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REVIEW

Water consumption by agriculture in Latin America and the Caribbean: impact of climate change and applications of nuclear and isotopic techniques

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Abstract

O. Salazar, C. Chinchilla-Soto, S. de los Santos-Villalobos, M. Ayala, L. Benavides, V. Berriel, R. Cardoso, E. Chavarrí, R. Meigikos dos Anjos, A.L. González, A. Nario, A. Samudio, J. Villarreal, R. Sibello-Hernández, and J. Govan, L. Heng. 2022. Water consumption by agriculture in Latin America and the Caribbean: impact of climate change and applications of nuclear and isotopic techniques. Int. J. Agric. Nat. Resour. XX-XX. The main aim of this review is to examine agricultural water consumption in the Latin American and Caribbean (LAC) regions to understand how climate change will impact water availability and how the application of nuclear and stable isotope techniques can be used as tools for improving water use efficiency (WUE) for crop production. The status of agricultural water management in some LAC countries, such as Argentina, Brazil, Chile, Costa Rica, Cuba, Mexico, Panama, Paraguay, Peru and Uruguay, is also reviewed. In the LAC region, water consumption for agricultural irrigation ranged between 35% and 86% of the total available water. However, the WUE is very low in some LAC countries. Although the region, in general, has adequate water resources, there is still a need to improve WUE to increase the productivity of agricultural water. The impact of climate change in some LAC countries may lead to intensification and expansion of agricultural activity. In these areas, the WUE can be improved through soil and water conservation, minimizing soil evaporation (E), as well as through better irrigation management, especially by using an integrated approach on an area-wide basis to manage all land use activities and farming systems within an agricultural catchment. Nuclear and stable isotope techniques using Keeling Plot or IMB methods can play important roles in improving WUE in agriculture in LAC countries by providing information related to soil water losses for improving irrigation systems.

Keywords: agricultural water management; consumptive water use; irrigation; water use efficiency

Introduction

Approximately 31% of the global available water supply is in the Latin America and Caribbean (LAC) region (FAO, 2000). However, these water resources are distributed unequally throughout the region, and more than half of the renewable water supply for the entire region is concentrated in one river, the Amazon. Pellegrini and Fernández (2018) reported that in Latin America, the cultivated land area increased from 83 to 175 million hectares (Mha), and the land area under irrigation increased from 5 to 18 Mha between 1961 and 2014. In LAC, agricultural land irrigation is the most common type of water consumption, covering 18 Mha, which corresponds to approximately 70% of the total available water in the region (ECLAC, 2018). Mekonnen et al. (2014) noted that the total water footprint in LAC in the period 1996-2005 was 1,162 billion m^3 yr^1, and 71% of it was used to support crop production (mainly maize, soybean, sugarcane, fodder crops and coffee) and 23% to support grazing.

Depending on the infrastructure available to the agricultural sector of each country, the agricultural water consumption ranged between 60% and 90% of the total available water. To improve agricultural food production in LAC, it is necessary for all countries involved to contribute to appropriate agricultural water management. While agricultural activities aim to increase food production to meet future societal needs, a decline in the productive base of irrigated land and water availability has been observed (Evans & Sadler, 2008). Water use efficiency (WUE) is an indicator that can be used to evaluate the water management practices used for a given crop (Pala et al., 2007). WUE is defined as the yield of harvested crop product achieved from the water available to the crop through rainfall, irrigation, and soil water storage. FAO (2018) described different ways to define WUE in agriculture; the crop yield could be measured as a value per cubic meter consumed or as nutritional value per cubic meter, while the water volume could represent either amount of water consumed or amount of water extracted.

With few exceptions, agricultural water use in LAC has been inefficient due to the predominance of traditional surface irrigation systems (Willaarts et al., 2014). While irrigation may increase the climatic resilience of agricultural production, its excessive use results in a decrease in the amount of water available for other uses (IPCC, 2014). Ringler et al. (2000) concluded that in LAC, much greater attention to water policy and management reform is needed to improve the efficiency and equity of irrigation and water supply systems.

Nuclear and stable isotope techniques have played an important role in improving WUE in agriculture (FAO, 2006). Recent work has proposed that stable isotope techniques may assist in the selection and evaluation of crop cultivars with greater tolerance to drought and improve the WUE (IAEA, 2012; Van Laere et al., 2019). Analyses of nuclear and stable isotope techniques have suggested that WUE may be improved by optimizing crop water productivity with greater yield per unit measure of water from rainfall or irrigation (FAO, 2006). It is important to note that effective irrigation management requires an understanding of crop water requirements (*ETc*), as well as knowledge of the average water status of the crop–soil system and its variation among and within management units (Fereres & Heng, 2014). Heng et al. (2014) highlighted that isotopic techniques (using oxygen-18 and deuterium isotopes) are important research tools to determine the relative magnitudes of evaporation (E) and transpiration (T) in different situations.

Due to growing concerns about the potential impact of climate change on water availability for agricultural production in LAC, further research is urgently needed to improve the techniques and management practices that may help to increase the WUE (Willaarts et al., 2014). The main aim of this review is to examine the agricultural water consumption in some LAC countries, such as Argentina, Brazil, Chile, Costa Rica, Cuba, Mexico, Panama, Paraguay, Peru and Uruguay, to understand how climate change will impact water availability and how nuclear and stable isotope techniques can be used as tools for improving the WUE in the region.

