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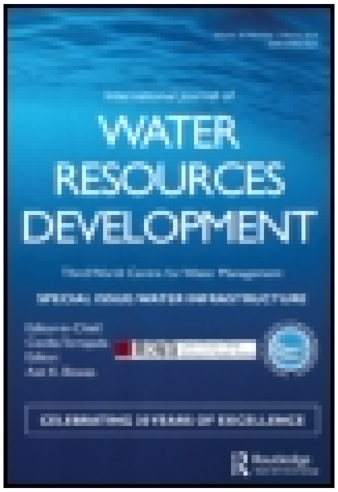

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Water footprints and irrigated agricultural sustainability: the case of Chile

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Water footprints and irrigated agricultural sustainability: the case of Chile

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ABSTRACT

This paper estimates the agricultural production water footprint (WF) of Chile, assessing green, blue and grey WFs of the main agricultural products for the main productive regions, taking into account climatic and soil differences. Chile's agricultural production blue WF is geographically concentrated in the lower portion of the Northern Dry Pacific and Central Chile area, which present less water availability. Thus, irrigated agricultural production in Chile, a semiarid country, is characterized by high water stress. In this scenario, public policies are required to incentivize better water management in order to reduce water vulnerability while boosting development.

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Agricultural water footprint; water productivity; crop consumptive water use; Chile

Introduction

In the wake of population growth and economic development there is increased pressure on the demand–supply imbalance of global water resources. Water shortage has become an important limiting factor for sustainable development in many nations. Moreover, water availability has been identified as one of the most important constraints for food production (Gerbens-Leenes & Hoekstra 2012; Gerbens-Leenes, Hoekstra, & van der Meer, 2009; Yang & Zehdner, 2002), economic development and growth (Bates, Kundzewicz, Wu, & Palutikof, 2008; Sullivan, 2002), and poverty reduction (Barker, van Koppen, & Shah, 1999; Bhattarai, Sakthivadivel, & Hussain, 2002; Lawrence, Meigh, & Sullivan, 2002).

In Latin America, water availability is being threatened by several factors. These include population growth, rapid urbanization, water contamination and increased water demands. Chile as a whole may be considered privileged in terms of water resources. The average total runoff is equivalent to 53,000 m^3/person/year, a value considerably higher than the world average (6600 m^3/person/year) (World Bank, 2011). However, there are significant regional differences: from Santiago to the north, arid conditions prevail with average water availability below 800 m^3/person/year, while south of Santiago water availability is significantly higher reaching over 10,000 m^3/person/year (see Figure A1 in the supplemental data online at http://dx.doi.org/10.1080/07900627.2015.1070710). Water withdrawals in Chile average

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approximately 4000 m^3/year (World Bank, 2011). Of this, almost 85% is used in non-consumptive hydroelectric generation. Consumptive water use in Chile is dominated by irrigation with 73% of consumptive water use. Thus, agricultural production is the greatest consumptive water user in Chile, which is the case in most developing nations (Molden et al., 2007).

In this scenario, decoupling agricultural production from water use is at the core of innovative strategies for efficient resource use and overall economic growth. At an aggregate level, countries with higher income levels tend to show higher water consumption (Donoso et al., 2014; Sullivan, 2002), while the lack of appropriate and reliable water supply is related to low national income levels (Lawrence et al., 2002). Therefore, Chile needs to adjust its agricultural processes so as to be less dependent of water availability.

To allow Chile to become a less vulnerable country in terms of water availability variations, public intervention is required. Policy-makers must focus their work on diminishing water usage while encouraging economic growth. Thus, knowledge about the availability of water and each economic sector's water use is crucial. The public sector must have detailed information of how water is managed so as to make the most effective decisions.

A useful tool to address the demand–supply imbalance of global water resources is the water footprint (WF). It is an indicator of freshwater use that decomposes water consumption into three corresponding categories: blue, green and grey. Blue WF refers to the volume of surface and groundwater consumed as a result of the production of a good or service. Green WF, on the other hand, is the volume of rainwater consumed during the production process. This is particularly relevant for agricultural and forestry products, where it refers to the total rainwater evapotranspiration. The third component, grey WF, is an indicator of freshwater pollution that can be associated with the production of a product over its full supply chain. It is defined as the volume of freshwater required to assimilate the load of pollutants based on natural background concentrations and existing ambient water quality standards. It is calculated as the volume of water required to dilute pollutants to such an extent that the quality of the water remains above agreed water quality standards.

