in terms of final goods (Distefano et al., 2020b) and prices (Distefano et al., 2019). The EEIO has been applied to assess the carbon (e.g., Lenzen et al., 2003), water (e.g., Zhang et al., 2019), waste (e.g., Reutter et al., 2017), and labour (e.g., Gómez-Paredes et al., 2015) footprints. In this study, we use the sub-national EEIO matrix (Haddad et al., 2019) to provide a broad framework to quantify the interactions between food production sectors with all other sectors on a low spatial scale (i.e., departments).

Hereinafter, we summarize the logic and the mathematical structure behind the EEIO approach. We consider an economy composed of eight macro-sectors ($\zeta = 8$), each one producing a different good or service. The total monetary output (x_s), in Colombian pesos (COP\$), of each sector s can be decomposed into three components: domestic intermediate trade ($\mathbf{Z}$), domestic final demand (f), and exports (η). The structure of the economy can be represented in a compact mathematical form as

$$\begin{bmatrix} Z_{1,1} & \dots & Z_{1,\zeta} \\ \dots & \dots & \dots \\ Z_{\zeta,1} & \dots & Z_{\zeta,\zeta} \end{bmatrix} i + \begin{bmatrix} f_1 \\ \dots \\ f_\zeta \end{bmatrix} + \begin{bmatrix} \eta_1 \\ \dots \\ \eta_\zeta \end{bmatrix} = \begin{bmatrix} x_1 \\ \dots \\ x_\zeta \end{bmatrix}$$

where i is the vertical summation vector composed of ones and the subscript indicates the number of the sector ($= 1, \dots, \zeta$). The first square matrix ($\mathbf{Z}_{(\zeta x \zeta)}$) traces the cross-sectoral exchanges, then the total sales of the sector s to any other sector k are given by the row-sum of $\mathbf{Z}$, i.e., $Z_{s.} = \sum_k^\zeta Z_{sk}$.[7] Similarly, we recover the total sales for domestic (f_s, viz within Colombia) and foreign (η_s, viz exports) consumption. Then, the total output, for each sector s, can be written as $x_s = Z_{s.} + f_s + \eta_s$. Likewise, we calculate the total purchases from the rest of the world by summing up the imports of both industries ($\tilde{Z}_s = \sum_k^\zeta \tilde{Z}_{ks}$) and households ($\tilde{f} = \sum_k^\zeta \tilde{f}_k$).[8]

Following the same logic, we disaggregate the national components into blocks by considering the trade across departments, i.e.:

$$\begin{bmatrix} Z^{1,1} & \dots & Z^{1,\delta} \\ \dots & \dots & \dots \\ Z^{\delta,1} & \dots & Z^{\delta,\delta} \end{bmatrix} i + \begin{bmatrix} f^{1,1} & \dots & f^{1,\delta} \\ \dots & \dots & \dots \\ f^{\delta,1} & \dots & f^{\delta,\delta} \end{bmatrix} i + \begin{bmatrix} \eta^1 \\ \dots \\ \eta^\delta \end{bmatrix} = \begin{bmatrix} x^1 \\ \dots \\ x^\delta \end{bmatrix}$$

Hence, the total output of sector s in department d (x_s^d) is given by the total sales to all other sectors (k) and the final demand of any other Colombian department $\tilde{d}$ (including self-loops) plus exports. Namely:

$$x_s^d = Z_{s.}^{d.} + f_s^d + \eta_s^d \quad (1)$$

where

$$Z_{s.}^{d.} = \sum_{\tilde{d}}^{\delta} \sum_{k}^{\zeta} Z_{sk}^{d\tilde{d}}, \quad (2)$$

$$f_s^d = \sum_{\tilde{d}}^{\delta} f_s^{d\tilde{d}} \quad (3)$$

where $Z_{sk}^{d\tilde{d}}$ is the intermediate trade from sector s in department d to sector k in $\tilde{d}$, and $f_s^{d\tilde{d}}$ is the final demand from department $\tilde{d}$ to sector s in department d. Then, the total output in department d is given by the sum of the sectoral outputs, that is $x^d = \sum_s^\zeta x_s^d$.

[7] In our case, given the high level of aggregation, each sector s is composed of several firms and sub-sectors. For this reason, we find positive (and large) values on the main diagonal, to with $Z_{ss} > 0$.

[8] Note that in both cases, we first aggregate the foreign sectors following the same classification used in this study (i.e., by eight macro-sectors), and then we calculate the column sum to find the imports.

This structure allows us to recover the so-called virtual flows by knowing the average use, per unit of output, of a given resource (e.g. Taherzadeh and Caro, 2019). Then, knowing the intensity coefficients (ω_s, in m^3/\$COP) and informal labour (l_s, in person/M\$COP), for each sector s, it is possible to calculate the *domestic* virtual water trade (VWT) and virtual informal labour (VIL) flows. The net (N) sectoral flows – defined by the difference between total inflows (purchases) and outflows (sales) – are given by:

$$NVWT_s = \sum_{k \neq s} \omega_k Z_{ks} - \omega_s (Z_{s.} + f_s), \quad (4)$$

$$NVIL_s = \sum_{k \neq s} l_k Z_{ks} - l_s (Z_{s.} + f_s). \quad (5)$$

Note that to obtain the overall net VWT or VIL at the country scale, we sum up the virtual flows for each sector s and department d. For the sake of completeness, we also calculate the virtual flows associated with international trade by following the same procedure. As is common in the literature (e.g., Deng et al., 2016), and due to the lack of available data, we assume that the rest of the world has (on average) the same structure as the Colombian economy in terms of sectoral water and informal labour intensity coefficients. This might be a source of biases and uncertainty, and results on international trade should be viewed with caution. However, since our objective is sub-national spatial dependence and imbalances, we mostly focus on domestic trade. Hence, the assumption regarding international virtual flows does not alter the key messages of this study.

5. Results

At the country level, the Colombian food production sectors (FPSs) generated, in 2015, about 12% of the national output and were responsible for almost 60% of the total water withdrawal. The FPSs also employed about 20% of the total workforce, although more than 54% were classified as informal workers (see Table B.3 in Appendix B). These data show the potential trade-offs that might emerge when dealing with water management and social interventions. This picture is further complicated by the high degree of spatial variability of these factors within the national borders. To provide a comprehensive and detailed analysis, we divide this section into four parts. First, we show how the sectoral inter-linkages (i.e., the supply chain) shape the virtual (water and labour) flows at the national scale. Then, we evaluate the reciprocal dependencies of the different Colombian departments. The last two sections extend the analysis by providing insights on the relations between the spatial departmental net VWT and VIL with water availability and social justice (poverty and income inequality), respectively.

5.1. Sectoral virtual flows

The networks of virtual water and informal labour flows across the national sectors, including international trade with the rest of the world (RoW) and domestic final demand, are shown in Fig. 2. Although the two circular graphs are derived from the same monetary IO table, the application of the two intensity coefficients (ω and l) results in considerable differences in the distribution and volumes of flows in the two networks.

In terms of VWT, the main providers of (virtual) water are the agriculture (violet) and energy (light orange) sectors, each accounting for about 38.5% of total VWT flows (~312 km^3). Most of the virtual water sent by agriculture goes to final demand (40%), the food processing sector (25.8%), and the rest of the world (17%). In contrast, a large part of the water withdrawal in the energy sector is used within the sector itself (28.6%), while "others" (26.6%) and final demand (40%) are the main external users. The coffee (blue) and the forestry and wood (light green) industries also play an important role, accounting for 8.8% and 4.9% of total VWT, respectively. In particular, the former sends around

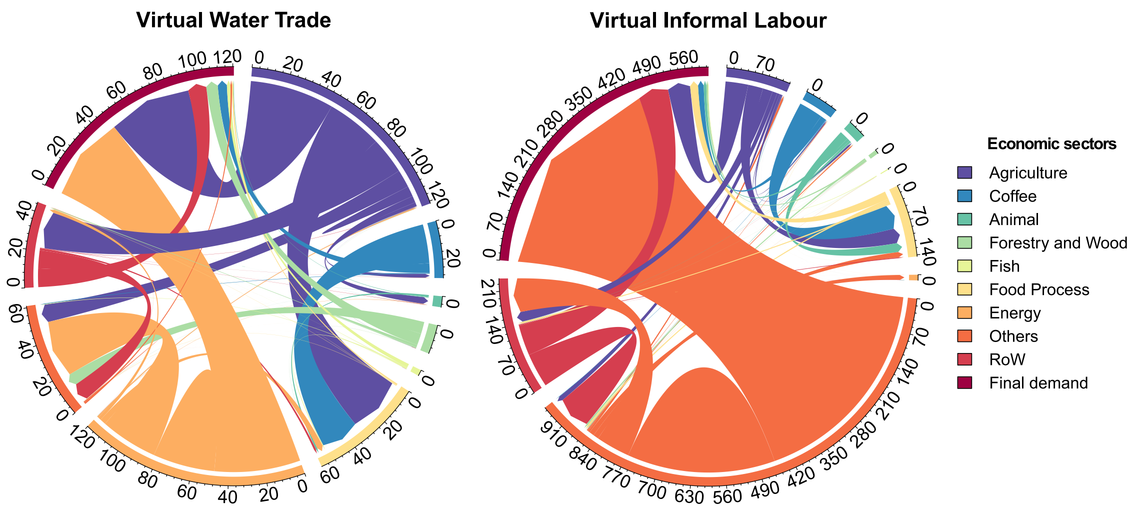

Fig. 2. Virtual water trade and virtual informal labour flows in 2015. Virtual water trade (km^3) (left panel) and virtual informal labour (10000 workers) (right panel) flows from each Colombian economic sector to the others (see Table B.2 for the full list of sectors), including international trade with the rest of the world (RoW) and domestic final demand.