Water consumption by agriculture in Latin America and the Caribbean

To examine the impact of agricultural water consumption in LAC, we focused on the perspective of agriculture as a water consumer, the importance and impacts of irrigation on agricultural land and the challenges to the adoption of innovative irrigation technologies in some LAC countries, such as the following:

Argentina

Agricultural consumption is the main use of water in Argentina and 75% of water resources are used for irrigation of fruits and vegetables such as table grapes, rice, olives, and stone fruit (FAO, 2016). Approximately 2.1 Mha are irrigated, covering 5% of the total agricultural land and accounting for 65% and 35% of the total surface water and groundwater use, respectively (FAO, 2016; Subsecretaría de Recursos Hídricos, 2017). Among different irrigation systems, the most commonly used are gravitational, such as flood and furrows (70% of the total), followed by sprinkler systems (21% of the total), drip irrigation (8%), and microsprinkler systems (1%) (SAyDS, 2015). The water resources in Argentina are unequally distributed around the country and 75% of the country's land is under arid and semiarid conditions. Gravitational irrigation methods support approximately 13% of the country's total agricultural production and they have been identified as one of the main processes responsible for soil salinization, especially in the arid and semiarid areas of the country (FAO, 2016).

Brazil

It was estimated in 2018 that 66% of the total consumption of 34.7 billion m^3 yr^{-1} of water in Brazil was used for irrigation (ANA, 2019). Since the 1960s, the land area under irrigation in Brazil has been growing and reached 7.3 Mha in 2019. Centre pivot is the main method utilized, covering 20% of this area (ANA, 2019). An area of 69 Mha is dedicated to crop production, and the main crops are soybeans (49%), maize (24%), sugarcane (13%) and rice (3%) (GYGA, 2020). The area under irrigation is small relative to the total amount of land in Brazil and these water resources can be heavily affected by the excessive use of agrochemicals and fertilizers (FAO, 2016). Therefore, one of the main challenges in Brazil is the development of innovative technologies adapted to local conditions to reduce water use in irrigation.

Chile

Anríquez and Melo (2018) noted that the agricultural sector is by far the main water consumer in Chile, consuming 17,000 million m^3 yr^1, which accounts for approximately 85% of all consumptive water use. They also highlighted that although production of export crops is growing rapidly, this growth does not result in comparable growth in water consumption. This is due to two factors: i) improved efficiency of irrigation technologies and ii) a transition toward new crops with greater WUE. In addition, excessive irrigation associated with surplus fertilizer application has transformed agriculture into an important nonpoint source of pollution around the country (Salazar et al., 2014, 2017, 2018).

Costa Rica

Costa Rica is a small country with a total area of 5.1 Mha and agriculture is one of the primary economic activities in that nation, covering 11% of the territory (Mora & Quirós, 2019), with a water consumption of 1,645 million m^3 yr^1, which corresponds to 74% of national water usage (CTIE-AGUA, 2018). A total of 28% of the land under agriculture (approximately 159,600 ha) has infrastructure for different types of irrigation in place: surface irrigation (60%), aspersion irrigation (29%) and localized irrigation (11%) (FAO, 2016).

Costa Rica exhibits high water availability, with renewable resources per capita estimated as 23,033 m^3 person^{-1} yr^1 (FAO, 2016), which is considerably higher than the water stress limit of 1,700 m^3 person^{-1} yr^1 indicated by FAO (Falkenmark & Widstrand, 1992; FAO, 2012). Weak legislation, poor management and pollution problems have created issues for water resources in the last two decades, and this situation is expected to be exacerbated by increased demand and the impact of climate change (Guzmán-Arias & Calvo-Alvarado, 2013).

Cuba

Cuba is a long and narrow island. As a result, its rivers have small basins, short courses, low flow and rapid evacuation to the sea. For this reason, water resources are limited, with large amounts of water being stored in the ground. The National Institute of Hydraulic Resources (INRH, 2007) reported usable water resources of approximately 24,000 million m^3 yr^1, of which 75% is surface water and 25% is groundwater. The local climatic conditions of Cuba require irrigation of agriculture from November to April because of low rainfall, while climatic conditions are favorable for crop development. For this reason, crop irrigation is important for Cuban food security because it can increase yields by up to 80%.

Mexico

The agricultural sector accounts for 76% of water use in Mexico and 61% of the water is derived from surface sources and the rest is obtained from underground sources (CONAGUA, 2018). According to the National Institute of Statistics and Geography (INEGI, 2017), 21% of the national land area was under irrigation, and the remaining (79%) was not; however, the yield (in ton ha^{-1}) of the area under irrigation was 2.2 to 3.3 times greater than that of the nonirrigated land area. Flood irrigation is the most common method of irrigation of crops in Mexico, primarily using surface water sources. However, this is the least efficient way to irrigate crops (FCEA, 2017), as globally, the WUE of surface irrigation in crops is less than 50%, and this type of irrigation wastes up to 25% of the volume to evaporation and infiltration, resulting in an efficiency of 35% to 85% (SIAP, 2013).

