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Article

Sustainability, Efficiency and Equitability of Water Consumption and Pollution in Latin America and the Caribbean

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Abstract: This paper assesses the sustainability, efficiency and equity of water use in Latin America and the Caribbean (LAC) by means of a geographic Water Footprint Assessment (WFA). It aims to provide understanding of water use from both a production and consumption point of view. The study identifies priority basins and areas from the perspectives of blue water scarcity, water pollution and deforestation. Wheat, fodder crops and sugarcane are identified as priority products related to blue water scarcity. The domestic sector is the priority sector regarding water pollution from nitrogen. Soybean and pasture are priority products related to deforestation. We estimate that consumptive water use in crop production could be reduced by 37% and nitrogen-related water pollution by 44% if water footprints were reduced to certain specified benchmark levels. The average WF per consumer in the region is 28% larger than the global average and varies greatly, from 912 m^3/year per capita in Nicaragua to 3468 m^3/year in Bolivia. Ironically, the LAC region shows significant levels of undernourishment, although there is abundant water and food production in the region and substantial use of land and water for producing export crops like soybean.

Keywords: Latin America and the Caribbean; Water Footprint Assessment; water scarcity; water pollution

1. Introduction

Latin America and the Caribbean (LAC) comprises 33 sovereign countries, recognized in the Community of Latin American and Caribbean States [1], plus a number of islands which are small dependent territories. The sovereign countries cover an area of 20.5 million km^2 (15.2% of the world's total land surface) and had a population of 609 million inhabitants in the year 2012 (8.6% of the world population) [2]. The actual total renewable water resources of LAC are about 18.5 billion m^3/year, which corresponds to 34% of the world resources [3]. LAC is therefore relatively well endowed with water resources. However, there are important regional differences. While countries like Guyana and Suriname had, in the year 2012, total renewable water resources of 318×10^3 and 228×10^3 m^3/capita/year, respectively, other countries, such as the Bahamas, Barbados and Saint Kitts and Nevis, have values as low as 57, 291 and 444 m^3/capita/year, respectively [3].

In 2011 agriculture accounted for 68% of the total freshwater withdrawal in LAC, whereas the industrial and domestic sectors accounted for 11% and 21%, respectively [2]. The relative abundance of water and remaining arable land in combination with global trade liberalization, have boosted LAC as an agricultural commodities exporter to the world market. Agricultural production increased by more than 50% from 2000 to 2012, with Brazil expanding production by more than 70%. Most food produced in LAC comes from rain-fed agriculture, which represents 87% of the total cropland area [4].

Agricultural developments in LAC are desirable in order to improve the economic and social conditions of the region and increase food production for both LAC and the world, which in turn can contribute to alleviate pressures on the world's freshwater resources and food security. However, this must be done in a sustainable way, dealing with both changes in production processes and consumption behavior [5,6]. Challenges include substantial differences in climate within the LAC region, different levels of economic development within and between countries, vast social inequalities, lack of appropriate accounting systems and transparency, and deficiencies in public administration and institutions that make implementation of policies challenging. For sustainable water allocation planning river basin managers must have access to accurate data on actual water availability per basin, taking into account basic human needs, environmental water requirements and the basin's ability to assimilate pollution.

In this paper, we carry out a geographic Water Footprint Assessment (WFA) to provide comprehensive insight regarding the state of freshwater appropriation in LAC river basins and the environmental, social and economic sustainability thereof. The goal of the paper is to understand current water allocation and pollution in LAC, assess the environmental sustainability, economic efficiency, and social equity of water use in the region and identify future challenges. We analyze the water footprint (WF) related to agricultural and industrial production and domestic water supply in the region, as well as virtual water trade with the rest of the world. We evaluate the environmental sustainability of the WF by comparing the blue WF to blue water availability per river basin, by evaluating the increasing use of land and green water resources for agriculture at the expense of natural vegetated areas, and by comparing grey WFs related to nitrogen and phosphorus to the assimilation capacity per river basin. We assess the efficiency of water use in LAC by comparing actual WFs of crop production to WF benchmarks, by analyzing economic water productivity of different crops and by estimating the export earnings per unit of water appropriated for production for export. Subsequently, we assess the equitability of water use within the LAC region by analyzing the differences in the WFs of consumers across the different countries in the region in relation to undernourishment. Finally, based on the outcome of the current study we identify pressing issues to be investigated in future work, which may use the results presented here as point of departure.

2. Method and Data

Green, blue and grey WFs have been estimated following the calculation framework as set out in The Water Footprint Assessment Manual [7]. The green and blue WFs refer to freshwater consumption (appropriation of rainwater and ground/surface water, respectively). The grey WF refers to the volume of water pollution, whereby we focus here on nitrogen. For assessing the sustainability, efficiency and equitability of water allocation and use we follow the three-pillar approach as proposed by Hoekstra [8,9], whereby WFs of production are compared to maximum sustainable WF levels by catchment, WFs of crop production are compared to certain WF benchmark levels, and average WFs per consumer per country are compared to a regional fair share.

The WF of production within a nation or geographic region is defined as the total freshwater volume consumed or polluted within the territory of the nation or region as a result of different economic activities (domestic water supply, agricultural and industrial production). In the current study, the LAC region includes the 33 countries recognized by CELAC plus 6 other island states recognized by FAO. Data on WFs of crop production in LAC were taken from Mekonnen and Hoekstra [10], who estimated the global WF of crop production with a crop water use model at a 5 by 5 arc minute spatial resolution. The WFs of grazing and animal water supply per country were taken from Mekonnen and Hoekstra [11]. The national level data were mapped at 5 by 5 arc minute spatial resolution using the global livestock density obtained from FAO [12].

Gross virtual-water flows are calculated by multiplying, per product, the trade volume with the WF per ton of product in the exporting nation. LAC's virtual water import and export related to trade in agricultural and industrial products were taken from Mekonnen and Hoekstra [13].

In order to assess environmental sustainability of the WFs, we compared—per catchment—the blue WF to blue water availability [14], *i.e.*, the blue water scarcity and the nitrogen- and phosphorus-related grey WFs to the available assimilation capacity [15], *i.e.*, the water pollution level (WPL). Those data were the basis for the identification of priority basins and related priority products Furthermore, we analyzed the limitations to green water resources availability by looking at the conflict between increasing use of land and green water resources for agriculture and biodiversity conservation. Water use efficiency in the region was analyzed by considering economic water productivities of crops, calculated by dividing the producer price (US$/ton) by the WF of the product (m^3/ton), per product category. Data on producer price per crop were obtained from FAO [16]. Additionally, we calculated the economic return of exported products by dividing the export value (US$/year) by the WF of the product (m^3/year). Data on export values of agricultural and industrial products were taken from ITC [17]. We used the WF benchmarks for crop production from Mekonnen and Hoekstra [18] to identify the potential for water productivity increases per crop. Equity of water allocation was studied by comparing the average WF per capita across countries within the region and the world average and by correlating the WF per capita and the proportion of undernourished people per country. Data on undernourishment were obtained from FAO [19].

3. The Green, Blue and Grey Water Footprint of Production

The total WF of national production in LAC in the period 1996–2005 was 1162 billion m^3/year (87% green, 5% blue and 8% grey). Crop production contributed most (71%) to this total, followed by grazing (23%), domestic water supply (4%), industrial production (2%) and animal water supply (1%) (Table 1). The contribution of different crops to the total WF related to crop production is shown in Figure 1. Maize and soybean contribute 18% each, followed by sugarcane (11%), fodder crops (7%) and coffee (7%). Wheat and rice are the other major crops, each having a 5% share of the total crop-related WF. Rice and sugar cane account for the largest share of the blue WF related to crop production, each accounting for 19%, followed by maize (6%) and wheat (5%). The WF of production per country is listed in Table A1. Brazil is the country with the largest total WF within its territory, accounting for 41% of LAC's total WF. The other major countries in terms of their WF are Argentina (16%) and Mexico (13%). Regarding the blue WF, Mexico comes out at the top with 29% of the total blue WF, followed by Brazil (24%), Argentina (10%) and Peru (8%).

On average, 21% of the WF of production in LAC (246 billion m^3/year) is not for domestic consumption, but for export (Table 1). In the agricultural sector, 22% of the total WF relates to production for export; in the industrial sector this is 16%. The largest share (97%) of the total WF for export comes from green water.

Table 1. Water footprint of production in Latin America and the Caribbean in the period 1996–2005.

	Water Footprint of Agricultural Production			**Water Footprint of Industrial Production**	**Water Footprint of Domestic Water Supply**	**Total**
	Related to Crop Production	**Related to Grazing**	**Related to Animal Water Supply**			
Water footprint of production (billion m^3/year)						
Green	739	269	–	–	–	1008
Blue	43.9	–	7.18	1.37	5.05	57.5
Grey	44.4	–	–	16.4	35.8	96.7
Total	827	269	7.18	17.8	40.9	1162
Water footprint for export (billion m^3/year)						
Green	236			–	–	236
Blue	3.5			0.16	0	3.7
Grey	4.0			2.68	0	6.7
Total	243			2.84	0	246
Water footprint for export (% of total)						
Green	23%			–	–	23%
Blue	7%			11%	0%	6%
Grey	9%			16%	0%	7%
Total	22%			16%	0%	21%

Data source: Mekonnen and Hoekstra [13].