21 km^3 of virtual water to the food processing sector, i.e., ~80% of the total water withdrawal from the coffee sector is indirectly transferred to the manufacture of coffee products. Instead, "others" sector (mostly manufacturing) and final demand indirectly requires around 6 km^3 of water each, associated with purchases from the forestry and wood sector.

Regarding virtual informal labour (VIL) flows, the picture changes drastically since almost 70% (i.e., ~8.67 million of informal workers) is associated with the "others" sector, of which around 3.1M workers (35.9%) are related to the trade within the industries of this macro-sector. However, the food production sectors employ about 2.55M of informal workers, half of whom are in the agriculture sector. The major VIL flows, within the FPSs, go toward the food processing sector that absorbs almost 1 million informal workers from the agriculture, coffee, and livestock sectors. The VIL associated with the energy sector is negligible representing 0.01%.

5.2. Spatial analysis

We now move to the spatial description by showing the sub-national virtual flows across the 32 departments and the capital city. Bogotá D.C. is considered separately since it represents a large share of the national output (about 24%). Fig. 3 reports the VWT and VIL flows across the Colombian departments, given by the sum of domestic intermediate trade (Z) and final demand (f). As the main purpose is to assess the spatial dependence within the national borders, we exclude international trade and exchanges within the department. Overall, the cross-departmental network covers about 52.48% (39.74%) of the total domestic VWT (VIL). For the sake of clarity, Fig. 3 only reports the top 22 (20) links – out of about a thousand connections –, i.e., flows greater than 1 km^3 (0.3M of workers), which make up approximately 34.2% (33.2%) of the total cross-departmental VWT (VIL). The colour of each department is proportional to the trade intensity index (TI) that is calculated as the sum of domestic monetary purchases plus sales from/to the other departments (TD) normalized by the maximum value (i.e., with respect to the department that trades the most). TI for a given department d is

$$TD_d = \sum_{\tilde{d}\neq d}^{\delta} (Z^{d,\tilde{d}} + Z^{\tilde{d},d} + f^{d,\tilde{d}} + f^{\tilde{d},d}), \quad (6)$$

$$TI_d = \frac{TD_d}{\max(TI)}. \quad (7)$$

This indicator provides a proxy of the trade connectivity strength of each department. In other words, a department that buys or sells large monetary volumes of goods and services is necessarily highly dependent on others. In contrast, low values of TI indicate that the department is economically "isolated".

Interesting outcomes emerge. In both cases, the highest bilateral flow is represented by the one that goes from Cundinamarca to Bogotá, which accounts for around 7.8% and 5.2% of the total cross-departmental VWT and VIL, respectively. Beyond these two departments, the most active are almost the same (Antioquia, Boyacá, Cauca, Meta, Santander, Tolima, and Valle del Cauca), but the ranking changes when we look at VWT or VIL (see Table B.5 in Appendix B) due to the differences in the economic structure (i.e., sector composition) that characterize each department. As expected, these departments show high TI and then create the biggest (VWT and VIL) links. However, although a high TI is a necessary condition to create large bilateral flows, it is not sufficient as the cases of Atlántico and Bolivar demonstrate. Although the latter two have a higher TI than those of Tolima and Boyacá (see Table B.4 in Appendix B), they are not present in the top links. This can be explained by the fact that Atlántico and Bolívar trade with a variety of departments, while most of the trade from/to Tolima and Boyacá is concentrated in a few departments (mostly Bogotá and Antioquia). Note that Antioquia and Bogotá make up jointly about 40% of the national economic output (about 24% and 15%, respectively) and are the two main importers since most of the arrows are directed towards them from the surrounding departments. This highlights the uneven distribution of water resources and the imbalance between urban and rural areas. The departments with the lowest TI are located in the southeast of the country, where economic activity is low. However, these areas are crucial to preserving the water cycle and climate, as they host part of the Amazon rainforest and a large proportion of the country's biodiversity (Poveda et al., 2006). Some key conclusions can be drawn: i) cross-departmental trade results in major spatial dependency, ii) the economic development of the most important departments (Antioquia and Bogotá) greatly depends on the resources of the neighbouring departments, and (iii) the ranking of the links changes when looking at either water resources or informal labour.

5.3. Poverty and inequality

In this subsection, we focus on income inequality and poverty-related to specific macro-sectors of the FPSs, namely agriculture (A),

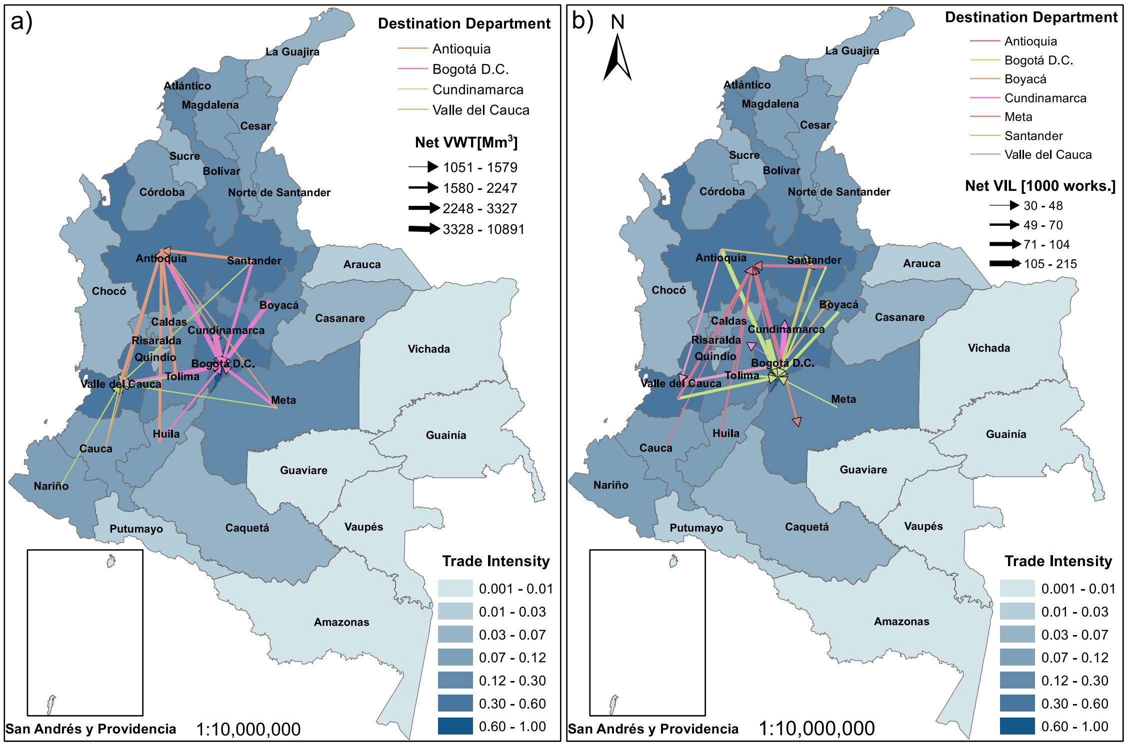

Fig. 3. Top virtual water trade and virtual informal labour flows in 2015. Top VWT [km^3] (a) and VIL [10000 workers] (b) flows across departments. The colours of the arrows indicate the destination department while their thickness is proportional the flow magnitude (i.e. weight of the link). The colour of each departments is proportional to the trade intensity index (see Eq. (7)).

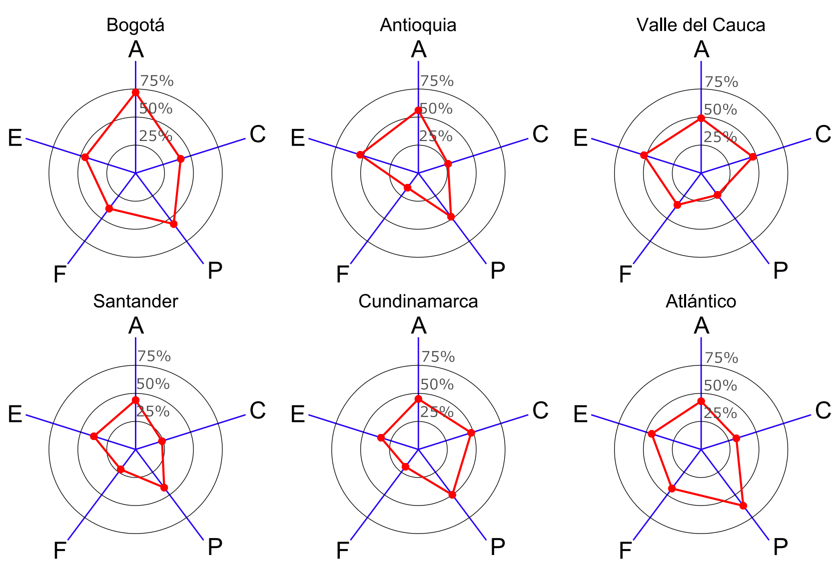

Fig. 4. Income inequality by sector in selected departments (2015). The Gini index is a measure of income inequality going from a minimum of 0 to a maximum of 100%. *A* corresponds to the agricultural sector (S1), *C* to coffee (S2), *F* to forestry and wood (S4), *P* to food processing (S10–S18), and *E* to energy (S33–S36). The selected departments represent the top six in terms of economic output and employment. Data on inequality and poverty are not available for the livestock (S3) and fishing (S5) sectors. See Table B.2 for the sectoral classification.

coffee (*C*), forestry and wood (*F*), food processing (*P*), and energy (*E*), since they are responsible for around 97% of water use and show high shares of informal workers in the workforce (with the exclusion of sector *E*).