Panama

The total consumptive water usage in 2010 was 1,037 million m^3 yr^1, of which 581 million m^3 was for municipal use (56% of the total), 446 million m^3 was used in agriculture (43% of the total), and 10 million m^3 was used in industry (~1% of the total). The main nonconsumptive water uses are hydroelectric power generation (9,770 million m^3) and navigation (2,626 million m^3) (INEC, 2013; ANAM, 2014). The water demand for irrigation in the Santa María and Grande River basins, where most of the land area under irrigation is located, is estimated to reach 1,523 million m^3 in 2020 and 1,705 million m^3 in 2030 (ANAM, 2014). In 2012, the area of agricultural land under irrigation was estimated to be 32,140 ha, with surface irrigation used in 23,900 ha (74%), sprinkler irrigation used in 3,740 ha (12%), and drip irrigation used in 4,500 ha (14%). Most of the water was sourced from surface water, and only 2% was sourced from subsurface water. The land under irrigation is located in the Chiriquí, Veraguas, Coclé, Herrera and Los Santos regions (INEC, 2013).

Paraguay

Paraguay is located in the basin of La Plata River, one of the largest bodies of water in South America. The mean annual precipitation ranges from 400 to 1,700 mm yr^1 in the western and eastern regions of the country, respectively. Paraguay is the country with the highest water availability per person in LAC, with an estimated 67,000 m^3 person^{-1} yr^1 (FAO & IICA, 2017). The predominant consumptive uses are human water consumption (56% of the total), agriculture and raising cattle (35%) and industry (9%), whereas the main nonconsumptive uses are hydroelectric power plants and navigation (Crespo & Martínez, 2000). According to FAO and IICA (2017), Paraguay has 4.6 Mha of agricultural land with only 136,000 hectares under irrigation, and most of the country is under rainfed conditions, with 4,086 hectares equipped for irrigation.

Peru

According to the National Institute of Statistics and Informatics (INEI, 2011), Peru has 7.1 million hectares of land used for agriculture, of which 36% is under irrigation and 64% is rainfed. Agriculture uses 13.5 million m^3 yr^1, representing 86% of the total consumptive water use. The INEI (2011) reported that irrigated agriculture contributes up to two-thirds of the value of agricultural production, mainly related to agricultural exports. There is an unequal water distribution between agricultural lands of the Pacific coast and the Andean area.

However, the WUE in irrigated lands is low; in particular, the application of excessive irrigation on agricultural land has favored soil degradation processes such as salinization and water logging in coastal areas. It is important to note that 50% of the water in the irrigation channels did not meet water quality standards for agricultural use due to contamination with microorganisms from domestic sewage, heavy metals from wastewater from mining activities and pesticides and nutrients from agricultural lands (ANA, 2013). In addition, during the rainy season, rivers transport a high sediment load, clogging emitters in drip irrigation systems and reservoirs.

Uruguay

In Uruguay, the precipitation deficit is the climate factor with the greatest effect on the productivity of local agricultural systems (Bidegain et al., 2012; Hernández et al., 2018). In particular, during the summer period (January and/or February), there are frequently long periods of water deficit for crops (INUMET, 2019). Climatic conditions are more complex due to a high mean summer evapotranspiration rate ranging from 160 to 185 mm month^{-1} (Castaño et al., 2011), especially when the soil in the country shows medium to low water retention capacity (Molfino & Califra, 2001). The majority of crops are under rainfed cultivation, with few areas under irrigation, so there is a high risk of water deficit stress affecting crops and pastures in the summer due to drought events period (MVOTMA, 2017). For instance, water extraction for crop irrigation is 3,630 hm^3 yr^{-1} (Hill, 2016), which is just enough to irrigate 2% of the agricultural land in the country (MVOTMA, 2017). Only some crops are 100% under irrigation, such as rice (180,971 ha), sugar cane (7,422 ha), and vegetables under protected cultivation (1,045 ha) (Arenare et al., 2018).

Based on previous descriptions by FAO (2016) and other studies that will be reported here, it is clear that agriculture is a major water consumer in most countries and that there is a broad range of the percentage of consumptive water use dedicated to the irrigation of agricultural land in LAC, from 43% to 86% (Table 1). In some countries in the Caribbean Region, such as The Dominican Republic, Grenada, and Trinidad and Tobago, irrigation of agricultural land represents less than 15% of the consumptive water usage.

Table 1. Water consumption by agriculture in some countries in Latin America and the Caribbean region (LAC).

Country	Agricultural land (1,000 ha)[1]	Agricultural irrigated land (1,000 ha)	Agricultural land equipped for irrigation (%)	Consumptive water use of agricultural sector (%)	References
Argentina	148,700	2,100	1,4	73	FAO (2016)
Brazil	350,253	6,950	2.0	67	ANA (2017); FAO (2016)
Chile	15,742	1,100	7.0	85	DGA (2016); Anríquez and Melo (2018)
Costa Rica	560	160	28.6	74	FAO (2016); CTIE-AGUA (2018);
Cuba	2989	558	18.7	65	FAO (2016)
Mexico	106,236	6,076	5.7	76	The World Bank Group, (2016); SIAP, (2017); CONAGUA, (2018)
Panama	2,257	32	1.4	43	CONAGUA (2016)
Paraguay	4,585	136	3.0	56	FAO and IICA (2017)
Peru	38,742	7,125	18.4	86	INEI (2012)
Uruguay	14,450	251	1.7	77	Dell´Acqua and Yussim (2016); MVOTMA (2017); Arenare et al. (2018)

Interestingly, some negative impacts of irrigation on soil and water quality have been previously observed, further demonstrating that excessive irrigation may exacerbate soil salinization and nonpoint pollution of surface water in some countries in LAC.