WFs have gained attraction in policy circles in several countries such as India, the Netherlands, North Africa and Spain (Antonelli & Tamea, 2015; Chahed, Besbes, & Hamdane, 2015; Wichelns, 2013). This indicator was introduced as a concept by Hoekstra and Hung (2002). It is derived from the concept of an ecological footprint (Wackernagel & Rees, 1996), which refers to the bio-productive area necessary to maintain a population. The WF analysis provides a multidisciplinary framework for informing water policy decision-makers (De Stefano and Llamas, 2012; Aldaya et al., 2008).

However, Wichelns (2011, 2013) cautions that when determining optimal water policy, water volumes determined by WF estimation alone are not sufficient indicators of the benefits or costs of water use; information is needed about the opportunity costs of water in each setting and use. Thus, current WF estimates only contain limited information about water use, providing no information about the impact of that footprint. Therefore, WF data need to be complemented with information regarding the sources and quantity of water used (Jewitt, 2009; Pfister, Koehler, & Hellweg, 2009).

Additionally, Witmer and Cleij (2012) point out that the WF indicator on its own is unsuitable for use in policy-making in relation to sustainability, given that consumed water volumes do not reflect the environmental impact of the production process. These authors nonetheless, emphasize that when WF components are placed in their geographical and water basin context, comparing them with their basin water supply, unsustainable production processes can be found. Furthermore, Dickin (2013) stresses that groundwater flow information should be used to refine the WF concept to emphasize the renewable or non-renewable components. Bearing in mind these limitations, this paper compares geographic estimates of blue WF with average water flows considering different geographical areas, thus taking into account hydrological conditions.

Traditional and conventional approaches to water management have focused on managing solely the blue component of the water cycle (Vanham & Bidoglio, 2013). However, as Vanham (2012) points out, it is important to include green water in water management analysis too. Following these considerations, this paper additionally assesses the regional green WF of the main agricultural products for the main productive regions, comparing them with regional average rainfall.

The three WF components have already been estimated for Chile. Mekonnen and Hoekstra (2011) estimate the aggregate production WF of different agricultural products by applying a high spatial resolution, indicating that it reaches 15.82 Gm^3/year. The main water user corresponds to agriculture, representing 75% of the aggregate production WF. This estimation, however, was conducted at the national level with a crop water-use model at a 5 × 5 arc minute spatial resolution, neglecting regional differences such as soil characteristics and properties and the climatic data of each productive region. This is particularly relevant for Chile, since, as has already been stated, the country's unique geography provides a variety of soil and climatic conditions. Therefore, any WF analysis must acknowledge and include these aspects so as to guide policy-makers in the right direction.

Thus, the objective of this paper is to estimate the green, blue and grey WF of the main agricultural products for the main productive regions of Chile, taking into account climatic and soil differences and comparing these with green and blue water supplies, so as to identify high water-stress areas.

WF estimation material and methods

Two main approaches for the assessment of WF exist in the literature: (1) the approach developed by the Water Footprint Network (Hoekstra, Chapagain, Aldaya, & Mekonnen, 2011) and (2) the life cycle analysis approach (Postle, George, Upson, & Hess, 2012). This study employs the approach developed by the Water Footprint Network because it considers soil, climatic and productive differences of the country.

Following Hoekstra, Chapagain, Aldaya, and Mekonnen (2009), estimations were performed to obtain the three components of the agricultural production WF:

- Green (WF_{green}).
- Blue (WF_{blue}).
- Grey WF (WF_{grey}).