Fig. 4 reports the level of income inequality calculated by the Gini index in the six richest departments that jointly account for about 65.7% of the national output (see Table B.4). Besides, Fig. 5 shows the distribution of MPI and net VIL across departments, and the sectoral monetary poverty indexes in a selection of poor departments. Here, heterogeneous outcomes emerge. Although Bogotá is the core of the Colombian economy, it shows a considerable level of income inequality in the selected sectors. The Gini index is about 50% in *E*, *C*, and *P*, while sector *A* reaches 75% (see Fig. 4). Thus, although this city does not present concerning levels in terms of MPI (left-hand map in Fig. 5),

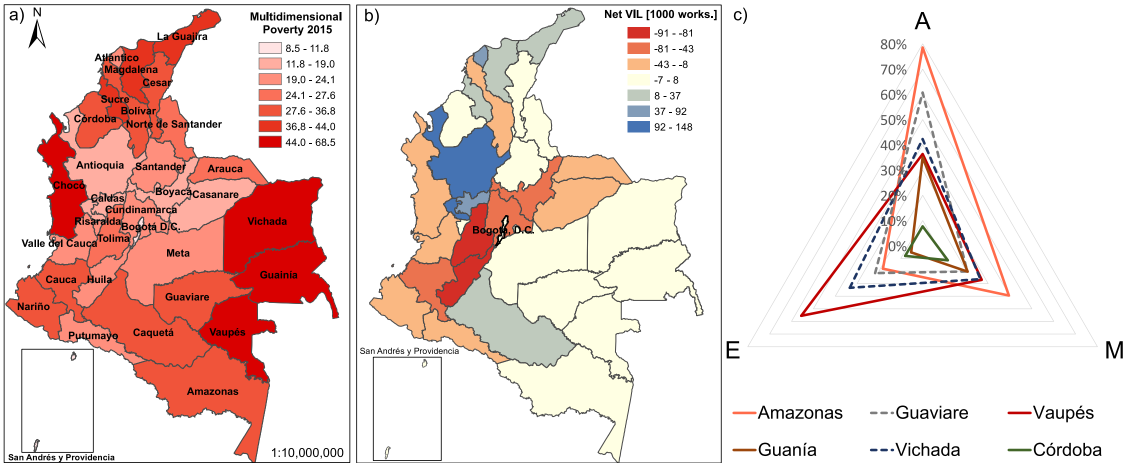

Fig. 5. Multidimensional poverty (a), net VIL (b), and monetary poverty index (2015) (c). The Multidimensional Poverty Index (MPI) is provided by departments. Monetary poverty is provided by the main sectors in the food system in these departments (poorest) and a non-FPS sector. Grey lines in a) and b) indicate the departments, and A corresponds to the agriculture sector, E to energy, and M to the manufacturing industry in c).

due to its high level of urbanization and the satisfactory provision of public utilities, it presents an uneven distribution of income that might exacerbate social tensions. Antioquia, the second richest department, reports lower levels of inequality in sectors C and F (below 25%), but around 50% in A, P and E (see Fig. 4). It is worth mentioning that even if Bogotá is located within the department of Cundinamarca, its Gini looks very different, especially in sectors A, E, and F. All in all, the highest levels of inequality are reported in sectors A and P, which are the largest since they jointly account for about 78% of total FPSs output. As regards net VIL (Fig. 5b), it appears that Tolima and Huila have the lowest values, which means that these departments employ a large number of informal workers to produce goods and services that are consumed elsewhere. By contrast, Antioquia is the most dependent on informal labour employed from other departments showing the highest net VIL (~1.5×10^5 workers). Surprisingly, although Bogotá is the core of cross-departmental trade (TI=1), it shows a net VIL close to zero, which indicates that imports and exports compensate in terms of VIL. This is probably because its economy is highly dependent on manufacturing, which is included in the sector "others".

Fig. 5a shows that most of the departments located in the south-eastern and northern zones report problematic social conditions. In these areas, half (or more) of the population suffers from deprivations of basic needs. We select six departments with the highest MPI scores and evaluate the PI at the sectoral level (Fig. 5c). Despite a high MPI (~30%), Córdoba shows a low level of PI (~15%) in each sector. It thus emerges that the monetary dimension (i.e., sectoral salaries) is not the only factor that affects the MPI. Nonetheless, in the five other poorest departments, there appears to be a clear link between poverty and the agricultural sector. As expected, these zones (mostly rural) show an extremely low level of economic activity that translate into economic "isolation" (i.e, low TI). This means that the current economic structure does not allow these departments to escape poverty simply through economic growth. They cannot benefit from an expansion of trade without effective policy interventions aiming to achieve better infrastructure and provide basic services to the population. Indeed, economic development alone does not automatically translate into greater welfare, as evidenced by the high MPI level in Cundinamarca. Moreover, informal labour and poverty are strictly linked in Colombia (Sánchez Torres and Chaparro Hernández, 2020).[9] Consequently, labour inclusion policies to reduce informality (i.e., jobs without legal contracts) could help eradicate poverty and reduce inequality (Abramo et al., 2019) and create a safety net for low-income people who are more vulnerable to climatic (Byers et al., 2018) and pandemic (Rasul et al., 2020) shocks.

5.4. *Water availability*

Since 43% of the territory has high water surpluses and just 1% a high deficit (IDEAM, 2015), Colombia is considered a water-abundant country. However, approximately 80% of the population and economic activities are located in basins with a water deficit (IDEAM, 2019). In order to identify current and future conditions of water availability throughout Colombia and how they are related to the water trade, we analyse the aridity index (AI) and the expected changes in precipitation (Figs. 6a,b). The AI map of 2014 in Fig. 6a gives a general framework of year-round water availability close to that of the Colombian monetary input–output matrix used in this study. Red (blue) areas represent high deficits (surpluses) of water. This figure provides evidence that the zones with the highest water surpluses are in the south and west of the country, where economic activities are less intensive. Instead, the northern and central zones, where the most populous cities in the country are located, show vast areas of medium to high water stress. The department with the greatest water deficit is La Guajira, which has an AI that exceeds 0.6, followed by the capital of Colombia and its surroundings.

As the AI is calculated from the surface water balance, whose main input is precipitation (Milly, 1994), when the other balance components are constant, the changes in precipitation are inversely related to the AI values. Thus, we use the earliest scenario of projected precipitation calculated by IDEAM et al. (2015) (Fig. 6b) as a proxy of the future conditions of water availability. The largest decreases in precipitation are expected in the northern and southern zones, which would intensify the already existing deficits in departments such as La Guajira, Magdalena, César, Atlántico, and Sucre. In the areas on the Andean mountain ranges, precipitation is expected to increase, which is not necessarily positive since it can mean more intensive rainfalls that can cause soil erosion, floods that affect crops, landslides, and so forth.

Under the future precipitation scenarios, all water supplying departments (i.e., $NVIL_d < 0$, reddish in Fig. 6c) will suffer reductions in water availability in at least part of their area. Norte de Santander and Cundinamarca have both areas with increases and decreases. Therefore food production shortages might happen on a smaller spatial scale than the departmental one. Although the supplying departments in the

[9] Data from the national household survey show a strong correlation between formality, measured as the number of people contributing to the pension system, and diverse measures of poverty such as monetary poverty ($p - value$ <0.01), MPI ($p - value$ <0.001), and unsatisfied basic needs ($p - value$ <0.01).

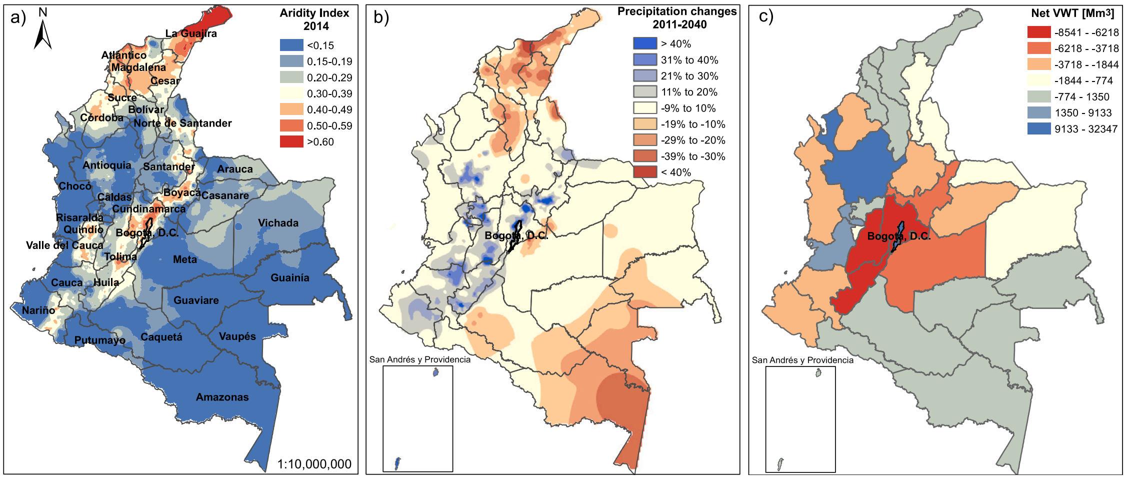

Fig. 6. Aridity index (a), expected changes in precipitation (b), and net VWT (c). Grey lines represent the departments. According to IDEAM (2015), values of AI in a) should be interpreted as high water surpluses (<0.15), surpluses (0.15–0.19), surpluses to moderate (0.20–0.29), moderate (0.30–0.39), moderate to deficient (0.40–0.49), deficient (0.50–0.59), and highly deficient (>0.60). Sources: IDEAM (2015), IDEAM et al. (2015). There is no available information on AI in San Andrés and Providencia.