In most LAC countries, the area under irrigation has expanded over time, and an increasing urban population will add pressure to relocate water from the agricultural sector to the urban drinking water supply (CEPAL, 2012). In addition, our results are consistent with previous reports that barriers to the adoption of innovative irrigation technologies are due to the heterogeneous socioeconomic characteristics of farmers, such as education levels and access to investment and financing credits (Villa-Cox et al., 2017). Levidow et al. (2014) noted that under current conditions, agricultural water management will be maintained at the unknown WUE level, and farmers will have weaker incentives to develop more efficient practices. Therefore, the authors call for a continuous knowledge exchange, based on which all relevant stakeholders can share greater responsibility across the entire water supply chain. It is important to note that these restrictions will be worse due to the impact of climate change on agricultural systems in LAC countries, a topic that will be addressed with examples in the following section.

Potential implications of global climate change for agricultural water management in Latin America and the Caribbean region

Reyer et al. (2017) noted that LAC will be severely affected by climate change, even under lower levels of global warming. Although it is possible that, at the beginning, moderate warming of the planet could favor crop production in temperate regions, eventually it will generate negative impacts in the semiarid and tropical regions of LAC. In this sense, if global warming progresses past 2050, the agricultural productivity of all LAC countries will be negatively affected (Tubiello & Rosenzweig, 2008). Local climate change scenarios in the LAC region are predicted to be the following:

Argentina

According to the Third National Communication of the Argentine Republic to the United Nations Framework Convention on Climate Change, it is likely that in the near future (2015–2039), the productivity of the main grain crops in Argentina's production areas will be maintained or even improved due to increasing CO_2 concentrations as a result of climate change. For much of northern and central Argentina, the higher temperatures projected for the next few decades, together with the continuation of the interdecadal variability of precipitation and the prolongation of the dry winter period, will create a need for better management of water resources. Likewise, it will be necessary to improve water management in the Pampas region to reduce the area and duration of waterlogging and the number of flood periods. In the cases of irrigation, there is a risk that the water supply will be reduced and exhibit greater seasonal availability.

The Study of the Potential for Expansion of Irrigation in Argentina (FAO, 2015) reported that in the face of the scenarios of higher temperature and lower availability of water resources, if investments are not made in current irrigation systems, production reductions, evaluated as equivalent to surface area losses, would amount to 325 thousand hectares, corresponding to 72% of the irrigated area with surface water and 28% of that irrigated with groundwater. For rainfed crops, management practices such as fallows, crop rotation, reduced tillage, and cover crops increase water availability and improve adaptation to water stress conditions (Álvarez et al., 2013; Bertolotto & Marzetti, 2017), especially in arid and semiarid areas. This technical knowledge is not being applied in all cases, and climate change adaptation programs will be an opportunity to increase its application (SAyDS, 2015). All this indicates that the management of productive systems and the adequate management of water resources will be a central aspect of climate change adaptation in Argentina.

Brazil

Climate change has caused reduced rainfall distribution and increased environmental temperatures, intensifying and prolonging periods of drought in Northeast, Southeast, and Midwest Brazil (Marengo, 2018; Cunha et al., 2019). This affects water availability, promoting a crisis of supply and availability in various economic sectors, especially agriculture. However, rainfall is also increasing. For instance, it has been observed that rainfall distribution patterns in Brazil are increasing, creating extreme events of excess or scarcity of water in recent decades (Silva Dias et al., 2013; Zandonadi et al., 2016). According to the National Water Agency (ANA, 2017), this phenomenon may be associated with the effect of climate change; approximately 85% of natural disasters were caused by droughts and floods, affecting 127 million people between 1991 and 2012. In economic terms, it is estimated that total losses were approximately USD$ 43.5 billion during 1995 and 2014 (CEPED, 2016).

Chile

Bozkurt et al. (2018) highlighted that in central and southern Chile (latitude ~ 30–45° S), drying and warming are likely to continue and strongly impact the future hydroclimatic conditions of agroecosystems and as such aggravate water stress due to climate change. They evaluated climate change scenarios with projected warming ranging from ~ + 1.2 °C to ~ +3.5 °C and decreases in precipitation from ~ − 3% to ~ − 30%. Similarly, Cabré et al. (2016) predicted a significant decrease in precipitation, and an increase in temperature over central and southern Chile

Costa Rica

In 2008, Costa Rica's National Meteorology Institute's (IMN, 2008) report on climate change predictions highlighted important differences throughout the country due to topography, mostly the two main slopes created by the central mountainous system: the Pacific slope and the Caribbean slope. Increases in temperature from 1.08 °C to 7.92 °C are predicted by the end of the century, as compared to the temperature from 1961–1990. In the same period, along the Caribbean Coast, it is likely that precipitation will increase up to 49%, while for the Pacific Coast and the central area, a precipitation reduction of up to 56% is expected. These scenarios will be accompanied by variations in cloud elevation and moisture stress in the tropical forest region, which will lead to less water production (Kalmakar et al., 2008; Lyra et al., 2016).