Blue WF estimation methodology

WF_{blue} measures the amount of water available consumed in a certain period. Therefore, the blue WF in a process step is calculated as according to Hoekstra et al. (2009):

$$WF_{\text{blue}} = Blue\ Water\ Evaporation + Blue\ Water\ Incorporation + Lost\ Return\ flow \quad (1)$$

More specifically, the blue component of a crop in a specific region WF (m^3/ton) is calculated as follows:

$$WF_{i\text{blue}} = \sum_j \frac{C_{WU\text{blue}ij}}{Y_{ij}} = \sum_j \frac{10 \times \sum_{d=1}^{n} E_{T\text{blue}ij}}{Y_{ij}} \quad (1a)$$

where $WF_{i\text{blue}}$ is region *i*'s total agricultural blue WF; Y_{ij} represents crop *j*'s yield in region *i* (tons/ha); $C_{\text{WUblue}ij}$ represents crop *j*'s blue water use for region *i* (m^3/ha); and $E_{T\text{blue}ij}$ is crop *j*'s total blue evapotranspiration for region *i*, which is estimated with CROPWAT following Allen, Pereira, Raes, and Smith (2006), considering region *i*'s specific soil and climatic conditions. Thus, Chile's total agricultural blue WF is:

$$WF_{\text{blue}} = \sum_i WF_{i\text{blue}} = \sum_i \sum_j \frac{10 \times \sum_{d=1}^{n} E_{T\text{blue}ij}}{Y_{ij}} \tag{1b}$$

Green WF estimation methodology

Green WF is an indicator of the productive use of precipitation stored in the soil or which temporarily stays on top of the soil or vegetation. Hence, green WF is as follows (Hoekstra et al., 2009):

$$WF_{\text{green}} = Green\ Water\ Evaporation + Green\ Water\ Incorporation \tag{2}$$

The regional green component is calculated adding each crop's WF (m^3/ton):

$$WF_{i\text{green}} = \sum_j \frac{C_{WU\text{green}ij}}{Y_{ij}} = \frac{10 \times \sum_{d=1}^{n} E_{T\text{green}ij}}{Y_{ij}} \tag{2a}$$

where $WF_{i\text{green}}$ is region *i*'s total agricultural green WF; Y_{ij} represents crop *j*'s yield in region *i* (tons/ha); $C_{\text{WUgreen}ij}$ represents crop *j*'s green water use for region *i* (m^3/ha); and $E_{T\text{green}ij}$ is crop *j*'s total green evapotranspiration for region *i*, which is estimated with CROPWAT following Allen et al. (2006), considering region *i*'s specific soil and climatic conditions. Chile's total agricultural green WF is therefore:

$$WF_{\text{green}} = \sum_i WF_{i\text{green}} = \sum_i \sum_j \frac{10 \times \sum_{d=1}^{n} E_{T\text{green}ij}}{Y_{ij}}. \tag{2b}$$

Each crop's $E_{T\text{green}ij}$ and $E_{T\text{blue}ij}$ is multiplied by 10 in order to transform each crop's green and blue water use to m^3/ha. More specifically, crop *j*'s evapotranspiration (mm/day) in region *i* under standard conditions, E_{Tcij}, and under non-standard conditions, such as reduced yields, E_{Tcakij}, is estimated as follows:

$$E_{Tcij} = E_{Toij} * K_{yij} \tag{3a}$$

$$E_{Tcakij} = E_{Toij} * K_{yij} * K_{si} \tag{3b}$$

where E_{Toij} represents crop's *j* reference or potential evapotranspiration for region *i*; K_{yij} is crop *j*'s productivity response factor in region *i*; and K_{si} is region's *i* water stress coefficient.

E_{Toij} and K_{yij} for each crop *j* and region *i* were estimated for each of the 15 Chilean political regions with data obtained from the Natural Resources Information Center (CIREN) and FAO (2013, 2008a, 2008b, 2008c), while K_{si} was calculated as:

$$K_{si} = \frac{A_{DTi} - D_{ri}}{(1 - p_i)A_{DTi}} \tag{4}$$

where A_{DTi} signifies the total water available in the plant's root zone (mm) for each region i; D_{ri} is region i's moisture depletion in the root zone (mm); and p_i represents the A_{DT} fraction that a crop can extract in the root zone without suffering water stress. The required soil characteristics and properties for each geographical area were extracted from Luzio and Alcayaga (1992).

Grey WF estimation methodology

The grey WF, on the other hand, is estimated with CROPWAT as follows:

$$WF_{greyij} = \frac{\frac{(\alpha_i \times A_{Rij})}{(C_{\mathrm{max}i} - C_{\mathrm{nat}i})}}{Y_{ij}} \tag{5}$$

where A_{Rij} is crop j's application level of the contaminant (kg/ha) in region i; α_i indicates region i's runoff and leaching fraction of the contaminant (%); $C_{\mathrm{max}i}$ is the quality standard that specifies the maximum allowable concentration (mg/L) in region i; and $C_{\mathrm{nat}i}$ represents the natural concentration of the contaminant (mg/L) in region i.