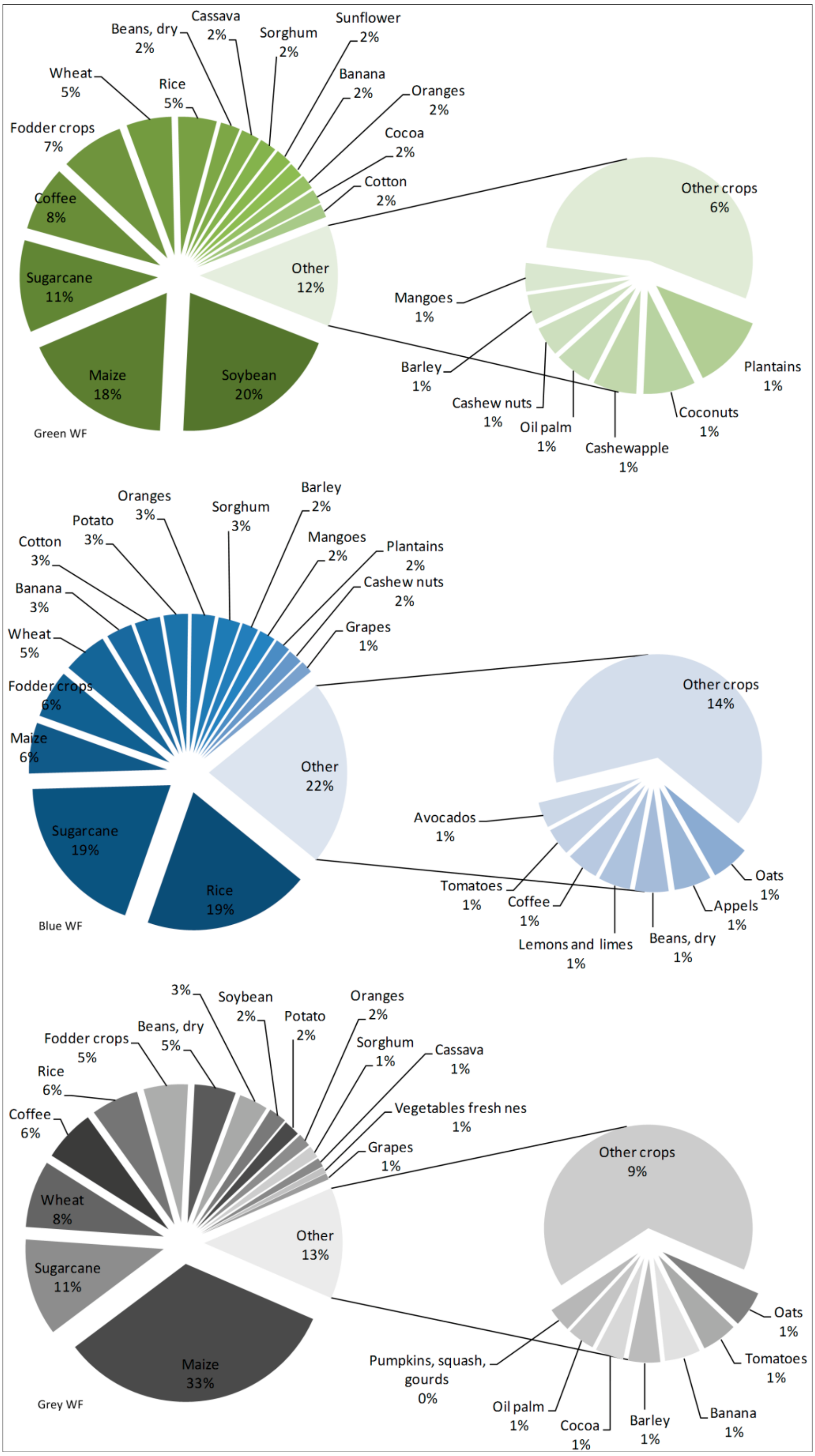


Figure 1. Contribution of different crops to the total green, blue and grey water footprint (WF) related to crop production in Latin America and the Caribbean (1996–2005). Data source: Mekonnen and Hoekstra [10].

The spatial distribution of the green, blue, grey and total WF of production in LAC is shown in Figure 2. The WF in the twenty major river basins in LAC is presented in Table 2. The Parana basin has the largest WF with 336 billion m^3/year (19% of the total WF). Other river basins with a significant share of the total WF are Amazon (73 billion m^3/year), Salado (52 billion m^3/year), Uruguay (48 billion m^3/year), Magdalena (36 billion m^3/year), and Tocantins (34 billion m^3/year). About 50% of the total WF of production in LAC is located in these six river basins. The largest blue WF in LAC is also found in the Parana basin (10% of the blue WF within LAC). The Amazon, Santiago and Uruguay are the river basins with a comparably large blue WF, each contributing 4% to the total blue WF of production.

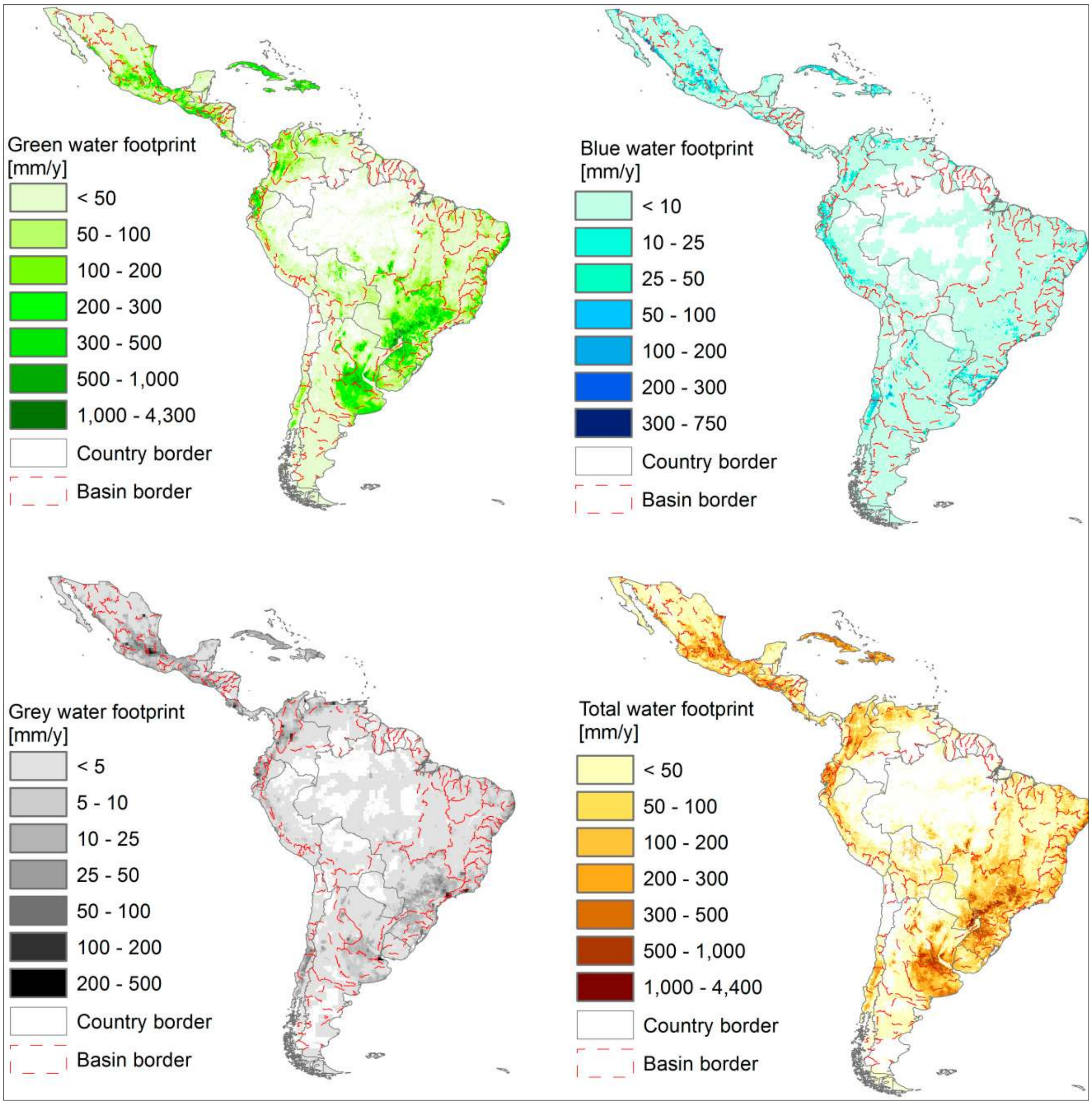


Figure 2. The green, blue, grey and total water footprints within Latin America and Caribbean (1996–2005). The data are shown in mm/year on a 5 by 5 arc minute grid. Data source: Mekonnen and Hoekstra [13].

Table 2. The top-20 river basins with the largest total water footprint of production in Latin America and the Caribbean (1996–2005).

Basin Name	Basin Area (1000 km^2) [a]	Population (million) [b]	Countries in the Basin	Water Footprint of Production (Million m^3/year) [b]		
				Green	Blue	Grey
Parana	2640	68	Brazil; Bolivia; Paraguay; Argentina	315,142	5587	15,616
Amazon	5880	25	Colombia; Venezuela; Guyana; Suriname; French Guiana; Ecuador; Peru; Brazil; Bolivia	66,553	2566	3692
Salado	266	1.9	Argentina	50,566	299	1541
Uruguay	266	5.0	Brazil; Uruguay; Argentina	44,069	2050	1737
Magdalena	261	25	Colombia	29,596	1672	4500
Tocantins	775	4.7	Brazil	32,169	532	1057
Sao Francisco	629	12	Brazil	24,689	1379	2102
Orinoco	952	12	Colombia; Venezuela; Brazil	23,363	1111	2744
Santiago	126	18	Mexico	14,757	2164	3917
Lake Mar Chiquita	154	4.1	Argentina	16,386	588	1017
Grisalva	128	7.0	Mexico; Guatemala	13,458	283	1911
Rio Jacui	70.8	2.6	Brazil	12,308	747	632
Panuco	83.0	18	Mexico	9031	1528	2996
Daule and Vinces	42.0	3.8	Ecuador	9538	963	1062
Parnaiba	337	3.7	Brazil	7616	240	678
Doce	86.1	3.9	Brazil	7016	238	567
Lempa	18.1	4.2	Guatemala; Honduras; El Salvador	4756	93	634
Papaloapan	39.9	2.6	Mexico	4538	169	701
Negro (Uruguay)	70.8	0.5	Brazil; Uruguay	4692	269	99
Esmeraldas	19.8	2.6	Ecuador	3968	253	644

[a] GRDC [20]; [b] for 2000 estimated based on CIESIN and CIAT [21]; [c] Own elaboration based on Mekonnen and Hoekstra [13].