The effects of climate change will lower the yields of several agricultural products (Ordaz et al., 2010), including rice, beans and corn, which are the basic products in the National Plan for Food Security (SEPSA, 2016). The registered temperature for 2006 already exceeded the optimal temperature for crop yield in the country; for precipitation, the amount registered for 2006 was lower than the optimal value; the expected increase in temperature and decrease in precipitation due to climate change will then worsen these already suboptimal conditions (Ordaz et al., 2010). The North Pacific Coast, part of the Central American Dry Corridor, will be one of the most critical points; the area has already experienced prolonged dry periods (Peralta-Rodríguez et al., 2012) and with an economy weaker than the country's average (Gotlieb et al., 2019), the region is more vulnerable. In the whole agricultural sector, losses equivalent to 4% to 12% of 2007 GDP are expected as a consequence of climate change (Ordaz et al., 2010), and repercussions for food security may be expected as well (Gotlieb et al., 2019).

Cuba

The relative scarcity of water in the country has been aggravated by the occurrence of natural phenomena such as prolonged droughts and seasonal changes. Water scarcity is further exacerbated by losses in hydrological networks, which in some areas can reach up to 60% of the volume delivered, and the occurrence of prolonged meteorological droughts that affect actual water availability. Drought events have been significantly increasing in frequency and occurring consistently in Cuba, as demonstrated by the droughts that have affected eastern Cuba from the early 1990s to the present day, including the very serious drought that occurred from May 2003 to May 2005 (Planos et al., 2013).

This combination of factors demonstrates the urgent need to closely monitor drought events, which, combined with high evaporation rates, cause the depletion of soils and a decrease in groundwater reserves. A historical analysis indicated that the average annual precipitation in Cuba between 1960 and 2000 was 1,329 mm (INRH, 2007). The average annual precipitation decreased by 200 mm (11.4%) during the first half of the 20th century and exhibited greater temporal variability. An analysis of the period between 1970 and 2010 indicated that the average annual precipitation decreased to approximately 1,000 mm, with a cumulative reduction from the first half of the last century of 33.3%.

Mexico

In Mexico, agriculture may be one of the sectors most affected by climate change (Ortiz et al., 2016); some of the impacts associated with temperature variation may be, depending on the region, decreases in yield due to heat stress, an increase in pests and plant diseases, an increase in fires, and a decline in water supply and water quality. More extreme events are predicted, such as more intense precipitation and drought, hailstorms and hurricanes, all of which will severely affect crops and aggravate soil erosion (SAGARPA & FAO, 2012).

Several studies have presented worrisome scenarios related to changes in the hydrological cycle in the country. A decrease in precipitation (~ -15% annual national average) is expected. As a result, surface runoff and aquifer recharge will decrease, and therefore, the availability of water will be reduced, which will add to water stress, especially with the population growth that is expected in the 21st century (Martínez-Austria & Patiño-Gómez, 2012). Higher values for potential evapotranspiration due to increased temperatures and decreased relative humidity are expected, which would expose crops to higher thermal stress. An increase in the percentage of land area that is unsuitable for corn cultivation due to the limiting factor of soil moisture availability of between 63.3% and 90.8% is estimated, assuming large population growth and weak economic development in the period from 2041 to 2060 (Tinoco-Rueda et al., 2011).

Therefore, the expected temperature increase based on the most likely climate change scenarios will have important repercussions for the global and local hydrological cycle and, consequently, on the availability of water resources (Martínez-Austria & Patiño-Gómez, 2012), which has been diminishing due to increasing population growth. The mean availability of water per capita in 1955 was 11,500 m^3 $person^{-1}$ yr^1, and by 2025, this quantity is estimated to be 3,500 m^3 $person^{-1}$ yr^1. In some regions, such as Baja California and the Bravo River Peninsula, the availability per inhabitant will be less than 1000 m^3 per year. It is predicted that water will be even more scarce in arid and semiarid areas (IMTA, 2007).

Paraguay

The effects of climate change that the country is currently experiencing could irreversibly damage the natural resource base on which agriculture and livestock production so strongly depend. The main growth engine for the Paraguayan agricultural sector has been the production and exports of soybeans, corn, and wheat, as well as livestock, all profitable activities. Risks to grain production in Paraguay are mainly due to agroclimatic factors and, to a lesser extent, to the incidence of pests and diseases.

The main risk factor for soybeans (the most economically important commercial crop in the country) is drought in the summer months (mainly in January), which is exacerbated by high temperatures and enhanced in production areas with soils with less water retention capacity (for example, relatively sandy soils in San Pedro and Canindeyú). The impact of drought on the soybean crop was significant in 2005, 2008 and 2011, when the average yield, both locally and nationally, was greatly reduced. Complementary irrigation to mitigate drought risk is not always an option due to frequent power cuts or changes in voltage tension (The World Bank Group, 2014).