South and East of the country have significant water surpluses, critical reductions in rainfall are expected. As part of the Amazon rainforest is located in this area, reduced rainfall can have consequences related not only to food production but also to natural diversity, climate change and climate variability in other zones (Poveda et al., 2020). Since the northern and central departments (e.g., Tolima, Cundinamarca, Boyacá, Valle del Cauca, Santander among others) of the country provide most of the national raw food (see Table B.4 in Appendix B), it is pertinent to say that the high variability in water availability might alter agricultural productivity, making both food security and employment highly vulnerable to climate change. Note that the precipitation change map does not consider seasonality, and for agricultural applications, the differences among seasons can be decisive.

This picture is further complicated by the historical lack of improvements in water efficiency in the Colombian agriculture sectors (Distefano et al., 2020a). It could be said that possible ways to compensate for future food shortages might be to implement strategies that increase the supply from other regions, at the risk of increasing regional imbalances, and/or to rely on imports, which seems unlikely because, as seen, the international trade of the Colombian FPSs is relatively small. This highlights the need for an in-depth assessment of the possible solutions and the role of the water footprint, mostly in PCs. From our point of view, VWT is more valuable at the country scale because it can support local governments' decisions to reduce sub-national imbalances, while international agreements on water management are still absent and more difficult to implement. Moreover, Colombia, like many other PCs, is currently unable to ensure safe water utilities for the entire population, especially in rural areas. This requires direct political action that cannot rely on imports of "virtual" water.

6. Discussion

Some limitations on the methodology applied in this study deserve attention. First, we provided a static picture of the complex relations among these variables, while the temporal evolution is a crucial feature to be considered for producing and analysing scenarios to support policy decisions. For future analyses, we expect to have data available for several years (beyond 2015) to develop a system dynamics model grounded on ecological macroeconomics (e.g., D'Alessandro et al., 2020). Second, the inclusion of small-scale spatial and sectoral disaggregation, together with various indicators, creates problems in terms of data inconsistency and lack of information that require some simplifying assumptions to recover missing data (see Appendix A.3). Third, virtual flows related to the rest of the world might be biased because we assumed the same water and labour coefficients as those present in Colombia. Although this is the most common assumption in the literature on footprint analyses, in future research, we aim to collect specific data on the origins of imported items to build confidence intervals for virtual flows related to international trade. Fourth, it should be noted that, because this study gives a static picture, it does not provide a direct assessment of Colombia's path towards the SDGs (in particular SDG 1, 6, 8, 13), but rather a baseline since we use data from 2015. The quantification of complex connections at a detailed spatial scale presented here exposes the vulnerabilities of the departments in matters of trade connectivity, labour informality and water availability. This information must be considered an important building block towards defining coherent policies focused on the implementation of better water management practices and the reduction of labour informality. Despite these limitations, some key conclusions can be drawn.

6.1. The WFL nexus across the departments

Table B.6 summarizes the main results by department presenting the most relevant characteristics observed in terms of water (AI, precipitation changes (ΔPr), and VWT), raw food production (RF) and food processing sectors (P), labour (VIL), poverty (MPI and PI) and trade intensity (TI). Some noteworthy results are discussed. Almost half of the departments (15) have high poverty indexes. Among them, there are 10 departments with probable current and/or future problems with water availability. Besides, eight of them are isolated from the rest of the country (low TI). Departments with high connectivity (Antioquia, Bogotá, Cundinamarca, Meta, Santander, and Valle del Cauca) have the lowest poverty indexes and are unlikely to have issues related to water availability. Among these, Meta, Cundinamarca and Santander are net exporter of virtual water, and Valle del Cauca and Cundinamarca are net exporters of informal workers. Furthermore, only Cundinamarca has a representative percentage of raw food production (11.9%). About half of the departments are water exporters, but the cases of Guaviare, Cesar and Huila deserve attention as they represent higher percentages of raw food production and are likely to have water availability issues. Rural departments with high percentages of local raw food production (e.g., Vichada, Guaviare and Amazonas) have very low percentages of production (< 0.1% of the national output) and food processing, high probabilities of water shortages in the future, and are isolated from the rest of the country. Also, they suffer from extreme poverty, especially Vichada. On the other hand, the departments with the highest percentages of processed food production (e.g., Caldas, Risaralda, Cundinamarca, Valle del Cauca and Córdoba) have high/medium connectivity, little poverty and most do not have water availability issues. Among the seven departments with the highest food processing percentages, Cauca, Cundinamarca and Córdoba are net exporters of water, and Caldas, Risaralada, and Atlántico are importers of informal labour.

Information obtained in this work and summarized in Table B.6 may be useful in the implementation of policies considering the heterogeneity across departments. For example, measures to eliminate poverty in Córdoba must take into account its high local food production (RF=10.0% and P=10.9%), despite the water deficit in part of its territory. Furthermore, this deficit may become more serious due to future reduced rainfall in the zone, also affecting other departments since it is a net exporter of virtual water. Another important case is that of La Guajira, the department with the highest aridity index (>0.6), which may well increase in the years to come. La Guajira needs urgent poverty-reduction policies (both monetary and multidimensional) and improved connectivity with the rest of the country. However, if one of the strategies is to increase food production (RF=3.9% and P=0.8%), it must be preceded by solving the water shortfall.

This overview demonstrates that simply looking at the national scale might lead to misleading interpretations about the socio-economic and environmental status of a country. Instead, a focus on administrative departments is important because they also represent the legal entities where local political decisions are taken, as discussed below.

6.2. Local policies and SDGs

The results of the present study highlight the spatial interdependence among some key variables related to the SDGs. The reduction of poverty (SDG1), inequality (SDG8) and hunger (SDG2) are closely related to decent work (SDG8) and sanitation (SDG6). However, the latter can only be accomplished if there is sufficient availability of water which depends, among other things, on climate change (SDG13). This leads to the need for public policies that guarantee the protection and sustainable use of water resources, mainly in places with high water deficits such as the North-East region. These policies can be the first step to avoid the exacerbation of poverty, which is high in this region. At the same time, the differences throughout the departments suggest that the actions to be taken cannot be generalized to the entire country, as both economic and social conditions are very distinct, and the natural environmental status does not allow the same economic activities.

This set of concerns is almost absent in Colombia's current SDG policy agenda. Besides specific national targets for each of the SDGs, Colombia has set up different targets for some of the SDGs in each department. However, assessments of the advances to reach these targets, made so far, have been done only at the national level. In its most recent report, the Colombian National Planning Department (DNP, 2020) points out that the general progress in reaching the national goals for 2019 was 74%. Climate change action is one of the goals that has seen the slowest progress. Nonetheless, the DNP also points out that the number of departments that have designed plans for climate change adaptation has been increasing, such that by 2019 there were 23. The fight against poverty has also seen some progress. However, this progress in overcoming poverty has been based on monetary transfers to different population groups, without any regard for mechanisms that account for poverty and labour informality associated with people's participation in the different economic sectors, particularly in the FPSs (DNP, 2020).

In addition to this balance, the DNP (2020) points out some progress in establishing policies to achieve regional goals. For instance, in 2019, the national government launched a national plan for the supply of drinkable water and sanitation in the rural sector and La Guajira department. In general, the development plans of most of the central-western departments (e.g., Antioquia, Bogotá, Tolima, etc.) appear closer to the 2030 agenda. It contrasts with the development plans of the south-eastern departments (e.g., Vichada, Arauca, Vaupés, Amazonas, etc.) that are economically isolated. Despite these advances, the policy agenda still looks at each goal in isolation, rather than recognizing the inter-linkages between several of the SDGs. For example, some of the municipalities in which the rural reform of the 2016 peace agreement (SDG16) is planned to be implemented are in the Caribe region (Atlántico, Bolívar, Magdalena, La Guajira, Cesar, Córdoba and Sucre). This reform, which aims to support the growth of agriculture, must first consider the viability of an increase in labour demand (SDG8), the reduction of both poverty (SDG1) and income inequality (Jiménez et al., 2021) (SDG10), and that it is a region with a high current water deficit (SDG6) and expected to increase in the coming years due to climate change (SDG13). All in all, a detailed evaluation that focuses not only on one aspect (e.g., food shortage) but on a comprehensive set of variables (economic sectors, social welfare, etc.) is necessary to design policies that aim to balance the impacts across sectors and departments and thus, ensure the attainment of the SDGs to which the country has committed.

7. Concluding remarks

In 2018, former president J.M. Santos approved the "Long-Term Green Growth Policy" plan to achieve the Colombian Sustainable Development Goals (SDGs) based on a new economic growth model grounded on competitiveness, efficiency, social inclusion, and preservation of natural resources.[10] Therefore, assessment of the success of these sustainable strategies must consider both biophysical and socio-economic constraints. The challenges involved in achieving the SDGs call for an integrated approach that enables the identification of policy priorities and instruments to improve the economic and social well-being throughout the regions without putting natural resources at risk (Rasul, 2020).