4. Virtual Water Flows

LAC's gross virtual water export to the rest of the world related to agricultural and industrial products was 277 billion m^3/year (88% green, 6% blue and 6% grey) in the period 1996–2005 (Table 3). The virtual water export was dominated by five major products contributing a little over three quarters of the total virtual water export from LAC to the rest of the world (Table 6). Soybean accounts for the largest share of virtual water export (36%), followed by coffee (14%), cotton (10%), livestock products (10%) and sugarcane (8%). The water footprint of these major export products was dominantly based on rainwater: soybean (99% green water), coffee (94%), cotton (62%), livestock products (92%) and sugarcane (87%). In total terms, LAC is a net virtual water exporter, with an average net virtual water export of 112 billion m^3/year over the period 1996–2005 (Table 3). The net export refers to green water only: LAC's net green virtual water export was 141 billion m^3/year. Regarding blue and grey water, LAC had net virtual water import: 16 and 12 billion m^3/year, respectively.

Table 3. Latin America and the Caribbean's virtual water trade balance (billion m^3/year). Period 1996–2005.

Products	Gross Virtual Water Import			Gross Virtual Water Export			Net Virtual Water Import			
	Green	Blue	Grey	Green	Blue	Grey	Green	Blue	Grey	Total
Related to crop products	88	30	17	220	14	8.8	−131	16	8.0	−107
Related to animal products	16	1.3	1.1	26	1.8	0.37	−9.8	−0.43	0.75	−9.5
Related to industrial products		1.0	9.7		0.60	6.3	0.00	0.44	3.4	3.9
Total	104	33	28	245	16	15	−141	16	12	−112

Source: Own elaboration based on Mekonnen and Hoekstra [13].

The gross virtual water import by LAC from the rest of the world related to import of agricultural and industrial products was 165 billion m^3/year (63% green, 20% blue and 17% grey). The largest share of the virtual water import relates to import of cotton products (42%) (mainly from the US and Pakistan), followed by wheat (12%) (mainly from the US and Canada) and livestock products (11%) (mainly from the US). About 54% of the total virtual water imports goes to Mexico. It accounted for about 50% of the total virtual water import to LAC related to crop, 83% related to livestock, and 47% related to industrial products.

The major destinations of LAC's virtual water exports were the US (22%), China (8%), Germany (6%), Netherlands (5%), Italy (5%), and Spain, France and Russia 4% each (Table A2). The virtual water trade balance of countries trading with LAC together with the gross virtual water flows to and from LAC are shown in Figure 3.

The international virtual water flows within LAC are small compared to the exchanges with the rest of the world. Most of the virtual water flows are related to crop products (88%). Virtual water flows related to trade in animal and industrial products contribute 9% and 3%, respectively. The virtual water flows within LAC are dominantly green water (88%), while blue and grey water contribute 5% and 7%, respectively.

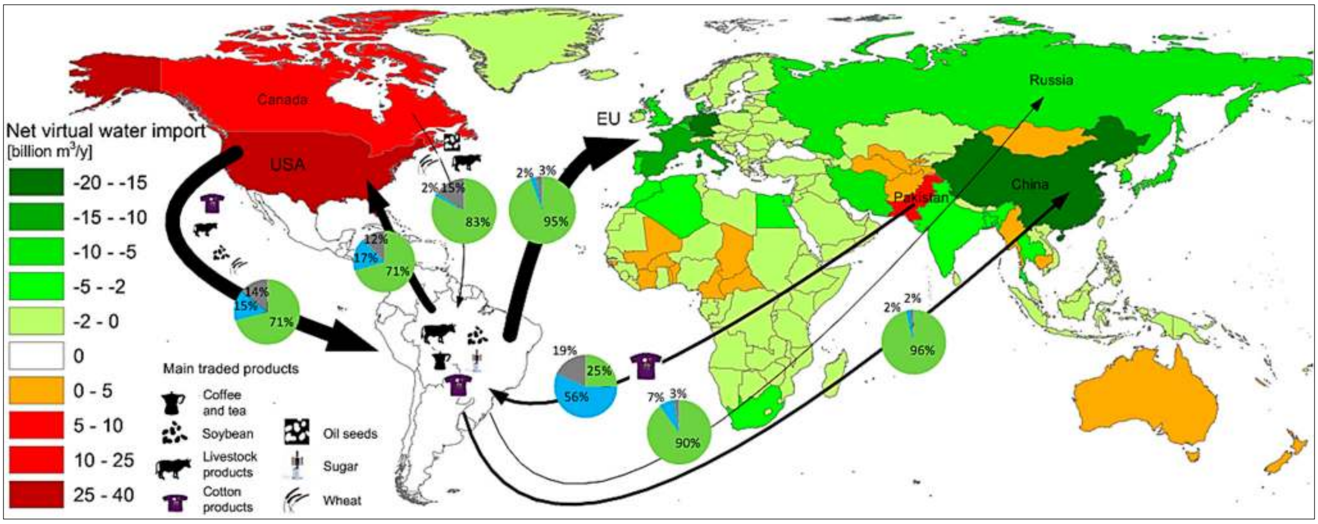


Figure 3. Global map showing countries with net virtual water import related to import of agricultural and industrial products from Latin America and the Caribbean (green) and countries with net virtual water export due to agricultural and industrial exports to Latin America and the Caribbean (red) over the period 1996–2005. Only the biggest gross virtual water flows (>10 billion m^3/year) are shown. Data source: Mekonnen and Hoekstra [13].

5. Environmental Sustainability of the WF in the Region

5.1. Blue Water Footprint versus Blue Water Availability

The expansion of irrigation in the LAC region, at an average annual rate of 250,000 hectares over the past five decades, reflects the economic importance of blue water resources in the region [22]. The total area equipped for irrigation in LAC is 15 million ha (*c.f.* world total: 308 million ha) and the area actually irrigated is 12 million ha (*c.f.* world total: 255 million ha) [23]. Areas of high irrigation density are located along the western coasts of Mexico and Peru, in central Chile, and in the growing areas along the border between Brazil and Uruguay. In addition, numerous other, smaller irrigation areas are spread across the LAC region. Areas predominantly irrigated with groundwater are found in a strip of about 500 km width and 2500 km length in Brazil and in the northeastern part of Argentina. In most regions of Southern America irrigation mainly depends on surface water. No water from nonconventional sources is used for irrigation [24].

Figure 4 shows the annual average monthly blue water scarcity in the LAC region at 30 × 30 arc minute resolution level, using data of Hoekstra and Mekonnen [25] for the ten-year period 1996–2005. Blue water scarcity is here defined as the ratio of the total blue WF to the blue water availability, thereby accounting for environmental flow requirements [7,14]. The blue WF exceeds blue water availability mainly in Mexico, but also in parts of Central America, along the west coast of South America (Peru, Chile), along the north coast (Venezuela), in the northeast of Brazil and in the southern part of South America (Argentina).

A detailed analysis of the monthly data shows that three of the 77 river basins are facing year-round severe water scarcity. Those are the Yaqui River Basin in northwestern Mexico (76,000 km^2, 651,000 people), the Loa River Basin, the main water course in the Atacama Desert in northern Chile (50,000 km^2, 196,000 people) and the Conception River Basin in northern Mexico (26,000 km^2, 193,000 people). In addition, 26 basins experience severe water scarcity at least one month per year (2,660,247 km^2, 82 million people).

Even though a large share of the blue WF of production in LAC is in the basins of the Parana (8%), Amazon (4%), Uruguay (4%) and Magdalena (3%), blue water scarcity in these basins is low throughout the year. Table 4 presents the ten river basins that have a share of blue WF above or equal to 0.4% and experience severe water scarcity at least one month in a year. For each river basin the major products (agricultural, industrial or domestic) are listed, based on their share of the total blue WF in each river basin.

The Santiago river basin (located in Mexico) not only has the largest blue WF, but also experiences severe water scarcity for five months in a year and moderate scarcity in one month. The Panuco river basin (also located in Mexico) is the second basin with a significant share of the blue WF and experiences a similar scarcity level. The major activities contributing to the blue WF in the basins of Santiago and Panuco are wheat, fodder crops, barley and maize, in competition with domestic water supply. The Colorado basin, located in Argentina and Chile, also has a large share of the blue WF and experiences severe scarcity for one and significant scarcity for two months in a year. Grapes and fodder crops are the major products contributing to the blue WF of that basin.

Our blue WF estimates do not include evaporation from artificial reservoirs, which could be substantial in the LAC region because hydropower generation is very extensive. The estimates also do not account for inter-basin water transfers. The blue WF and blue water scarcity assessment could be improved if we would account for the effect of dams and inter-basin water transfers on both the blue WF and blue water availability.