Peru

According to The World Bank Group (2013), changes in climatic factors observed between 1960 and 2006 at the national level indicate that temperature is increasing, while rainfall does not exhibit a clear trend. Projected climate for large regions of the country still has a high degree of uncertainty, and information about the potential effect on agriculture in general and water availability in particular is limited. Existing projections for 2030 foresee a general increase in temperature, while predicted direction of change in rainfall is variable. According to the Ministry of Agriculture and Irrigation (MINAG) projections (MINAG, 2012) for 2030, no major impacts on yields of crops important to the country's food security are expected on the north coast, since any increases in temperature in that region would be offset by an increase in rainfall in the middle and upper parts of the basins. However, significant changes in yield in the mountains and jungle are expected. On the central and southern coasts, production may be affected by an increase in water stress, indicating that special attention should be given to the management of water resources and irrigation systems in these areas.

Regarding extreme events, the observed trends indicate that the El Niño-Southern Oscillation (ENSO) is becoming more intense and frequent compared with previous decades. For this reason, a greater impact is anticipated. Depending on the region, flood, droughts and heat waves may occur. These factors will have an impact on agricultural production and irrigation infrastructure (MINAG, 2012). The projections of extreme events are still debatable and questionable (MINAG, 2012).

Another effect of climate change on irrigated agriculture is the reduction in the surface area of glaciers and moors, which would result in a reduction in the natural capacity for water storage. This may result in a decrease in river flow at times of low flow (accentuating droughts) and an increase in peak flows in the rainy season (generating a greater risk of flooding). On the other hand, the artificial storage capacity of Peru is approximately 160 m^3 per capita, equivalent to 7% of the average for Latin America (ANA, 2013). Both the artificial and natural storage capacity are decreasing due to the aforementioned melting of the glaciers, degradation of the moors, progressive sedimentation in reservoirs, low investment in new storage infrastructure and lack of protection of the upper basins and its land and water resources (ANA, 2013).

Uruguay

Giménez et al. (2009) and Bidegain et al. (2012) carried out a statistical study of climate data to identify trends and their relation to climate change in Uruguay. Using regression analysis, they found that precipitation in spring and summer tended to increase in comparison with historical data, while water shortage events showed a tendency to decrease. Although in the last decade of the 20th century there were extreme water scarcity events reported in some periods, the impact of water scarcity is also related to the resistance of the crop to water stress (Bidegain et al., 2012). Giménez et al. (2009) reported that during the last century, the maximum air temperature decreased, mainly during the summer period, while the minimum air temperature increased in all seasons.

In terms of projections of extreme events, a greater number of heat waves in future decades is predicted (Bentancur & Molinari, 2019). Regarding extreme precipitation events, based on these projections, there will be a slight increase in the southern region, and no change to the frequency of those events in the northern region (Bentancur & Molinari, 2019). According to the models, the frequency of extreme precipitation events the warm season may be double that in the cold season. The projections for water deficit predict a decrease that will be more pronounced in the cold season (Bentancur & Molinari, 2019).

Therefore, in LAC, impact of climate change on crop productivity may vary greatly, depending on the specific crop and region. Although climate change will generally reduce agricultural yields, there may be exceptions to this, such as an increase in rice yield in several LAC countries (Reyer et al., 2017). In the southeastern part of South America, crop productivity may be maintained or even increased by 2050, while in central America, crop productivity decrease in the next 15 years, creating a risk to food security for the poorest habitats of the region (Field et al., 2014). For instance, Jones and Thornton (2003), in one of the first works about the effect of climate change on maize production in LAC, predicted that the maize yield in 2055 in the mesic subtropical cold winter environment will be higher due to an increase in temperature, while in the dry tropical environment, the yield will decrease due to a reduction in precipitation. Spinoni et al. (2019) reported several drought hotspots affected by climate change in Amazonia and southern South America, resulting in increased water scarcity and direct effects on agricultural production in these areas in recent decades.

It has been shown in this section that climate change will significantly impact water availability for agricultural production in LAC. Further research is urgently needed to improve agricultural water management through, for instance, the application of nuclear and isotopic techniques that may help to increase WUE.

Application of nuclear and isotopic techniques to evaluate water use efficiency in crop production

Improving WUE in crop production requires an increase in crop water productivity, which is an increase in the marketable crop yield per unit of water used by the plant and a reduction in water losses from the plant rooting zone (Hatfield & Dold, 2019). Soil water can be lost from the soil surface through soil evaporation (E) or plant transpiration (T). The combined processes are referred to as evapotranspiration (ET). Water can also be lost through runoff and deep infiltration through the soil. This can be due to rainfall events, excessive application of irrigation or management practices. Information on ET can help to identify factors affecting E and T under different irrigation management practices, crop species and growth stages, which is essential for improving the WUE of crops.

Many methods are available to quantify water loss from the plant rooting zone and partition total ET as a component of soil evaporation and crop transpiration, including the eddy covariance method, mini-lysimeters and canopy cover determination (Evett et al., 2012). However, the dynamic nature of E and T poses a challenge to some of the above methods.