In this vein, this study elaborated a water–food–labour nexus framework grounded on data from sub-national cross-departmental trade to ascertain the impact of the food production sectors on water use, food security and social well-being. First, we contributed to the literature by calculating the virtual water trade and virtual informal labour flows at a low spatial scale (i.e. administrative department). Second, we showed that there are inequalities within the country related to the food production sectors in terms of income inequality and fragile workers (i.e. informal labour). Notably, we unravelled that the economic development of the richest departments (Antioquia and Bogotá) is highly dependent on the resources of their surrounding trading partners. Third, by quantifying the "embedded" social and water flows associated with monetary trade, we pointed out that potential threats to food security might emerge, even in a relatively water-abundant country, because of spatial imbalances Indeed, most of the rural departments that provide food (and "virtual water") to the other departments are exposed to water stress conditions. Expected changes in precipitation due to climate change might exacerbate this situation.

Finally, we argued that a holistic framework, informed by quantitative analysis, is necessary to effectively tackle poverty, labour security, and water scarcity issues that are particularly urgent in all of the PCs. This is because the social, economic, and natural resource dimensions are strongly interrelated even at a low spatial scale. Local disparities, beyond the global scale, call for local policy responses, coordinated at the national level, to follow a balanced path to attain (possibly conflicting) SDGs.

[10] See https://rb.gy/eu2cvt and https://www.ods.gov.co/en for more details.

Table B.1
Variables and data-sources.

Variable	Data source	Citation/link	Notes
Interregional I-O (monetary, in COP$)	DANE; DNP	Haddad et al. (2019)	
Aridity Index	IDEAM	IDEAM et al. (2015)	
Water intensity coefficients	DANE	DANE (2015)	https://rb.gy/cs59s7
Multidimensional poverty index	DANE	https://rb.gy/ylbur5	https://rb.gy/qvxvcr
Informal workers	DANE	https://rb.gy/rlphpk	https://rb.gy/hva5ti
Gini index *Monetary poverty index*	DANE	https://rebrand.ly/hjeh62k https://rb.gy/zfuarg	https://rb.gy/a8ty9l; https://rb.gy/rdn8xl
Expected change in precipitation	IDEAM	IDEAM (2015)	

DANE is the National Administrative Department of Statistics, DNP is the National Planning Department, IDEAM is the Colombian Institute of Hydrology, Meteorology and Environmental Studies.

Table B.2
Correspondence of aggregated sectors with national accounts.

Sectors	National accounts correspondence	*id*
Agriculture	Agriculture and related services activities	*S1*
Coffee	Permanent coffee crops	*S2*
Livestock	Livestock, hunting and related services activities	*S3*
Forestry and Wood	Forestry and timber extraction	*S4*
Fishing	Fishing and aquaculture	*S5*
Food processing	Processing and preservation of meat and meat products from bovine, buffaloes, pigs and other meats n.c.p.; processing and preservation of meat and meat products from poultry, and processing and preservation of fish, crustaceans and molluscs	*S10*
	Manufacture of oils and fats of vegetable and animal origin	*S11*
	Manufacture of dairy products	*S12*
	Manufacture of mill products, starches and products derived from starch; Manufacture of bakery; manufacture of macaroni, noodles, couscous, and similar farinaceous products and preparation of prepared animal feed	*S13*
	Manufacture of coffee products	*S14*
	Manufacture of sugar and manufacture of panela	*S15*
	Manufacture of cacao, chocolate and confectionery products	*S16*
	Processing and preservation of fruits, legumes, vegetables and tubers; manufacture of other food products (prepared and preserved meals by canning or freezing, manufacture of soups and broths in a solid state, powder or instant, among others)	*S17*
	Manufacture of beverages (including ice) and manufacture of tobacco products	*S18*
Energy	Electric power generation; transmission of electrical energy and distribution and commercialization of electrical energy	*S33*
	Gas production; distribution of gaseous fuels through pipelines; steam and air conditioning supply	*S34*
	Catchment, treatment and distribution of water	*S35*
	Wastewater evacuation and treatment; Recovery of materials (recycling)	*S36*
Others	Manufacturing; Mining; Construction; Transports; Services; Finance; Public	*S6-S9* *S19–S32* *S37–S54*

CRediT authorship contribution statement

T. Distefano: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **A. Saldarriaga Isaza:** Methodology, Data curation, Visualization, Writing – original draft, Writing – review & editing. **E. Muñoz:** Data curation, Visualization, Writing – original draft, Writing – review & editing. **T. Builes:** Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data and the Matlab codes are freely available in Zenodo under the identifier 10.5281/zen520odo.5163000.

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Appendix A. Allocation of national coefficients

As explained in Section 4, the EEIO approach requires the average use of water (or informal workers) per unit of sectoral output. Since this information is available only at the national scale, we defined a procedure to recover the departmental coefficients.

A.1. Water coefficients

The vector of total water withdrawal for the 8 macro-sectors (w) at the national scale was provided by DANE (2015). The procedure to construct the vector of water use for any departmental-sector pair (ds) is as follow:

1. calculate the economic efficiency of sector s in department d as $\eta_s^d = \frac{VA_s^d}{x_s^d}$, where VA_s^d is the value added and x_s^d is the output;
2. calculate the sectoral weighted average water efficiency as $\overline{\eta_s} = \sum_d^{\delta} \eta_s^d \cdot x_s^d / \sum_d x_s^d$, where δ=33 is the number of departments;
3. calculate the "adjusted output" as $\tilde{x}_s^d = \overline{\eta_s} \cdot x_s^d / \eta_s^d$;
4. calculate the quota of "adjusted output" as $q_s^d = \tilde{x}_s^d / \sum_d^{\delta} \tilde{x}_s^d$;
5. calculate the sectoral water use (w_s) to be allocated in department d, as $w_s^d = w_s \cdot q_s^d$.

Table B.3
Main economic statistics and water use at the national level (2015).

Colombia (2015)	*Agriculture*	*Coffee*	*Livestock*	*Wood*	*Fishing*	*Food Processing*	*FPSs*	*Energy*	Others	*TOT*
Output [M $COP]	38431	8239	26182	2382	2459	99973	**177666**	59088	*1204188*	1440942
Value Added [M $COP]	27339	5299	12265	1796	1425	27219	**75343**	24599	*630601*	730543
Water [M m^3]	120136	27423	1472	15146	3118	1366	**168662**	120079	*1569*	290310
Labour [×1000 workers]	2289	782	567	148	31	741	**4558**	120	*18069*	22747
Wages [M $COP]	7588	2591	1880	490	104	8683	**21336**	3932	*249039*	274307
Output [%]	2.67	0.57	1.82	0.17	0.17	6.94	**12.33**	4.10	*83.57*	100.00
Value Added [%]	3.74	0.73	1.68	0.25	0.20	3.73	**10.31**	3.37	*86.32*	100.00
Water [%]	41.38	9.45	0.51	5.22	1.07	0.47	**58.10**	41.36	*0.54*	100.00
Labour [%]	10.06	3.44	2.49	0.65	0.14	3.26	**20.04**	0.53	*79.43*	100.00
Wages [%]	2.77	0.94	0.69	0.18	0.04	3.17	**7.78**	1.43	*90.79*	100.00
Informal [% Lab.]	53.29	82	53.29	53.29	53.29	38.9	**54.48**	1.30	*48.01*	
Informal [×1000 workers]	1220	641	302	79	17	288	**2547**	2	*8675*	11223

See Table B.2 for the description of the eight aggregated sectors. FPSs stands for food production sectors composed by sectors from S1 to S5 and from S10 to S18 (see Table B.2). Authors' elaboration.

Table B.4
Main economic statistics of the 33 Colombian departments.

Department	*TI*	*Output*	Raw food	Food proc.	Energy	Other
Antioquia	0.588	14.90%	12.92%	18.21%	20.01%	14.50%
Atlántico	0.194	4.82%	0.84%	7.42%	9.66%	4.62%
Bogotá D.C.	1.000	23.90%	0.03%	16.73%	15.11%	26.46%
Bolívar	0.192	3.91%	2.57%	0.66%	3.26%	4.30%
Boyacá	0.157	2.85%	4.38%	1.78%	5.35%	2.72%
Caldas	0.086	1.67%	2.58%	3.81%	2.72%	1.38%
Caquetá	0.032	0.43%	1.09%	0.24%	0.09%	0.42%
Cauca	0.103	1.84%	3.45%	2.68%	1.65%	1.68%
Cesar	0.070	1.71%	2.75%	1.48%	1.30%	1.68%
Córdoba	0.092	1.78%	3.31%	2.80%	2.27%	1.57%
Cundinamarca	0.384	6.23%	13.78%	12.41%	11.51%	4.97%
Chocó	0.032	0.41%	1.11%	0.06%	0.14%	0.41%
Huila	0.095	1.77%	4.30%	1.11%	2.22%	1.64%
La Guajira	0.052	1.00%	0.74%	0.11%	1.74%	1.05%
Magdalena	0.073	1.33%	3.40%	1.22%	0.71%	1.23%
Meta	0.180	3.91%	4.71%	1.65%	1.20%	4.18%
Nariño	0.081	1.46%	3.58%	0.47%	0.62%	1.45%
N. Santander	0.081	1.60%	2.36%	0.60%	1.14%	1.66%
Quindío	0.047	0.79%	1.99%	0.71%	0.56%	0.73%
Risaralda	0.087	1.68%	1.78%	3.49%	1.09%	1.55%
Santander	0.302	6.44%	8.05%	2.04%	4.39%	6.81%
Sucre	0.048	0.83%	1.31%	0.41%	0.53%	0.85%
Tolima	0.120	2.39%	5.94%	2.51%	1.84%	2.18%
Valle Cauca	0.391	9.68%	8.95%	16.44%	9.73%	9.16%
Arauca	0.027	0.07%	0.20%	0.06%	0.01%	0.07%
Casanare	0.064	1.71%	2.63%	0.79%	0.88%	1.77%
Putumayo	0.023	0.43%	0.39%	0.05%	0.07%	0.49%
San Andrés	0.010	0.16%	0.03%	0.03%	0.10%	0.18%
Amazonas	0.004	0.07%	0.21%	0.01%	0.06%	0.07%
Guainía	0.002	0.04%	0.05%	0.01%	0.00%	0.04%
Guaviare	0.005	0.08%	0.24%	0.01%	0.02%	0.08%
Vaupés	0.002	0.03%	0.03%	0.00%	0.00%	0.03%
Vichada	0.003	0.06%	0.32%	0.01%	0.01%	0.05%
National total		*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*

TI stands for trade intensity as defined in Eq. (7), Raw food includes the sectors from S1 to S5, while Food processing, Energy and "others" are defined in Table B.2.