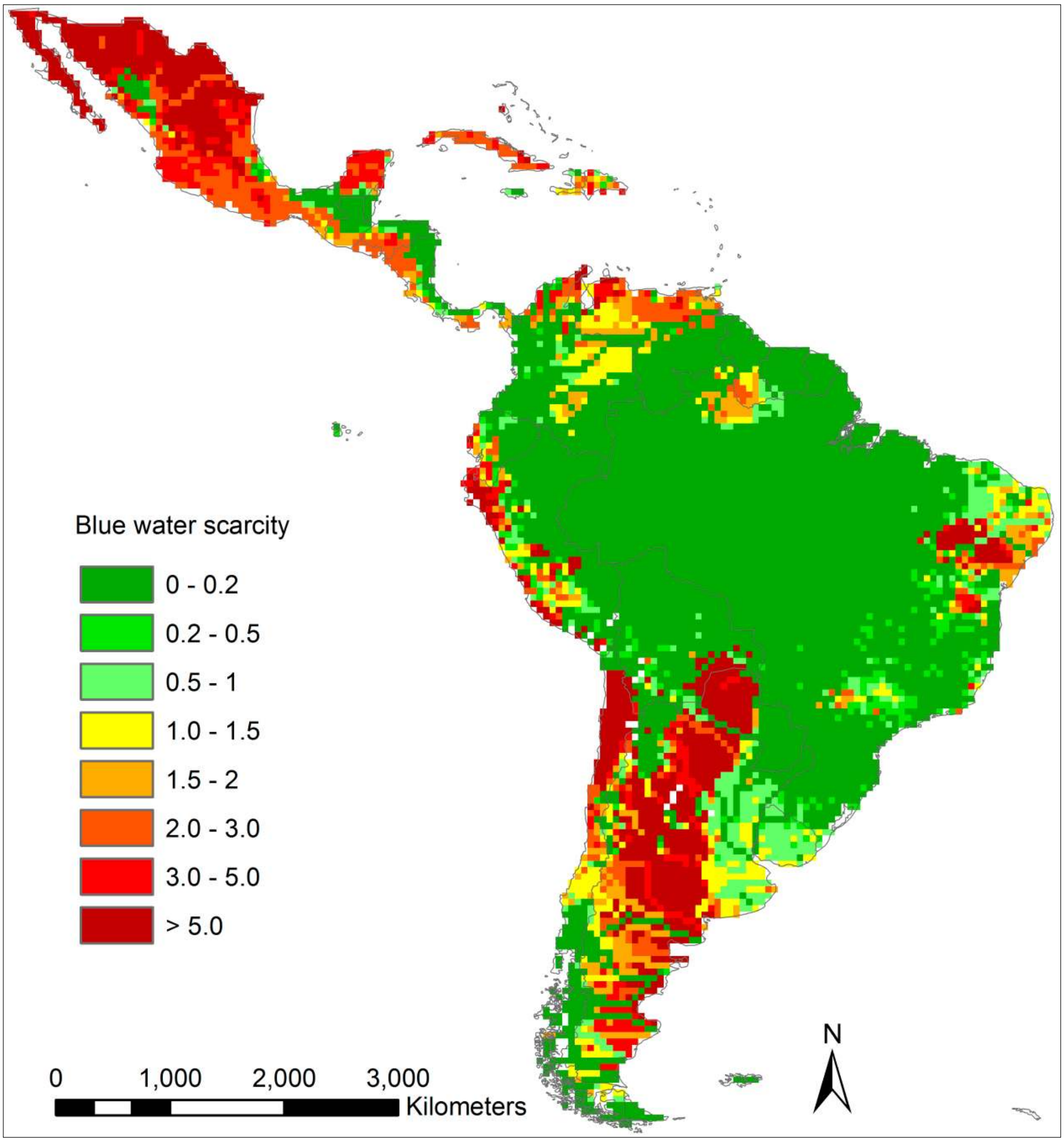


Figure 4. Annual average monthly blue water scarcity in Latin America and the Caribbean estimated at a resolution level of 30 × 30 arc minute grid cells. Low blue water scarcity corresponds to green colors (<1.0), moderate to yellow (1.0–1.5), significant to orange (1.5–2.0) and severe to red (>2.0).

Table 4. The blue water scarcity and contribution of major products in ten priority basins (1996–2005).

River Basin	Population (million) [a]	Percentage of the Total Blue Water Footprint of Production in LAC Located in this Basin [b]	Number of Months per year that a Basin Faces Moderate, Significant or Severe Water Scarcity [c]			Products with Significant Contribution to the Blue Water Footprint in the Basin (% Contribution) [a]
			Moderate	Significant	Severe	
Santiago (Mexico)	18	3.8%	1	0	5	Wheat-18%, Fodder crops-15%, Barley-13%, Domestic-12%, Maize-11%, Other perennials-15%
Panuco (Mexico)	18	2.7%	1	0	4	Fodder crops-19%, Domestic-17%, Sugarcane-13%, Barley-10%, Maize-6%, Wheat-6%, Citrus fruits-5%, Other perennials-16%
Colorado (Argentina, Chile)	3.3	2.6%	0	2	1	Grapes-38%, Fodder crops-10%, Other perennials-25%, Other annuals-19%
Rapel (Chile)	0.7	1.1%	1	0	2	Maize-27%, Rice-10%, Sugar Beets-6%, Wheat-15%, Other annuals-14%, Other perennials-18%
Lake Mar Chiquita (Argentina)	4.1	1.0%	1	1	4	Sugarcane-20%, Domestic-10%, Wheat-9%, Cotton-8%, Fodder crops-8%, Soybeans-8%, Maize-6%, Citrus fruits-5%, Other annuals-11%, Other perennials-7%
Yaqui (US and Mexico)	0.7	0.8%	0	0	12	Wheat-53%, Maize-11%, Fodder crops-8%, Other annuals-10%, Other perennials-6%
Jaguaribe (Brazil)	2.1	0.6%	1	1	3	Fodder crops-22%, Sugarcane-5%, Other perennials-58%
Fuerte (Mexico)	0.5	0.5%	2	0	3	Sugarcane-19%, Potatoes-11%,Wheat-11%, Pulses-9%, Maize-6%, Other annuals-18%, Other perennials-13%
Negro (Uruguay)	0.5	0.5%	0	0	1	Rice-97%
Chira (Peru)	0.7	0.4%	0	2	5	Rice-26%, Maize-16%, Citrus fruits-9%, Sugarcane-9%, Cotton-6%, Other perennials-17%, Other annuals-8%

[a] for 2000 estimated based on CIESIN and CIAT [21]; [b] Own elaboration based on Mekonnen and Hoekstra [13]; [c] Hoekstra *et al*. [14].

5.2. Limitations to Land and Green Water Resources Availability

LAC is producing and supplying more and more food to other parts of the world using rainwater. Many parts of the region have abundant green water resources, which suggest that there is room for expansion of rain-fed agriculture. However, this "abundance of green water" is misleading, because a great part of the green water resources in the region is attached to forested lands. Claiming new land and associated green water resources for agriculture will be at the expense of natural vegetation. The economy of LAC is highly dependent on its rich biodiversity, yet it is increasingly under threat from human activities [26]. Although there are numerous biodiversity policies and measures in the region, collectively they do not effectively conserve its biological resources [27].

Across the region, the agricultural sector makes significant contributions to GDP, export revenues, employment, and rural livelihoods. Argentina's and Brazil's growing shares of international agricultural markets are explained by the enormous growth in soybean production and exports from both countries between 1995 and 2011. During that period, soybean production increased by 198% in Brazil and by 287% in Argentina, while soybean exports increased by 329% in Brazil and 980% in Argentina [28]. Soybean export has a share of 36% of the total virtual water export from LAC to other countries of the world. The green WF of soybean production amounts to 99%. With an abundance of green water and hence favorable conditions for excellent agricultural production, in some of the basins in those countries blue water scarcity is low throughout the year. But it is important to note that drastic land-use changes are occurring in the region, which generally take place with little or no planning [29].

The land area in LAC is about 2050 million, out of which 85% is already taken up by agricultural and forest area [16]. Given that the remaining area is partly built-up area and barren land, expansion of the agricultural sector has limits with respect to land availability. There is a trade-off between biodiversity conservation and food production. It must also be considered that some areas are difficult to use for agricultural production, such as high mountains or deserts.

It is not easy to determine the land that needs to be allocated to nature and biodiversity conservation. Myers [30], Svancara *et al.* [31] and the Convention on Biological Diversity [32] point that at least 10%, and perhaps as much as 20%, of tropical moist forest needs to preserve biodiversity. Svancara *et al.* [31] show that proposed protection percentages in conservation assessments (30.6 percent ± 4.5 percent) and threshold analyses (41.6 percent ± 7.7 percent) are significantly greater than average policy-negotiated values (13.3 percent ± 2.7 percent). While the regions of Central America, the Caribbean and South America meet the 2010 conservation target of 10% protected terrestrial area (according to FAO [16])—11.7% was protected in the Caribbean in 2010, 14.4% in Central America and 21.6% in South America—it must be questioned whether this is sufficient to conserve biodiversity. Figure 5 shows that in all LAC countries except Venezuela the biodiversity hotspot area were larger than the protected area in the year 2004. According to Butchart *et al.* [33], the rate of biodiversity loss in the world does not slow down, despite increasing efforts and some local successes.