Following Hoekstra et al. (2009, 2011), nitrogen is the contaminant employed to estimate the grey WF. Due to the lack of information on the leaching run-off fraction of nitrogen for different geographical regions of Chile, we assumed it to be 10% for all regions, following Chapagain, Hoekstra, Savenije, & Gautam (2006). This assumption tends to over (under)-estimate grey WF in the north (south) of Chile. This is because nitrate contamination is not expected to be an important agriculturally diffuse pollution problem in the north due to the restricted transport mechanism of the contaminant given the hydrological deficit, which characterizes this area (Donoso, Cancino, & Magri, 1999). In the centre and south of Chile, on the other hand, there is an increased transport of nitrates through surface runoff and percolation due to the fact that average rainfall increases, irrigation practices are characterized by lower efficiencies and nitrogen consumption is greater, in relation to the north zone (Donoso et al., 1999).

The quality standard for nitrogen for each geographical location was obtained from DS 90-2000 (2000) of the Environmental Ministry of Chile, which establishes the maximum allowable contaminant concentration for continental and marine waters of Chile. The natural nitrogen concentration was obtained from Donoso et al. (1999). Nitrogen fertilization doses for each agricultural product and region are based on data from Donoso et al. (1999) and Rodríguez (1993); only for olive crops was the nitrogen fertilization doses calculated based on the quantity of nitrogen applied per tree (INIA, 2009). Rodriguez (1993) establishes the required fertilization doses to reach a given crop yield. Thus, based on actual climatic, soil and yield data we estimate the required nitrogen doses.

Agricultural products included in the analysis

The WF is estimated for the main agricultural product categories for the main production regions of Chile based on the Agricultural Census (INE, 2014). The cultivated area of each product category was collected from the Agricultural Census of 2007 (INE, 2007). Specific historic climatic data of each productive region were obtained from the Chilean Meteorological Yearbooks of the Chilean Meteorological Office (Dirección Meteorológica de Chile, 2014).

The main agricultural product categories were selected based on their total surface. The different agricultural product categories were ranked from the highest cultivated area to the lowest. Figure A2 in the supplemental data online presents the main agricultural product categories and their productive surface in relative terms. Forages are the most important

Table 1. Specific products considered.

Products	Agricultural surface of the category with respect to total agricultural surface (%)	Specific products considered	Surface coverage of the category's cultivated area (%)
Cereals	28	Oats Corn Wheat	86.1
Forage	30	Alfalfa Prairies	85.5
Fruits	19	Almonds Blueberries and raspberries Cherries Plum Orange, clementine and lemon Peach Kiwi Apple Walnut Olive Avocado Pear Table grape	87.0
Legumes and tubers	4	Potatoes	75.8
Vineyards	7	Vineyard	99.4
Surface coverage	89	–	–

Source: Own elaboration based on Agricultural Census data (INE, 2014).

agricultural production category, representing 30% of the total cultivated surface. Cereal production is the second most important, followed by fruits, vineyards, and legumes and tubers. These product categories, which represent 89% of the total cultivated surface, are considered in the estimation of Chile's agricultural production WF. The estimation does not consider vegetable, nurseries or seed production.

Within the cereal category, this study considers wheat, corn and oats, which together represent 86.1% of the cereal cultivated area. Potatoes are the only product considered in the legume and tubers category since they represent 75.8% of the category's cultivated area, according to the Agricultural Census of 2007 (INE, 2007). Alfalfa and prairies are the products included in the forage production category; these cover 85.5% of this category's cultivated area.

The fruit species considered within the fruit category are table grapes, avocados, apples, olive trees, walnuts, cherries, plums, peaches, kiwis, almonds, pears, raspberries and blueberries, oranges, clementines, and lemons. These fruit species account for 87% of the total fruit cultivated area. Finally, the total surface of vineyards was considered in this study. Table 1 presents the product categories, the specific crops and their surface coverage of the category's cultivated area.