Table B.5
Ranking of top bilateral cross-departmental links.

Rank	VWT	exporter	importer	share (%)	VIL	exporter	importer	share (%)
1	**10890.7**	*Cundin.*	*Bogotá*	7.77	**214.5**	*Cundin.*	*Bogotá*	5.22
2	**3326.555**	*Boyacá*	*Bogotá*	2.37	**160.0**	*Bogotá*	*Cundin.*	3.89
3	**2742.935**	*Antioquia*	*Bogotá*	1.96	**103.9**	*Bogotá*	*Antioquia*	2.53
4	**2247.451**	*Valle Cauca*	*Bogotá*	1.60	**96.2**	*Antioquia*	*Bogotá*	2.34
5	**2137.995**	*Tolima*	*Bogotá*	1.52	**69.8**	*Valle Cauca*	*Bogotá*	1.70
6	**2109.952**	*Santander*	*Antioquia*	1.50	**65.6**	*Valle Cauca*	*Antioquia*	1.60
7	**2090.707**	*Valle Cauca*	*Antioquia*	1.49	**61.4**	*Bogotá*	*Santander*	1.50
8	**1970.888**	*Santander*	*Bogotá*	1.41	**52.8**	*Santander*	*Antioquia*	1.28
9	**1925.017**	*Meta*	*Bogotá*	1.37	**51.5**	*Boyacá*	*Bogotá*	1.25
10	**1886.583**	*Tolima*	*Antioquia*	1.35	**51.4**	*Bogotá*	*Valle Cauca*	1.25
11	**1823.747**	*Huila*	*Antioquia*	1.30	**47.6**	*Santander*	*Bogotá*	1.16
12	**1578.639**	*Antioquia*	*Valle Cauca*	1.13	**45.8**	*Bogotá*	*Boyacá*	1.12
13	**1462.58**	*Huila*	*Bogotá*	1.04	**45.3**	*Antioquia*	*Valle Cauca*	1.10
14	**1362.529**	*Tolima*	*Valle Cauca*	0.97	**41.8**	*Antioquia*	*Santander*	1.02
15	**1275.92**	*Bogotá*	*Cundin.*	0.91	**40.6**	*Tolima*	*Bogotá*	0.99
16	**1219.374**	*Cundin.*	*Antioquia*	0.87	**40.6**	*Bogotá*	*Meta*	0.99
17	**1215.845**	*Santander*	*Valle Cauca*	0.87	**39.8**	*Huila*	*Antioquia*	0.97
18	**1205.668**	*Cauca*	*Valle Cauca*	0.86	**38.2**	*Tolima*	*Antioquia*	0.93
19	**1198.375**	*Cauca*	*Antioquia*	0.85	**34.0**	*Bogotá*	*Tolima*	0.83
20	**1126.692**	*Meta*	*Antioquia*	0.80	**31.1**	*Meta*	*Bogotá*	0.76
21	**1070.728**	*Nariño*	*Valle Cauca*	0.76	**31.1**	*Cundin.*	*Antioquia*	0.76
22	**1050.881**	*Meta*	*Valle Cauca*	0.75	**29.7**	*Cauca*	*Antioquia*	0.72

Share indicates the percentage of the flow lying on the link to total domestic flow (excluding within department trade). VWT (VIL) is expressed in km^3 (1000 workers).

Table B.6
Summary of the main results by department (2015).

Department	Water	FPSs	Labour	Poverty	Connection
Antioquia	AI: low to moderate ΔPr: increases /decreases VWT: net importer	RF: 4.6% P: 8.5%	VIL: net importer	MPI: low PI: low	TI: high
Atlántico	AI: high ΔPr: decreases VWT: net importer	RF: 0.1%P: 10.7%	VIL: net importer	MPI: low PI: medium(sect asym.)	TI: medium
Bogotá D.C.	AI: moderate to high ΔPr: increases VWT: net importer	RF: 0.0%P: 4.9%	VIL: close to 0	MPI: low PI: low	TI: high
Bolívar	AI: low to high ΔPr: decreases VWT: close to 0	RF: 3.5%P: 1.2%	VIL: net exporter	MPI: medium PI: medium(sect asym.)	TI: medium
Boyacá	AI: low to high ΔPr: increases VWT: net exporter	RF: 8.3%P: 4.3%	VIL: net exporter	MPI: low PI: medium(sect asym.)	TI: medium
Caldas	AI: low ΔPr: increases VWT: net importer	RF: 8.3%P: 15.9%	VIL: net importer	MPI: low PI: medium	TI: medium
Caquetá	AI: low to moderate ΔPr: decreases VWT: close to 0	RF: 13.6%P: 3.9%	VIL: net importer	MPI: medium PI: high(sect asym.)	TI: isolated
Cauca	AI: low to moderate ΔPr: increases VWT: net exporter	RF: 10.1%P: 10.1%	VIL: net exporter	MPI: medium PI: high	TI: medium
Cesar	AI: moderate to high ΔPr: decreases VWT: net exporter	RF: 8.6%P: 6.0%	VIL: close to 0	MPI: medium PI: high	TI: medium
Córdoba	AI: low to high ΔPr: no changes VWT: net exporter	RF: 10.0%P: 10.9%	VIL: close to 0	MPI: medium PI: high	TI: medium
Cundin.	AI: low to high ΔPr: increases VWT: net exporter	RF: 11.9%P: 13.9%	VIL: net exporter	MPI: low PI: low	TI: high
Chocó	AI: low to moderate ΔPr: no changes VWT: net exporter	RF: 14.3%P: 1.0%	VIL: net exporter	MPI: high PI: high	TI: isolated
Huila	AI: moderate to high ΔPr: increases VWT: net exporter	RF: 13.0%P: 4.4%	VIL: net exporter	MPI: low PI: high	TI: medium

(*continued on next page*)

Table B.6 (*continued*).

Department	Water	FPSs	Labour	Poverty	Connection
La Guajira	AI: very high ΔPr: decreases VWT: close to 0	RF: 3.9%P: 0.8%	VIL: net importer	MPI: high PI: high(sect asym.)	TI: isolated
Magdalena	AI: low to high ΔPr: decreases VWT: net importer	RF: 13.8%P: 6.4%	VIL: net importer	MPI: medium PI: high	TI: medium
Meta	AI: low to moderate ΔPr: no changes VWT: net exporter	RF: 6.5%P: 2.9%	VIL: close to 0	MPI: low PI: low	TI: high
Nariño	AI: low to high ΔPr: increases VWT: net exporter	RF: 13.1%P: 2.3%	VIL: net exporter	MPI: medium PI: high	TI: medium
N. Santander	AI: low to high ΔPr: increases /decreases VWT: net exporter	RF: 7.9%P: 2.6%	VIL: close to 0	MPI: medium PI: high	TI: medium
Quindío	AI: low to moderate ΔPr: increases VWT: net exporter	RF: 13.4%P: 6.2%	VIL: close to 0	MPI: low PI: medium	TI: isolated
Risaralda	AI: low to moderate ΔPr: increases VWT: net importer	RF: 5.7%P: 14.5%	VIL: net importer	MPI: low PI: low	TI: medium
Santander	AI: low to high ΔPr: increases /decreases VWT: net exporter	RF: 6.7%P: 2.2%	VIL: close to 0	MPI: low PI: low	TI: high
Sucre	AI: moderate to high ΔPr: decreases VWT: close to 0	RF: 8.4%P: 3.4%	VIL: close to 0	MPI: high PI: high	TI: isolated
Tolima	AI: low to high ΔPr: increases VWT: net exporter	RF: 13.3%P: 7.3%	VIL: net exporter	MPI: medium PI: medium	TI: medium
Valle Cauca	AI: low to high ΔPr: increases VWT: net importer	RF: 5.0%P: 11.8%	VIL: net exporter	MPI: low PI: low	TI: high
Arauca	AI: low to moderate ΔPr: no changes VWT: net exporter	RF: 14.8%P: 5.3%	VIL: close to 0	MPI: medium PI: low	TI: isolated
Casanare	AI: low to moderate ΔPr: decreases VWT: net exporter	RF: 8.3%P: 3.2%	VIL: close to 0	MPI: low PI: low	TI: isolated
Putumayo	AI: high ΔPr: decreases VWT: net exporter	RF: 4.8%P: 0.9%	VIL: net exporter	MPI: medium PI: low	TI: isolated
San Andrés	AI: ND ΔPr: decreases VWT: close to 0	RF: 1.1%P: 1.1%	VIL: close to 0	MPI: low PI: low	TI: isolated
Amazonas	AI: high ΔPr: decreases VWT: close to 0	RF: 15.2%P: 0.9%	VIL: close to 0	MPI: medium PI: low	TI: isolated
Guainía	AI: high ΔPr: decreases VWT: close to 0	RF: 7.0%P: 2.0%	VIL: close to 0	MPI: high PI: medium	TI: isolated
Guaviare	AI: high ΔPr: decreases VWT: net exporter	RF: 15.6%P: 1.2%	VIL: close to 0	MPI: medium PI: low	TI: isolated
Vaupés	AI: high ΔPr: decreases VWT: close to 0	RF: 5.5%P: 0.2%	VIL: close to 0	MPI: high PI: medium	TI: isolated
Vichada	AI: moderate to high ΔPr: decreases VWT: net exporter	RF: 27.8%P: 1.4%	VIL: close to 0	MPI: high PI: medium	TI: isolated