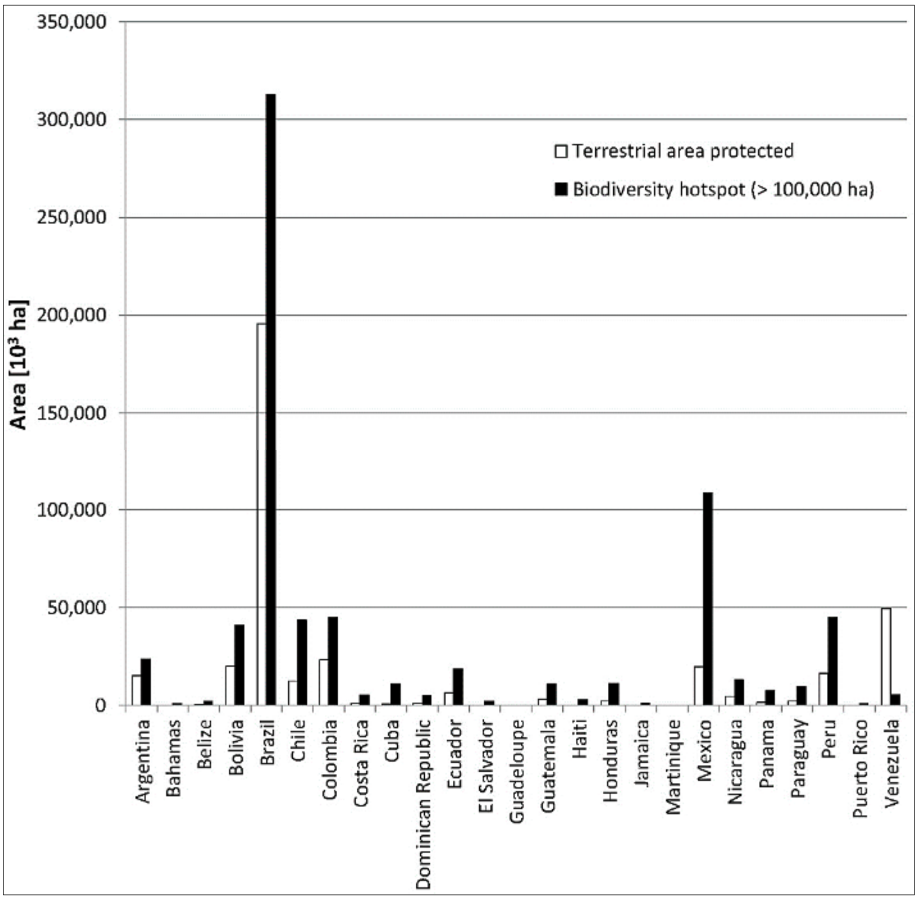


Figure 5. Protected terrestrial areas [32] and biodiversity hotspot areas [34] in Latin America and the Caribbean. The area protected in the year 2004 is shown in order to allow for a comparison with Conservation International's 2004 Hotspot Revisited Analysis [34]. A region must meet two strict criteria to be considered a hotspot: it must contain at least 1500 species of vascular plants (>0.5% of the world's total) as endemics, and it has to have lost at least 70% of its original habitat [35].

Globally, South America suffered the largest net loss of forests between 2000 and 2010—about 4.0 million ha/year; decreasing after a peak in the period 2000–2005. The average net loss of forest was 4.2 million ha/year in the 1990s, 4.4 million ha/year in the period 2000–2005, and 3.6 million ha/year in the period 2005–2010. The regional figures primarily reflect the developments in Brazil, which accounts for 60% of the forest area in this region [36]. In the period 2000–2010, three of the ten countries with the largest annual net loss of forest area globally are in the LAC region: Brazil with −2,642,000 ha/year, or −0.49%, Bolivia with −290,000 ha/year or −0.49% and Venezuela with −288,000 ha/year or −0.60%.

Extensive grazing is one of the main causes of the rapid deforestation in the tropical rainforests of the region and will continue to expand mostly at the expense of forest cover (Figure 6). Wassenaar *et al.* [37] project that, although there are substantial differences among countries, both concerning the spatial patterns of deforestation and the substitution trends between land uses, nearly two-thirds of the deforested land will be converted to pasture.

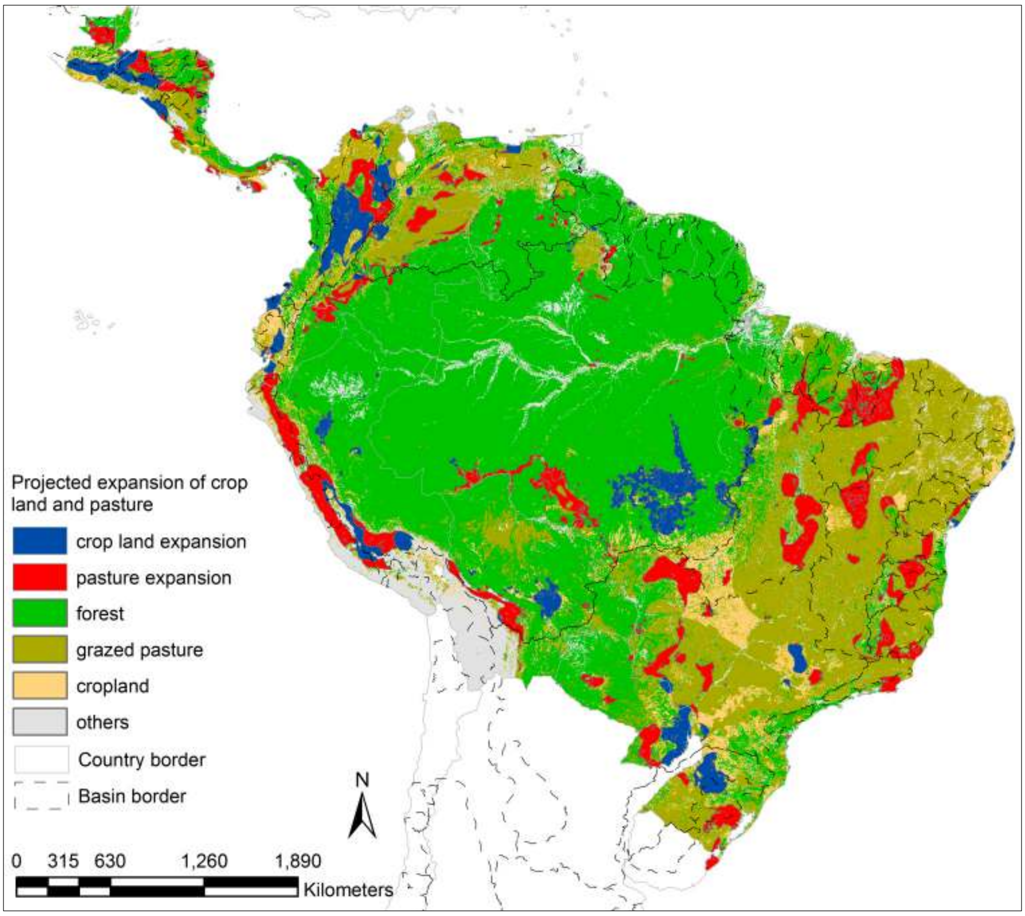


Figure 6. Expansion of cropland and pasture to forested area in South and Central America. Data source: FAO [38]. Data represent projection for the year 2010 based on Wassenaar *et al.* [37] study.

Export-oriented industrial agriculture has become another main driver of South American forest and savannah removal. A large share of the deforested area is dedicated to large-scale production of soybeans and other feed crops driven by the sharp increase in global demand for livestock products [39,40]. This increased demand for feed, combined with other factors, has triggered increased production and exports of soybean and other feed crops from Latin America, leading to extensive deforestation. Soybean and other feed crops are mainly exported to China and the European Union [41].

In summary, the conversion of natural ecosystems into grazing lands and cropland are currently the main reasons for biodiversity loss and ecosystem degradation in the LAC region [36]. The destruction of large areas of tropic forests as well as of wooded grasslands of the Cerrado in South America due to unsustainable agricultural practices is of major concern [26,27]. Given the need to protect remaining natural areas, there is little room for expansion of rain-fed agriculture. Also outside the forested lands there is little room for expansion. In the period 1996–2005, the combined agricultural and forest area accounted for 87% of the total land area in Central America, 81% in the Caribbean, and 84% in South America. Given that the remaining area is in part built-up area and barren land, additional land for agriculture is limited. Efficient use of the existing agricultural lands and associated green water resources is therefore crucial to increase total production. As pointed out by Molden *et al.* [42], water productivities and yields in rain-fed agriculture can often be substantially improved through adequate management practices.

5.3. Grey Water Footprint Versus Assimilation Capacity

Pollution from nutrients is identified as one of the five main pressures on biodiversity in Latin America, which presents a generally rising trend [27]. Anthropogenic pollution due to nitrogen (N) and phosphorus (P) in LAC has been investigated here using the water pollution level (WPL) as defined by Hoekstra *et al.* [7]. WPL is the ratio of the total grey WF in an area (typically a watershed, catchment or river basin) to the runoff from the area. WPL values exceeding 1.0 imply that ambient water quality standards are violated. In large parts of LAC, WPLs for N and P are close to or higher than 1.0. In parts of Mexico, Central America, and along many regions of the coast of South America the pollution assimilation capacity of the rivers has been fully consumed (Figure 7). Particularly high WPL levels are found in Mexico and in the south cone of Latin America.

Water pollution is partly related to lack of water treatment infrastructure and governance in the water sector. Although there is infrastructure to treat about 35%, only 20% of wastewater is effectively treated in LAC [43]. More than 70% of sewage is discharged into the nearest water bodies without any treatment, causing alarming water pollution problems [28]. In most river basins, the untreated wastewater from the domestic and industrial sectors accounts for the largest share of the total N-related grey WF (Table 5). Throughout the LAC region, river basins and aquatic habitats are used as sinks for garbage, mining effluent, and industrial and agricultural waste. The region's heaviest polluter is Brazil—the country with the most abundant water resources. Smaling *et al.* [40] mention "massive use of pesticides" in the agricultural sector in Brazil. While large investments in wastewater treatment have been planned for large LAC cities such as Buenos Aires, Mexico City, Bogota, Lima, and São Paulo, they have been delayed for many years because of the lack of strong institutions and policy frameworks that are hindering effective implementation [43].