Results and discussion

Considering the main agricultural production and the different political regions, Chile's total estimated agricultural WF in 2007 was 9.51 Gm^3/year. Of this total, WF$_{blue}$ represents 54.1% (5.15 Gm^3/year), while WF$_{green}$ is 37% (3.52 Gm^3/year) and WF$_{grey}$ accounts for 7.9% (7.5 Mm^3/year) of the total WF. The high values of the blue component of the WF is due to the important role that irrigated agriculture plays in Chile's economy. As stated above, irrigation and other agricultural activities account for almost 75% of the water use.

Table 2. Characteristics of the Northern Dry Pacific, Central Chile and Southern Humid Pacific areas.

	Hydrographic areas		
Item	Dry Pacific	Central Chile	Southern Humid Pacific
Agricultural surface (ha)	174,315.3	983,758.4	565,882.0
Irrigated surface (ha)	109,850.1	899,095.1	84,867.6
Average irrigation efficiency (%)	55.4	51.5	59.6
Rainfall (m^3/s)	810.02	4,882.10	3,2973.00
Average water flow (m^3/s)	45.13	2,767.80	27,604.00

Source: Authors' own elaboration based on CNR (2010); data recollected are from 2006–07 (INE, 2007) and Peña et al. (2011).

Table 3. Crop WF production (m^3/ton) per unit, 2007.

	WF production (Hm^3/ton)			
Crops	Blue WF production	Green WF production	Grey WF production	Total WF production
Cereals				
Corn	5.14	1.11	1.50	7.75
Oats	0.78	5.64	1.74	8.16
Wheat	7.58	7.95	1.99	17.51
Forage				
Alfalfa	0.86	1.51	–	2.36
Prairie	39.48	23.53	–	63.00
Fruit				
Almonds	29.17	3.59	6.13	38.89
Apple	1.87	1.27	0.11	3.25
Avocado	7.87	2.26	1.12	11.25
Berries (blueberry and raspberry)	10.26	2.88	–	13.14
Cherry	14.54	2.73	0.50	17.78
Citrus (orange, mandarin and lemon)	2.24	0.38	0.19	2.80
Grape	2.89	0.25	0.29	3.44
Kiwi	3.15	0.90	0.40	4.44
Olive	13.79	5.93	0.00	19.72
Pear	2.12	0.27	0.15	2.54
Peach	4.07	0.43	0.42	4.92
Plum	2.71	0.37	0.47	3.55
Walnuts	33.72	3.38	3.49	40.59
Legumes and tubers				
Potato	2.06	0.61	0.14	2.81
Vines				
Vinifera grape	44.41	10.73	–	55.15

Source: Authors' own elaboration.

For the purposes of this study, the country was divided into three hydrographic areas in terms of agricultural land, irrigated surface, irrigation efficiency, rainfall and surface water flows: Northern Dry Pacific, Central Chile and Southern Humid Pacific. The characteristics of these areas are presented in Table 2.

Chile's agricultural production WF is geographically concentrated in the Central Chile area (for more detailed results, see Table A1 and Figure A3 in the supplemental data online). Here, agricultural production WF in 2007 presented values within the 0.50 and 2.50 Gm^3/year range, while all other regions had an agricultural production WF below 0.50 Gm^3/year. This area, while having the most water-consuming activities, is characterized by low average rainfall

(Figure A4 in the supplemental data online) and water flows. Therefore, these regions have important water stress situations that triggers an economical vulnerability for the country.

Chile's WF_{blue} is lowest at both ends of the country because of the low agricultural production that exists in these areas; in the extreme north water availability is very low, while in the extreme south there are colder climatic conditions.

Agricultural WF_{blue} was lower than the available water flows in each hydrographic area (see Figure A5 in the supplemental data online). However, considering that approximately 84% of water flows are not used and flow into the sea (DGA, 2014), WF_{blue} represents 65%, 41% and 0.005% of the available resource in the Northern Dry Pacific, Central Chile and Southern Humid Pacific hydrographic areas respectively. Additionally, agricultural WF_{blue} is similar in the Northern Dry and Southern Humid Pacific Hydrographic areas, even though the Northern Dry Pacific area has 0.15% of the available resources than the Southern Humid Pacific area.

On the other hand, the Araucanía region in the south presents the highest agricultural production WF_{green}, with 1.1 Gm^3/year. More abundant rainfall can explain this fact. Agricultural WF_{green} increases towards the south of the country (see Figure A6 in the supplemental data online).