AI stands for aridity index, ΔPr for precipitation change, FPSs for food production sectors – with RF = raw food (S1–S5) and P = food processing (S6) and the percentages are calculated with respect to the departmental output –, MPI and PI for multidimensional and monetary poverty, TI for trade intensity, and VWT and VIL refers to virtual water and informal labour flows. Low poverty refers to both multidimensional and monetary values under 25, medium to those between 25 and 40, and high to those greater than 40. VWT (VIL) close to zero refers to values between −300 and 300 (−10 and 10). High connectivity refers to TI values greater than 0.3, medium to those between 0.3 and 0.07, and isolated to less than 0.07.

Note that when comparing the same sector across departments, we assume that the product is homogeneous, hence a department-sector pair is relatively more efficient than another if it can create more value-added (i.e., wages and profits) per unit of output. In other words, when considering sector s, department d_1 is more efficient than d_2 if $\eta_s^{d_1} > \eta_s^{d_2}$.

With this in mind, we assume that the more efficient a department-sector pair is, the less water (per unit of output) it requires. To this end, in step 3 we put more weight on ds pairs that are less efficient with respect to the average (i.e., $\overline{\eta_s}$) by "adjusting" the corresponding output. This step allows us to allocate more water to relatively less efficient ds pairs but respecting the national sectoral use of water, i.e., $\sum_d^{\delta} w_s^d = w_s$.

A.2. Informal labour coefficients

The vector of the number of informal employment for the 8 macro-sectors (I) at the national scale was provided by DANE. The procedure to construct the vector of the number of informal workers for any departmental-sector pair (ds) is as follow:

1. calculate the wage-to-output ratio for sector s in department d, as $\gamma_s^d = \frac{wage_s^d}{x_s^d}$, where $wage_s^d$ is the total wages for all the employees;
2. calculate the sectoral weighted average wage-to-output ratio as $\overline{\gamma_s} = \sum_d^{\delta} \gamma_s^d \cdot x_s^d / \sum_d x_s^d$, where $\delta = 33$ is the number of departments;
3. calculate the "adjusted output" as $\tilde{x}_s^d = \gamma_s^d \cdot x_s^d / \overline{\gamma_s}$;
4. calculate the quota of "adjusted output" as $b_s^d = \tilde{x}_s^d / \sum_d^{\delta} \tilde{x}_s^d$;
5. calculate the sectoral informal employment (I_s) to be allocated in department d, as $I_s^d = I_s \cdot b_s^d$.

Note that by comparing the same sector across departments, we assume that the labour productivity is the same. For instance, considering sector s, if $\gamma_s^{d_1} > \gamma_s^{d_2}$, then department d_1 must employ more workers (per unit of output) than d_2. With this in mind, we assume that the higher the wage-to-output ratio, the higher is the occupation. To this end, in step 3 we put more weight on the ds pairs that have a larger γ_s^d with respect to the average (i.e., $\overline{\gamma_s}$) by "adjusting" the corresponding output. This step allows us to allocate more workers to relatively more labour-intensive ds pairs, such as $\sum_d^{\delta} I_s^d = I_s$.

A.3. Gini and poverty index

The indexes of income inequality (i.e., Gini index) and monetary poverty (PI), by department and economic sector, were computed with data from the Integrated Household Survey (2015), provided by the National Administrative Department of Statistics (DANE).[11] This survey has two databases, one covering 24 departments and the other eight departments in the Amazonía and Orinoquía regions. The indexes were computed as follows:

- *PI*: we calculated the per capita income per household considering the department where the household is located and the economic sector in which it participates. To determine if a household is poor, its income is compared with DANE's national poverty line for 2015, i.e., COP 223,638 (DANE, 2016).
- *Gini index*: taking into account the income by the household, department and economic sector, we used the package 'reldist' in R to estimate the index of each economic sector and department.

Appendix B. Tables

See Tables B.1 and B.6.

[11] See https://rb.gy/hk4abe.

References

Abramo, L., Cecchini, S., Morales, B., 2019. Social Programmes, Poverty Eradication and Labour Inclusion. Lessons from Latin America and the Caribbean. ECLAC, p. 267.

Acquaye, A., Feng, K., Oppon, E., Salhi, S., Ibn-Mohammed, T., Genovese, A., Hubacek, K., 2017. Measuring the environmental sustainability performance of global supply chains: A multi-regional input-output analysis for carbon, sulphur oxide and water footprints. J. Environ. Manag. 187, 571–585.

Albrecht, T.R., Crootof, A., Scott, C.A., 2018. The water-energy-food nexus: A systematic review of methods for nexus assessment. Environ. Res. Lett. 13 (4), 043002.

Allan, J.A., 2003. Virtual water-the water, food, and trade nexus. Useful concept or misleading metaphor? Water Int. 28 (1), 106–113.

Alsamawi, A., Murray, J., Lenzen, M., Reyes, R.C., 2017. Trade in occupational safety and health: Tracing the embodied human and economic harm in labour along the global supply chain. J. Cleaner Prod. 147, 187–196.

Andrián, L., 2018. Development Challenges in Colombia. Technical report, Inter-American Development Bank, p. 10.

Beltran-Peña, A., Rosa, L., D'Odorico, P., 2020. Global food self-sufficiency in the 21st century under sustainable intensification of agriculture. Environ. Res. Lett. 15 (9), 095004.

Byers, E., Gidden, M., Leclère, D., Balkovic, J., Burek, P., Ebi, K., Greve, P., Grey, D., Havlik, P., Hillers, A., et al., 2018. Global exposure and vulnerability to multi-sector development and climate change hotspots. Environ. Res. Lett. 13 (5), 055012.

Chamas, Z., Abou Najm, M., Al-Hindi, M., Yassine, A., Khattar, R., 2021. Sustainable resource optimization under water-energy-food-carbon nexus. J. Cleaner Prod. 278, 123894.

Chen, S., Tan, Y., Liu, Z., 2019. Direct and embodied energy-water-carbon nexus at an inter-regional scale. Appl. Energy 251, 113401.

Conway, D., Van Garderen, E.A., Deryng, D., Dorling, S., Krueger, T., Landman, W., Lankford, B., Lebek, K., Osborn, T., Ringler, C., et al., 2015. Climate and southern Africa's water–energy–food nexus. Nature Clim. Change 5 (9), 837–846.

D'Alessandro, S., Cieplinski, A., Distefano, T., Dittmer, K., 2020. Feasible alternatives to green growth. Nat. Sustain. 3 (4), 329–335.

DANE, I., 2015. Hacia la construcción de la cuenta del agua a nivel nacional. Bogota.

DANE, 2016. Pobreza monetaria y multidimensional en Colombia 2015. Technical report, National Administrative Department of Statistics (DANE), p. 41.

Dearing, J.A., Wang, R., Zhang, K., Dyke, J.G., Haberl, H., Hossain, M.S., Langdon, P.G., Lenton, T.M., Raworth, K., Brown, S., et al., 2014. Safe and just operating spaces for regional social-ecological systems. Global Environ. Change 28, 227–238.

Deng, G., Ma, Y., Li, X., 2016. Regional water footprint evaluation and trend analysis of China—based on interregional input–output model. J. Cleaner Prod. 112, 4674–4682.

Distefano, T., 2020. Water Resources and Economic Processes. Routledge, Oxon and New York, p. 320, ISBN: 9780367111403.

Distefano, T., Chiarotti, G., Laio, F., Ridolfi, L., 2019. Spatial distribution of the international food prices: Unexpected heterogeneity and randomness. Ecol. Econom. 159, 122–132.

Distefano, T., Isaza, C.A.S., Muñoz, E., 2020a. The future of water and economics: A regional approach in Colombia. In: Water Resources and Economic Processes. Routledge, pp. 281–301.

Distefano, T., Tuninetti, M., Laio, F., Ridolfi, L., 2020b. Tools for reconstructing the bilateral trade network: A critical assessment. Econ. Syst. Res. 32 (3), 378–394.

DNP, 2015. Análisis Resultados Pobreza Multidimensional 2008–2014. Technical report, Departamento Nacional de Planeación, p. 28.

DNP, 2020. Informe Anual de Avance en la Implementación de los ODS en Colombia. Technical report, Departamento Nacional de Planeación, p. 94.

Endo, A., Tsurita, I., Burnett, K., 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.