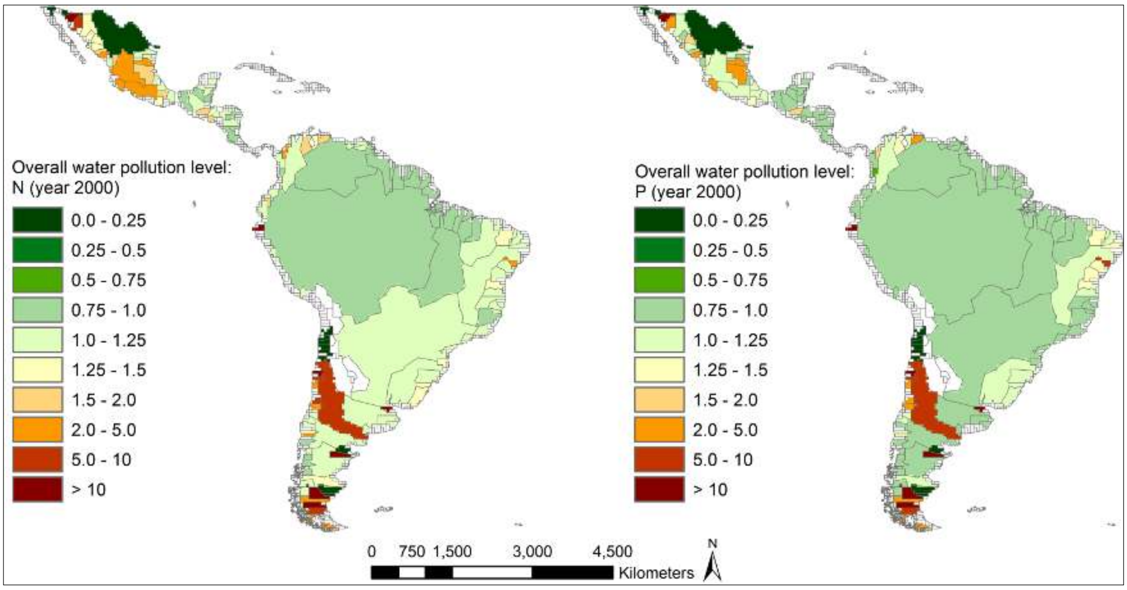


Figure 7. Water pollution level for nitrogen (N) and phosphorus (P) per river basin in the Latin America and the Caribbean region (year 2000). Data source: Liu *et al.* [15].

Table 5. The nitrogen-related water pollution level (WPL) and contribution of major sectors in twelve priority basins (1996–2005).

Basin Name	Percentage of the Total N-Related Grey WF in LAC Located in this Basin [a]	N-Related WPL [b]	Products with Significant Contribution to the N-Related Grey WF in the Basin (% Contribution) [a]
Parana	16.1%	1.14	Domestic-22%, Maize-18%, Industrial-17%, Sugar cane-16%, Wheat-6%
Magdalena	4.7%	1.19	Domestic-69%, Coffee-12%, Industrial-5%, Rice-5%
Santiago	4.1%	2.06	Domestic-42%, Maize-34%, Industrial-12%
Amazon	3.8%	0.94	Domestic-29%, Industrial-17%, Maize-13%, Rice-8%
Panuco	3.1%	1.83	Domestic-54%, Maize-20%, Industrial-16%
Orinoco	2.8%	0.95	Domestic-58%, Coffee-12%, Industrial-8%, Rice-7%, Maize-7%
Sao Francisco	2.2%	1.11	Domestic-29%, Industrial-25%, Maize-14%, Cotton-8%, Dry beans-7%, Sugar cane-5%
Grisalva	2.0%	1.04	Maize-54%, Domestic-21%, Industrial-8%, Sugar cane-6%
Uruguay	1.8%	1.02	Maize-31%, Domestic-15%, Rice-13%, Industrial-12%, Wheat-10%, Soybeans-5%
Salado	1.6%	1.36	Wheat-28%, Maize-27%, Fodder crops-19%, Domestic-9%
Daule and Vinces	1.1%	1.11	Domestic-53%, Industrial-24%, Maize-8%, Rice-7%
Tocantins	1.1%	0.96	Domestic-22%, Industrial-19%, Cotton-17%, Maize-16%, Rice-11%

[a] Own elaboration based on Mekonnen and Hoekstra [13]; [b] Liu *et al.* [15].

6. Water Use Efficiency in the Region

Total green and blue WFs and economic water productivity (US$/m^3) per crop category are shown in Figure 8. Vegetables (mainly tomatoes, chili and peppers, and carrots) have the highest economic return per unit of water consumed (0.86 $/m^3). Tobacco and natural rubber have the second largest economic water productivity, followed by roots and tubers, which are key to prosperity in several countries of the region. Cereals and oil crops, accounting for the largest share of crop-related water consumption in the region (about 55%), have an economic water productivity of about 0.08 $/m^3.

LAC's total earnings related to export of agricultural and industrial products were US$ 315 billion per year (Table 6), with an associated economic water productivity of about 1.14 US$/m^3. Export gains associated with industrial products contributed about 79% to the total export earnings, with an average water productivity of 36 US$/m^3. Among the agricultural export products, cotton has the highest return per unit of water used (0.58 US$/m^3), followed by livestock products (0.20 US$/m^3), sugarcane and coffee (0.15 US$/m^3 each). Soybeans have a very modest economic revenue of 0.12 US$/m^3. Reallocation of water may improve the economic value of water use, but for further reaching conclusions on optimal crop choices, obviously other factors than water have to be taken into account.

By comparing the WF of crops in LAC with global benchmark values from Mekonnen and Hoekstra [18] we are able to identify the potential for increasing water productivities per crop. Figure 9 shows a comparison of the (production-weighted) average green-blue and grey WFs (m^3/ton) of different crops in LAC to the global benchmark values at the best 25th percentile of production. Most of the average crop WFs in the region are larger than the global benchmark values. This should be an incentive for the LAC countries to improve their water productivities in both rain-fed and irrigated agriculture. If all countries in LAC would reduce the green-blue WF of crop production to the level of the best 25th percentile of current global production, the water saving in LAC crop production would be about 37% compared to the reference water consumption. Furthermore, if every LAC country would reduce the nitrogen-related grey WFs in crop production to the level of the best 25th percentile of current global production, water pollution related to crop production in LAC would be reduced by 44% compared to the current situation.

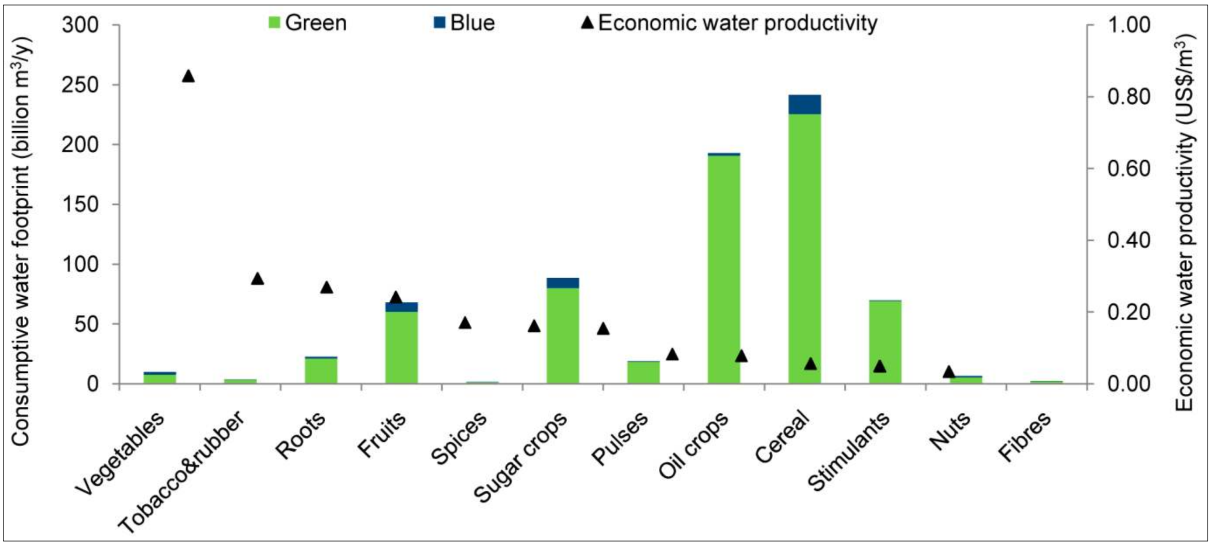
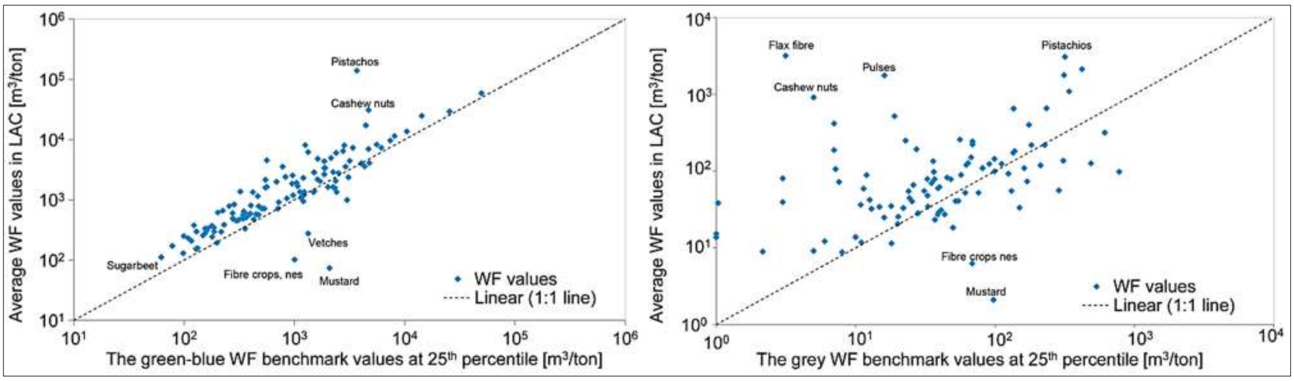


Figure 8. Green and blue water footprints and economic water productivity of major crop categories in Latin America and the Caribbean (1996–2005). Data source: water footprints from Mekonnen and Hoekstra [10].

Table 6. Top-10 products that account for large shares of Latin America and the Caribbean virtual water exports, export earnings and water productivity (1996–2005).