Stable isotopes of the atoms that make up water (hydrogen and oxygen) can exist as light and heavy isotopes. These isotopes can be used to identify water losses through E from the soil surface since light isotopes (^1H and ^{16}O) evaporate more readily than heavy isotopes (^2H and ^{18}O). The natural isotopic ratios of hydrogen ($^2H/^1H$) and oxygen ($^{18}O/^{16}O$), which are often expressed as delta units (δ^2H and $\delta^{18}O$) in soil water, water vapor within the plant canopy and plant leaves, can provide estimates of T, and water lost through E (Wang & Yakir, 2000; Yepez et al., 2003; Kool et al., 2014).

Two isotopic approaches using stable isotopes containing water (^{18}O and ^2H) are generally used. The Keeling plot (Keeling, 1961) and isotopic mass balance (IMB) (Hsieh et al., 1998; Ferretti et al., 2003) methods have been used to help identify factors that minimize soil evaporation losses and improve irrigation management. The Keeling plot method is based on the isotopic mass balance mixing relationship of atmospheric water vapor above and below the crop canopy. Atmospheric water vapor samples taken within the mixed boundary layer are assumed to represent a mixture of isotopes and concentrations between the background atmosphere and the evaporating surface of the crop. The IMB method is based on the mass balance of water (initial and final plus water added as irrigation or rainfall and those lost as evaporation and transpiration), as well as the conservation of isotope mass balance in the system.

There are few reports discussing the application of the nuclear and isotopic techniques mentioned above for the determination of WUE in LAC countries. Most of studies of nuclear and isotopic techniques have been carried out within the framework of projects with the International Atomic Energy Agency (IAEA) and FAO to develop sustainable management strategies for food security for farmers in LAC countries, as reported in the literature:

In Argentina, studies of nuclear and isotopic techniques have focused on hydrology, geology, soil fertility, environmental pollution, climate change and other areas in the natural sciences. However, there have been few published reports related to the application of these techniques to calculate WUE. The Agronomic Applications Division of the National Atomic Energy Commission (CNEA) has studied N balance and water in agroecosystems using these techniques.

In Brazil, studies on tropical trees performed simultaneous analysis of bulk $\delta^{13}C$ on tree rings, $\delta^{13}C$-CO_2 and atmospheric $CO_{2,}$ and based on the evaluation of the effect CO_2 level on the tree rings, found it was correlated with an improvement in the WUE. In addition, Bertholdi et al. (2018) suggested that $\delta^{13}C_{leaf}$ values have a negative relationship with stomatal conductance, which is directly related to WUE.

In Costa Rica, most of the studies applying nuclear and isotopic techniques (mostly $\delta^{18}O$ and δ^2H) were performed to understand water movement (precipitation origin and patterns) and aquifer recharge. Some recent studies have addressed the isotopic characterization of precipitation throughout the country (Sánchez-Murillo et al., 2016a), the influence of moisture on the coasts, and variations due to atmospheric phenomena such as *El Niño* (ENSO) (Sánchez-Murillo et al., 2017; Esquivel-Hernández et al., 2019).

To our knowledge, only a few studies have focused on crop WUE; currently, project B8-512 from the University of Costa Rica has been working to calculate the evapotranspiration partition using the AquaCrop model to estimate WUE for two varieties of the bean *Phaseolus vulgaris* under different irrigation conditions and validating this information with $\delta^{18}O$ and δ^2H data for evapotranspiration partitioning.

Some studies have been published in Cuba using water isotopes to obtain information about groundwater. For example, Peralta et al. (2015) used nuclear and isotopic techniques to characterize the karst aquifer of the Artemisa - Quivicán subbasin, which constitutes an important water source that supports agricultural development in the provinces of Artemisa and Havana. These authors used isotopes ($\delta^{18}O$ and $\delta^{2}H$) as natural tracers to assess the renewal of water in the aquifer (recharge), identify the origin and age of the waters, and describe the existing hydraulic interconnections with other aquifers and occurrence of saline intrusion, which led to proposals of sustainable measures for the use of the aquifer.

In Mexico, the isotopic techniques that have been used in hydrology have mostly focused on the study of groundwater, for instance, the origin of aquifer recharge with $\delta^{18}O$ and $\delta^{2}H$, water quality, contamination sources, the origin of geothermal waters, hydrogeology and surface flow using $\delta^{13}C$ (Felstead et al., 2015; Robertson et al., 2017). On the other hand, Goldsmith et al. (2012) used $\delta^{2}H$ and $\delta^{18}O$ to trace water inputs and fluxes in a seasonally dry tropical montane cloud forest in Veracruz, Mexico. Other studies have focused on the relationship between carbon isotope discrimination and grain yield in wheat under different water regimes, such as those carried out by Xu et al. (2007) and Monneveux et al. (2005). However, few studies have utilized these isotopic techniques to evaluate WUEs in crops.

In Peru, there is little research on isotopic techniques to evaluate the efficient use of water in agricultural production. In recent years, δ18° and δ2H isotopic techniques have been utilized in the study of hydrodynamics and aquifer recharge (Valencia, 2014, 2016).