FAO, 2016. Climate change and food security: risks and responses. In: Climate Change and Food Security: Risks and Responses. Technical report, Food and Agriculture Organization of the United Nations, Rome, Italy.

FSIN, 2020. Global report on food crises: Joint analysis for better decisions. In: Global Report on Food Crises: Joint Analysis for Better Decisions. Technical report, Food Security Information Network.

Galvis, L.A., Meisel-Roca, A., 2010. Persistencia de las desigualdades regionales en Colombia: Un análisis espacial. In: Documentos de Trabajo Sobre EconomÍa Regional, Vol. 120. Technical report, Banco de la República de Colombia, p. 44.

Gao, J., Xu, X., Cao, G., Ermoliev, Y.M., Ermolieva, T.Y., Rovenskaya, E.A., 2021. Strategic decision-support modeling for robust management of the food–energy–water nexus under uncertainty. J. Cleaner Prod. 292, 125995.

Gómez-Paredes, J., Yamasue, E., Okumura, H., Ishihara, K.N., 2015. The labour footprint: A framework to assess labour in a complex economy. Econ. Syst. Res. 27 (4), 415–439.

Haddad, E., Araujo, I., Galvis, L., 2019. Matriz Insumo-Producto Interregional de Colombia, 2015 (Nota Técnica). Technical report, Núcleo de Economia Regional e Urbana da Universidade de São Paulo (NEREUS).

Haddad, E., Faria, W., Galvis-Aponte, L.A., Hahn-De-Castro, L.W., 2016. Matriz Insumo-Producto Interregional Para Colombia, 2012. Technical report, Banco de la República, Cartagena, p. 77.

Hameed, M., Moradkhani, H., Ahmadalipour, A., Moftakhari, H., Abbaszadeh, P., Alipour, A., 2019. A review of the 21st century challenges in the food-energy-water security in the middle east. Water 11 (4), 682.
Hoff, H., 2011. Understanding the nexus. Background paper for the bonn2011 nexus conference: The water, energy and food security nexus. In: The Water, Energy and Food Security Nexus Solutions for the Green Economy. (November), Stockholm Environment Institute, Stockholm, p. 51.
IDEAM, 2015. Estudio nacional del agua 2014. In: Estudio Nacional Del Agua 2014. Technical report, IDEAM, Bogotá, D.C., p. 496.
IDEAM, 2019. Estudio Nacional del Agua 2018. Technical report, IDEAM, Bogotá, D.C., p. 452.
IDEAM, PNUD, MADS, DNP, CANCILLERÍA, 2015. Escenarios de Cambio Climático para Precipitación y Temperatura para Colombia 2011–2100. Herramientas Científicas para la Toma de Decisiones – Estudio Técnico Completo: Tercera Comunicación Nacional de Cambio Climático. Technical report, IDEAM, Bogotá, D.C., p. 278.
IPCC, 2019. Scenario process for AR5.
Jiménez, D.E., Saldarriaga-Isaza, A., Cicowiez, M., 2021. Distributional and economy-wide effects of post-conflict agricultural policy in Colombia. Eur. Rev. Agric. Econ. jbab020.
Karabulut, A.A., Crenna, E., Sala, S., Udias, A., 2018. A proposal for integration of the ecosystem-water-food-land-energy (EWFLE) nexus concept into life cycle assessment: A synthesis matrix system for food security. J. Cleaner Prod. 172, 3874–3889.
Lazaro, L.L.B., Giatti, L.L., de Oliveira, J.A.P., 2021. Water-energy-food nexus approach at the core of businesses–How businesses in the bioenergy sector in Brazil are responding to integrated challenges? J. Cleaner Prod. 303, 127102.
Lenzen, M., Murray, S.A., Korte, B., Dey, C.J., 2003. Environmental impact assessment including indirect effects—A case study using input–output analysis. Environ. Impact Assess. Rev. 23 (3), 263–282.
Mahlknecht, J., González-Bravo, R., 2018. Measuring the water-energy-food nexus: The case of Latin America and the Caribbean region. Energy Procedia 153, 169–173.
Mahlknecht, J., González-Bravo, R., Loge, F.J., 2020. Water-energy-food security: A nexus perspective of the current situation in Latin America and the Caribbean. Energy 194, 1–17.
Milly, P.C.D., 1994. Climate, soil water storage, and the average annual water balance. Water Resour. Res. 30 (7), 2143–2156.
Namany, S., Al-Ansari, T., Govindan, R., 2019. Sustainable energy, water and food nexus systems: A focused review of decision-making tools for efficient resource management and governance. J. Cleaner Prod. 225, 610–626.
O'Neill, D.W., Fanning, A.L., Lamb, W.F., Steinberger, J.K., 2018. A good life for all within planetary boundaries. Nat. Sustain. 1 (2), 88–95.
Pacheco Flórez, M., Saldarriaga Isaza, A., 2019. Non-renewable resources, diversification and economic activity in the departments of Colombia. Ensayos Economía 29 (54), 29–52.
Pineda-Escobar, M.A., 2019. Moving the 2030 agenda forward: SDG implementation in Colombia. Corp. Gov.: Int. J. Bus. Soc. 19 (1), 176–188.
Poveda, G., Espinoza, J.C., Zuluaga, M.D., Solman, S.A., Garreaud, R., van Oevelen, P.J., 2020. High impact weather events in the andes. Front. Earth Sci. 8 (May), 1–32.
Poveda, G., Waylen, P.R., Pulwarty, R.S., 2006. Annual and inter-annual variability of the present climate in northern South America and southern Mesoamerica. Palaeogeogr. Palaeoclimatol. Palaeoecol. 234 (1), 3–27.
Rasul, G., 2016. Managing the food, water, and energy nexus for achieving the sustainable development goals in south Asia. Environ. Dev. 18, 14–25.
Rasul, G., 2020. A framework for improving policy priorities in managing COVID-19 challenges in developing countries. Front. Public Health 8, 589681.
Rasul, G., Neupane, N., Pasakhala, B., Gurung, P., Nepal, A.K., Sharma, E., 2020. Deepening regional cooperation for enhancing water, energy, and food security and addressing COVID-19 challenges in the hindu Kush Himalayan Region. In: Water Resources and Economic Processes. Routledge, pp. 139–164.
Rasul, G., Sharma, B., 2016. The nexus approach to water–energy–food security: An option for adaptation to climate change. Clim. Policy 16 (6), 682–702.
Reutter, B., Lant, P., Reynolds, C., Lane, J., 2017. Food waste consequences: Environmentally extended input-output as a framework for analysis. J. Cleaner Prod. 153, 506–514.
Rosa, L., Rulli, M.C., D'Odorico, P., 2020. Water stranding in the energy and agriculture sectors: The case of hydraulic fracturing in water scarce irrigated regions. In: Water Resources and Economic Processes. Routledge, pp. 98–114.
Sánchez Torres, R.M., 2020. Poverty and labor informality in Colombia. IZA J. Labor Policy 10 (1), 20200006.
Sánchez Torres, M., Chaparro Hernández, S., 2020. Un piso de protección social para preservar la vida: informalidad, pobreza y vulnerabilidad en tiempos de COVID-19. In: Documentos FCE-CID Escuela de Economía N° 35. Technical report, Universidad Nacional de Colombia Sede Bogotá, Bogotá, D.C., p. 28.
Sherwood, J., Clabeaux, R., Carbajales-Dale, M., 2017. An extended environmental input–output lifecycle assessment model to study the urban food–energy–water nexus. Environ. Res. Lett. 12 (10), 105003.
Smajgl, A., Ward, J., Pluschke, L., 2016. The water-food-energy nexus - realising a new paradigm. J. Hydrol. 533–540, 533–540.
Taherzadeh, O., Caro, D., 2019. Drivers of water and land use embodied in international soybean trade. J. Cleaner Prod. 223, 83–93.
Tamea, S., Carr, J.A., Laio, F., Ridolfi, L., 2014. Drivers of the virtual water trade. Water Resour. Res. 50 (1), 17–28.
United Nations, 2018. Achieving the Sustainable Development Goals in the Least Developed Countries. A compendium of Policy Options. Technical report, United Nations Conference on Trade and Development, New York and Geneva, p. 210.
Van Vuuren, D.P., Bijl, D.L., Bogaart, P., Stehfest, E., Biemans, H., Dekker, S.C., Doelman, J.C., Gernaat, D.E., Harmsen, M., 2019. Integrated scenarios to support analysis of the food–energy–water nexus. Nat. Sustain. 2 (12), 1132–1141.
Wang, J., Wang, K., Wei, Y.-M., 2020. How to balance China's sustainable development goals through industrial restructuring: A multi-regional input–output optimization of the employment–energy–water–emissions nexus. Environ. Res. Lett. 15 (3), 034018.
Wiedmann, T., Lenzen, M., 2018. Environmental and social footprints of international trade. Nat. Geosci. 11 (5), 314–321.
Xiao, Z., Yao, M., Tang, X., Sun, L., 2019. Identifying critical supply chains: an input-output analysis for food-energy-water nexus in China. Ecol. Model. 392, 31–37.
Zhang, C., Chen, X., Li, Y., Ding, W., Fu, G., 2018. Water-energy-food nexus: Concepts, questions and methodologies. J. Cleaner Prod. 195, 625–639.
Zhang, S., Taiebat, M., Liu, Y., Qu, S., Liang, S., Xu, M., 2019. Regional water footprints and interregional virtual water transfers in China. J. Cleaner Prod. 228, 1401–1412.