Product	Virtual Water Export (Billion m³/year) [a]				Export Value (Billion US$/year) [b]	Economic Value (US$/m³) [c]
	Green	Blue	Grey	Total		
Soybeans	98	0.14	0.68	99	12	0.12
Coffee	37	0.23	2.1	39	6.0	0.15
Cotton	18	8.6	2.4	29	17	0.58
Livestock products	26	1.7	0.37	28	5.7	0.20
Sugarcane	19	1.9	0.89	22	3.4	0.15
Maize	9.1	0.10	0.75	10	1.0	0.10
Sunflower seed	8.4	0.03	0.09	9	0.86	0.10
Industrial products	0.0	0.60	6.3	7	250	36
Cocoa beans	6.6	0.00	0.09	7	0.40	0.06
Wheat	5.4	0.21	0.39	6	0.43	0.07
Other crops	18	2.7	1.4	22	19	0.87
Total	245	16	15	277	315	1.14

[a] Own elaboration based on Mekonnen and Hoekstra [13]; [b] ITC [17]; [c] Own elaboration.



(**a**) (**b**)

Figure 9. Distribution of the average green-blue and grey water footprint (WF) of different crops in Latin America and the Caribbean (LAC) against the global benchmark values for best 25th percentile of production. Period 1996–2005. (**a**) Green-blue WF; (**b**) Grey WF. Data sources: water footprints from Mekonnen and Hoekstra [10] and benchmark values from Mekonnen and Hoekstra [18].

7. Equity of Water Allocation in the Region

The average WF of consumption in the LAC region was about 1769 m^3/year per capita (83% green, 6% blue and 11% grey) over the period 1996–2005. The WF mostly comes from the consumption of agricultural products, which accounts for about 93% of the total WF. Domestic water supply and consumption of industrial products contribute 4.5% and 2.4%, respectively. Animal products account for the largest share (54%) of the WF related to consumption of agricultural products; cereal products account for 18%. The WF per capita in LAC is 28% above the global average WF, due to the combination of relatively high per capita consumption levels (particularly of meat) and larger WFs per ton of products consumed.

The WF of consumption ranges from 912 m^3/year per capita in Nicaragua to 3468 m^3/year per capita in Bolivia (Figure 10). The large WF in Bolivia is mainly due to the relatively low water productivities of the livestock sector in the country, *i.e.*, large WFs per ton of product consumed. The per capita consumption of meat in Bolivia is 0.8 times the LAC average, but the WF per ton of meat is four times the LAC average. The small per capita WFs in Nicaragua and Guatemala are the result of both the low level of consumption and the smaller WF per ton of consumed products. The per capita consumption of meat in Nicaragua is about one third of the LAC average and the WF per ton of meat is about 0.6 times the LAC average.

In order to assess the fairness of water allocation in the region, it would have been interesting to look at the WF variations within countries, but due to a lack of data we were not able to assess the WFs of different communities within a county. In order to address this limitation, we used the proportion of undernourished population as a proxy of the equity of water allocation within a country. Figure 11 shows the WF related to consumption of agricultural products and the proportion of undernourished population. Although there is no strong correlation between the size of the national WF per capita and the proportion of the undernourished population, countries with smaller average per capita WF tend to have a larger proportion of undernourished people. Since the WF of national consumption is a function of the volume of consumption and the WF per unit of the commodities consumed, a country with a large WF (e.g., Bolivia) may still have a relatively large proportion of undernourished people.

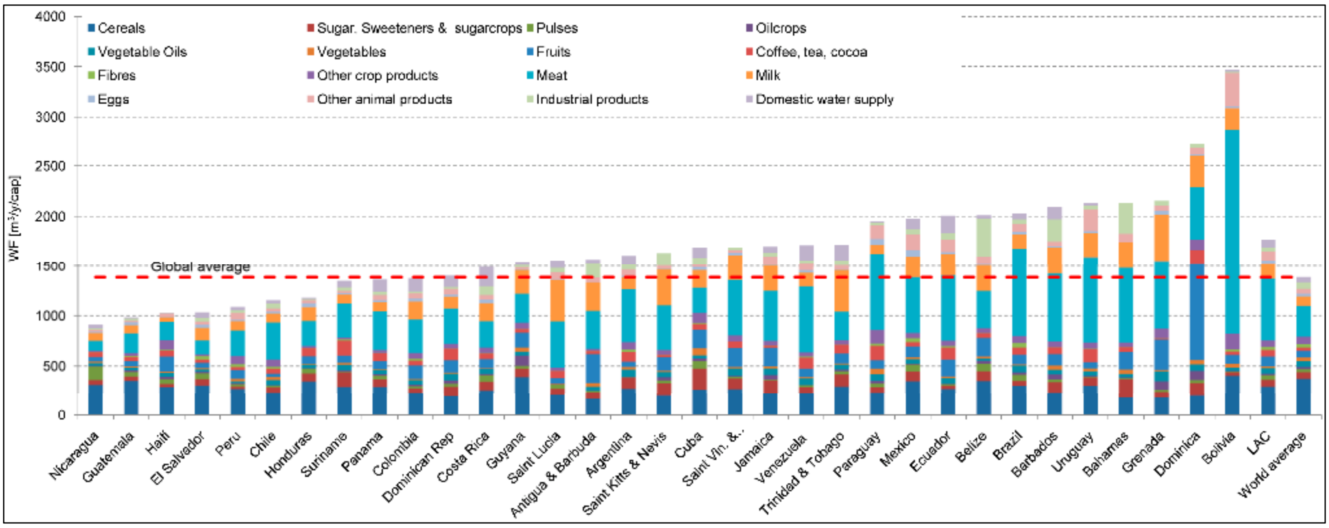


Figure 10. Water footprint of national consumption for Latin America and the Caribbean countries, shown by product category (1996–2005). Data source: Hoekstra and Mekonnen [44].

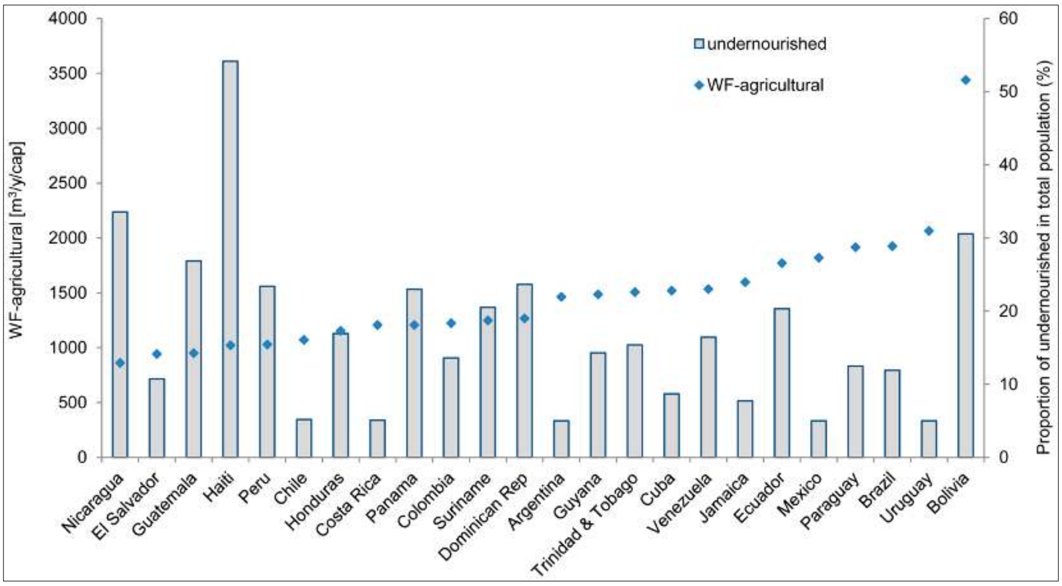


Figure 11. Water footprint related to consumption of agricultural products (WF-agricultural) and proportion of population undernourished for Latin American and the Caribbean countries. Data sources: water footprints from Hoekstra and Mekonnen [43] and undernourishment data from FAO [19].

The inequitable allocation of the limited water resources of the region to final consumers, combined with the increasing volumes of water used for producing export commodities, will not be sustainable in the long run. As discussed in the previous section, countries need to raise their water productivities in order to produce more with the limited available resources, so that there is more to share. In addition, however, one may need to explore the idea of "fair water footprint shares per community" as proposed by Hoekstra [8,9].

8. Conclusions

This is the first comprehensive study on WF, virtual water trade and related environmental, social and economic impacts in LAC. The study shows that the total WF of national production in LAC was 1162 billion m^3/year in the period 1996–2005. Crop production contributed 71%, followed by grazing (23%). Five crops—maize, soybean, sugarcane, fodder crops and coffee—account for 61% of the total WF of crop production. About 21% of the WF within the region is related to production for export. The gross virtual water export of LAC to the rest of the world related to agricultural and industrial products was 277 billion m^3/year. About 78% of this total virtual water export is related to export of soybean, coffee, cotton, livestock products and sugarcane, and most of it was destined to the EU (36%), the US (22%) and China (8%). Vegetables (mainly tomatoes, chili and peppers, and carrots) have the highest economic return per unit of water consumed (0.86 $/$m^3$). Cereals and oil crops, accounting for the largest share of the total green and blue WF (about 55%) related to crop production, give much lower economic returns.

Sustainability. Severe blue water scarcity was observed mainly in Mexico, in parts of Central America, along parts of the western and northern coasts of South America, in northeast Brazil and in large parts of Argentina. Three of the 77 river basins studied are facing year-round severe blue water scarcity. In addition, 26 basins experience severe blue water scarcity at least one month per year. Expanding irrigation in those basins is not an option. Given that the opportunities to expand rain-fed agriculture without further losses to natural areas and biodiversity are limited as well, efficient use of the available green water resources in existing agricultural areas is crucial. Making more efficient use of green water in rain-fed agriculture can also lessen the need for irrigated agriculture in the water-scarce parts of the region and thus contribute to the reduction of blue water scarcity in these water-short areas. Regarding water pollution, we find that pollution levels for nitrogen and phosphorus are close to or higher than 1.0 in large parts of LAC, forming a significant pressure on biodiversity in the region. Particularly high WPL levels are found in Mexico and in the southern half of South America.