The grey agricultural production WF is significantly lower than the blue and green WFs and is geographically concentrated between Central Chile and the Southern Humid Pacific areas. The Metropolitan and Araucanía regions concentrate 85.4% of the agricultural production's WF_{grey}. Its high value can be explained by the intensification of agriculture in these regions.

It is important to point out that 7.00 Gm^3/year (73.6% of the total agricultural production WF) corresponds to the production WF of five agricultural products: prairies, wheat, corn, vineyards and apples. Prairies account for 26% of the total agricultural WF with water consumption of 2.50 Gm^3/year. It is followed by wheat production, which represents 22% of agriculture's production WF (2.10 Gm^3/year), corn, vineyards and apple production with relative production WFs of 10%, 8% and 7% with respect to Chile's total agricultural production WF (for detailed results, see Table A2 and Figure A7 in the supplemental data online).

Each crop's WF production (m^3/ton) per unit in 2007 is presented in Table 3.

The results indicate that the crops with the highest WF production per unit are prairies, vineyards, walnuts and almonds with WF productions per unit of 6300, 5514, 4059 and 3889 m^3/ton respectively. Olive, cherries and wheat also present high WF productions per unit. On the other hand, alfalfa, pears, citrus and potatoes present the lowest WF productions per unit at 236, 254, 280 and 281 m^3/ton, respectively.

The WF_{blue} is mainly determined by the production of prairies, wheat, vineyards and corn; these crops represent 62.8% of the total agricultural blue WF production (see Figure A8 in the supplemental data online). The green WF, on the other hand, is due to two crops, prairies and wheat, that concentrate 65.9% of total green WF. Finally, wheat, corn and apples produce 70.3% of the grey WF.

Chile's agricultural transformation between 1950 and 2007 is characterized by large changes in the composition of production. The total cultivated area increased by 10% between 1955 and 2007, reaching 26,000 km^2 in 2007. However, its composition varied substantially. Since 1955 there has been a reduction in the land devoted to cereals, but significant increases in land devoted to forestry and fruits (see Figure A9 in the supplemental data online). Fruit production grew in the country's central zone, while traditional cereals tended to concentrate in the south. Dairy and beef, reliant on rain-fed pastures, remained mainly in the south. During the Agrarian Reform period of 1965–73 there was little significant change in land use. Most large changes in the composition of production occurred after the structural reforms of the mid-1970s. Trade, exchange rate and property rights policies following liberalization, privatization and deregulation after 1978 are likely to have had at least as great an impact on producer incentives in the choice of crops as any previous land redistribution outcomes. Had these changes in land devoted to different outputs not occurred, Chile's agricultural production WF would have been higher since the cultivated area of cereals and prairies would be greater while the surface dedicated to fruits would be lower.

Conclusions

Considering geographic and climatic differences from north to south, there has been an increase in the availability of water resources. However, Chile's agricultural production blue WF is geographically concentrated in the lower portion of the Northern Dry Pacific and Central Chile areas. Here, agricultural production WF presents values within the 0.50–10 Gm^3/year range.

These areas, while having the highest agricultural water-consuming activities, are characterized by reduced water flows and low average rainfall with respect to the Southern Humid Pacific area, where irrigated agriculture's blue WF is lowest. Therefore, these regions present important water stress situations that trigger the economical vulnerability of irrigated agriculture. Agricultural WF_{blue} is similar in the Northern Dry and Southern Humid Pacific Hydrographic areas, even though the Northern Dry Pacific area has 0.15% of the available resources than has the Southern Humid Pacific area.

The vulnerability of these regions requires policies to incentivize better water management, greater agricultural water productivity, more efficient agricultural production processes, the assessment of water scarcity-resistant crops and of water reuse systems, among other strategies. In the Northern and Central regions, these policies could diminish water dependence and reduce irrigated agriculture's vulnerability.

Considering that Chile's current agricultural situation is under great pressure, a detailed management tool, such as the WF estimates compared with water supplies, should be considered for public policy decisions. Having specific information about the water being used by each crop in each region as well as the availability of water allows decision-makers to incentivize the best agricultural techniques to become less dependent on water availability reductions. By achieving this important goal Chile will be able to increase irrigated agriculture's sustainability.

Disclosure statement

No potential conflict of interest was reported by the authors.

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