In Uruguay, Berriel et al. (2014) applied the technique of carbon isotope discrimination ($\Delta^{13}C$) to compare the WUE of three species from an improved meadow in Uruguay. In this study, it was shown that the $\Delta^{13}C$ indicator is useful for assessing the impact of water deficit on productivity and changes in the floristic composition of mixed grasslands because this indicator is capable of integrating the water status of plant species. Berriel et al. (2019) studied the WUE of two different cover crops, *Crotolaria juncea* and *Crotolaria spectabilis*, under controlled conditions (without water limitations and with drought events). The results showed that *C. spectabilis* possessed a higher WUE than *C. juncea*. In addition, in both species, a negative linear relationship was found between WUE and $\Delta^{13}C$ ($r=0.8$; $p<0.0001$). These results would allow the use of the carbon isotope discrimination technique to evaluate *Crotolaria* species in the field. In addition, this study found that *C. spectabilis* could be recommended as a cover crop under conditions of moderate water deficit in temperate zones such as Uruguay.

Thus, related to the water topic in most LAC countries, nuclear and isotopic techniques have been mainly utilized in the study of hydrodynamics and aquifer recharge. Although there is an urgent need to raise efficiency by increasing crop productivity and reducing water consumption in LAC, there are some countries that have not developed studies on the application of nuclear and isotopic techniques to evaluate WUE in crop production. Clearly, LAC countries differ in terms of the application of nuclear and isotopic techniques, due to the lack of equipment and resources in local research agencies. In addition, information on the WUE of different irrigation technologies and the process of E and T under different climatic conditions and crop management using, for instance, Keeling Plot or IMB, is often unavailable in LAC. Research into the application of nuclear and isotopic techniques to evaluate WUE in crop production is therefore crucial to increase our understanding of wise water usage in LAC countries.

Conclusions

Agriculture is a major water consumer in LAC countries, where consumptive water use by irrigated agricultural land ranges between 35% and 86% of the total. Negative impacts of irrigation on soil and water quality have been reported, further demonstrating that excessive irrigation may exacerbate soil salinization and nonpoint pollution of surface water. Since agriculture is the main consumer sector of water, it represents a prime area for the implementation of adaptation strategies to improve the quantity and quality of available water. Additionally, climate change increases climatological and hydrological uncertainty, making planning and design of hydraulic infrastructure, as well as reservoir operation, more difficult.

In most LACs, water scarcity is not only due to population increases and the effects of climate change, but also due to poor resource management. Therefore, in the LAC, there is a need for innovative cultivation systems and alternative crops that are more suitable for the new hydrological and climatological conditions expected in each region, offering new opportunities for the economic development of the most affected areas. The impact of climate change may lead some LAC countries to intensify and expand agricultural activities, which could affect their vulnerability due to the deterioration of the physical and/or chemical qualities of soil and water, as well as the loss of biodiversity.

Nuclear and isotopic techniques offer new opportunities to evaluate WUE in crop production in LAC countries using Keeling Plot or IMB methods. They can play an important and sometimes unique role in providing essential information related to the loss of soil water from the surface through E or through T in order to develop strategies aimed at improving agricultural water use efficiency and, hence, providing solutions for mitigating an increase in water scarcity. Therefore, it is urgent that studies that apply nuclear and isotopic techniques to evaluate WUE in crop production in LAC countries be conducted.

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Resumen

O. Salazar, C. Chinchilla-Soto, S. de los Santos-Villalobos, M. Ayala, L. Benavides, V. Berriel, R. Cardoso, E. Chavarrí, R. Meigikos dos Anjos, A.L. González, A. Nario, A. Samudio, J. Villarreal, R. Sibello-Hernández, y J. Govan, L. Heng. 2022. Consumo de agua por la agricultura en América Latina y el Caribe: impacto del cambio climático y aplicaciones de técnicas nucleares e isotópicas. Int. J. Agric. Nat. Resour. XX-XX. El objetivo principal de esta revisión es examinar el consumo de agua por la agricultura en las regiones de América Latina y el Caribe (LAC) para comprender cómo el cambio climático afectará la disponibilidad de agua y cómo la aplicación de técnicas nucleares y de isótopos estables se puede utilizar como herramientas para mejorar el uso del agua (WUE) para la producción de cultivos. También se revisa el estado de la gestión en la agricultura del agua en algunos países de la LAC, como Argentina, Brasil, Chile, Costa Rica, Cuba, México, Panamá, Paraguay, Perú y Uruguay. En la región de LAC, el consumo de agua para riego agrícola varió entre el 35 % y el 86 % del total de agua disponible. Sin embargo, la WUE es muy baja en algunos países de LAC. Aunque la región, en general, cuenta con recursos hídricos adecuados, aún existe la necesidad de mejorar la EUA para aumentar la productividad del agua para la agricultura. El impacto del cambio climático en algunos países de LAC puede conducir a la intensificación y expansión de la actividad agrícola. En estas áreas, la EUA se puede mejorar a través de la conservación del suelo y el agua, minimizando la evaporación del suelo (E), así como a través de una mejor gestión del riego, especialmente mediante el uso de un enfoque integrado en toda el área para gestionar todas las actividades de uso de la tierra y la agricultura dentro de una cuenca. Las técnicas nucleares y de isótopos estables que utilizan los métodos Keeling Plot o IMB pueden desempeñar un papel importante en la mejora de la WUE en la agricultura en los países de LAC al proporcionar información relacionada con las pérdidas de agua del suelo para mejorar los sistemas de riego.

Palabras clave: Eficiencia en el uso del agua, manejo del agua agrícola, riego, uso consuntivo del agua.

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