Efficiency. We find that by reducing the green-blue WF of crop production to the level of the best 25th percentile of current global production, the water saving in LAC crop production would be about 37% compared to the reference water consumption. Furthermore, the water pollution related to crop production in LAC could be reduced by 44% compared to the current situation by improving the nitrogen-related grey water footprint in crop production to the level of the best 25th percentile of current global production.

Equitability. The study shows that allocation of water in the region is inequitable from a consumer point of view. The average WF per consumer in the region is 28% larger than the global average and varies greatly, from 912 m^3/year per capita in Nicaragua to 3468 m^3/year per capita in Bolivia. Ironically, the LAC region shows significant levels of undernourishment, although there is abundant water and food production in the region.

Priority basins and products. The study identified priority basins and areas from the perspectives of blue water scarcity, water pollution and deforestation. Per basin, priority products were listed. For the LAC region as a whole, we found that particularly wheat, fodder crops and sugarcane are priority products related to blue water scarcity. The domestic sector is the priority sector regarding water pollution from nitrogen. Soybean and pasture are the priority products related to deforestation. The WFs of the priority crops (soybean, wheat, fodder crops and sugarcane) are larger than the global benchmarks for both green-blue WF and the grey WF. Soybean, which contributes 18% to the crop-related WF in LAC and 36% to the total virtual water export from the region, has a very modest economic return per unit of water consumed (0.12 US$/$m^3$).

Response. By linking priority products to localized unsustainable conditions in the region, the study provides a starting point for the determination of adequate response strategies and allocation of resources. An important response strategy could be to raise water productivity, particularly in rain-fed agriculture. As 87% of the total WF of production and 97% or the total WF for export comes from green water, it is clear that efficient use of the green water resources in existing rain-fed agriculture, rather than expanding agricultural lands, is crucial to increase production and at the same time conserve biodiversity. Furthermore, making more efficient use of green water in rain-fed agriculture can lessen the need for irrigated agriculture in the water-scarce parts of the region and thus contribute to the reduction of blue water scarcity in these water-short areas. There is ample room for improvements in water productivity and yields in rain-fed agriculture, which represents 87% of LAC's cropland [4,41]. Improvement in agricultural practices and water management must come along with technical support to small farmers, engagement of river basin managers and policy makers, and good quality data at the river basin level. The current work points to hotspots that should receive particular attention. Another important response strategy could be to reduce nutrient-related water pollution and discharge of untreated water from the domestic sector. Nutrient pollution could also be reduced by optimizing fertilizer use while maintaining or even increasing land and water productivities.

Local water accounting and assessment—considering the environmental needs—are crucial to develop adequate response strategies. Sustainable water management and protection of the environment in Latin America and the Caribbean will not be achieved unless water and land resources are accounted and assessed comprehensively in the future. Mechanisms need to be adopted that constrain the exploitation of land and water resources within environmental thresholds and agricultural practices need to be developed that lead to more value (economic, environmental and social) per drop. Three issues stand out in particular (i) informed sustainable, efficient and equitable strategies to increase land and water productivities must be developed; (ii) the export growth potential, given environmental, social and economic sustainability constraints must be estimated; and (iii) the basic needs and quality of life of people must be improved by land and water allocation policy dedicated to this target.

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Author Contributions

Mesfin Mekonnen, Markus Pahlow, Maite Aldaya and Erika Zarate designed and performed research. Mesfin Mekonnen and Markus Pahlow analyzed data; Mesfin Mekonnen, Markus Pahlow, Maite Aldaya, Erika Zarate and Arjen Hoekstra contributed to writing the paper. All authors approved the final manuscript.

Appendix

Table A1. The water footprint of national production (million m^3/year).

Country	Water Footprint of Crop Production			Water Footprint of Grazing	Water Footprint of Animal Water Supply	Water Footprint of Industrial Production		Water Footprint of Domestic Water Supply		Total Water Footprint		
	Green	Blue	Grey	Green	Blue	Blue	Grey	Blue	Grey	Green	Blue	Grey
Antigua and Barbuda	21	0.09	0.00	18	0.44	0.05	0.95	0.30	2.7	39	0.9	3.7
Argentina	157,605	4306	4958	18,589	773	138	1508	491	2724	176194	5708	9189
Bahamas	53	0.00	0.00	2.0	0.49	0.00	0.00	0.00	0.00	55	0.49	0.00
Barbados	136	0.54	6.6	20	1.1	2.0	38	3.0	27	156	6.6	72
Bolivia	12,552	389	90	19,007	189	5.0	64	18	130	31559	601	284
Brazil	303,743	8934	15,917	132,223	3158	533	7487	1202	8526	435,966	13,826	31,930
Belize	664	6.1	80	12	1.6	5.5	89	1.0	8.3	677	14	177
Cayman Islands	1.9	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	1.9	0.02	0.00
Chile	6510	2374	2981	2633	123	158	534	142	373	9143	2797	3888
Colombia	31,779	1338	1979	18,394	486	20	380	539	4851	50,173	2384	7210
Costa Rica	4420	291	310	991	35	23	427	79	701	5412	428	1437
Cuba	18,577	1823	629	2010	102	50	581	156	993	20,587	2130	2204
Dominica	215	0.00	1.9	14	0.33	0.00	0.00	0.00	0.00	229	0.33	1.9
Dominican Republic	5877	1017	0.00	2511	62	3.0	50	109	907	8389	1191	957
Ecuador	15,277	2057	603	11,167	129	45	855	212	1908	26,444	2443	3366
El Salvador	4702	66	401	500	26	10	190	32	288	5202	134	879
French Guiana	107	6.5	0.00	5.9	0.41	0.00	0.00	0.00	0.00	113	6.9	0.00
Grenada	129	0.29	0.00	3.8	0.28	0.00	0.00	0.00	0.00	133	0.6	0.00
Guadeloupe	296	8.4	0.00	43	1.4	0.00	0.00	0.00	0.00	338	10	0.00
Guatemala	12,360	299	777	888	52	14	157	13	96	13,248	378	1030
Guyana	1592	249	98	41	5	0.5	10	3.0	27	1632	257	135
Haiti	5849	187	0	1581	50	0.5	10	5.0	45	7430	243	55
Honduras	6447	122	442	1126	48	5.0	95	7.0	63	7573	182	600

Table A1. *Cont.*

Country	Water Footprint of Crop Production			Water Footprint of Grazing	Water Footprint of Animal Water Supply	Water Footprint of Industrial Production		Water Footprint of Domestic Water Supply		Total Water Footprint		
	Green	Blue	Grey	Green	Blue	Blue	Grey	Blue	Grey	Green	Blue	Grey
Jamaica	1849	59	31	307	12	3.5	67	14	126	2156	89	224
Martinique	295	13	0.00	34	0.93	0.00	0.00	0.00	0.00	329	14	0.00
Mexico	83,105	13,885	11,382	25,916	995	215	2649	1359	9022	109,021	16,453	23,053
Montserrat	2.4	0.00	0.00	11	0.21	0.00	0.00	0.00	0.00	14	0.21	0.00
Nicaragua	4896	147	133	982	63	1.5	29	19	171	5877	230	333
Panama	1930	54	147	626	31	2.0	17	55	314	2556	141	478
Paraguay	29,977	135	540	2868	176	2.0	32	10	83	32,845	323	655
Peru	11,399	4096	1800	6641	188	102	501	168	721	18,040	4553	3022
Puerto Rico	559	13	0.0	323	9.4	0.00	0.00	0.0	0.0	882	22	0.0
Saint Kitts and Nevis	54	0.01	0.06	2.4	0.19	0.00	0.00	0.0	0.0	56	0.2	0.1
Saint Lucia	3.6	0.01	0.00	12	0.54	0.00	0.00	1.3	11	15	1.8	11
Saint Vincent and the Grenadines	122	0.00	0.00	6.2	0.39	0.00	0.00	0.0	0.0	128	0.4	0.0
Suriname	275	73	28	15	2.7	1.0	19	3.0	27	290	80	74
Trinidad and Tobago	453	8.7	17	29	3.9	4.0	57	21	184	482	38	257
Uruguay	3932	698	234	7572	180	2.0	38	8	72	11,504	888	344
Venezuela	11,340	1239	854	12,001	277	30	561	381	3429	23,341	1926	4844
LAC total	739,103	43,895	44,441	269,123	7183	1373	16,444	5052	35,829	1,008,227	57,503	96,714

Source: Mekonnen and Hoekstra [13].

Table A2. Top-10 gross virtual water exporters to and importers from LAC (billion m^3/year) (1996–2005).

Country	Top-10 Gross Virtual Water Exporters to LAC				Country	Top-10 Gross Virtual Water Importers from LAC			
	Green	Blue	Grey	Total		Green	Blue	Grey	Total
USA	73	16	14	102	USA	43	10	7.6	61
Pakistan	6.0	13	4.3	23	China	21	0.47	0.40	22
Canada	9.0	0.18	1.7	11	Germany	16	0.31	0.71	17
China	1.6	0.35	2.0	4.0	The Netherlands	13	0.24	0.34	14
India	1.3	0.36	0.46	2.2	Italy	13	0.44	0.37	13
Thailand	1.1	0.06	0.49	1.6	Spain	12	0.20	0.40	12
Indonesia	1.5	0.00	0.09	1.6	France	11	0.17	0.32	12
Spain	0.60	0.76	0.14	1.5	Russia	10	0.80	0.27	11
Australia	1.0	0.07	0.07	1.2	Japan	7.9	0.28	0.61	8.8
Korea	0.55	0.33	0.25	1.1	UK	7.7	0.31	0.40	8.4
Others	9.0	2.0	3.8	15	Others	91	2.7	4.0	98
LAC total	104	33	28	165	LAC total	245	16	15	277

Source: Mekonnen and Hoekstra [13].

Conflicts of Interest

The authors declare no conflict of interest.

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