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Estimating the global production and consumption-based water footprint of a regional economy

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ABSTRACT

The current scenario of increasing use and pollution of water resources and the effects of climate change on natural supply coexist with a high trade interconnection, where impacts are transmitted from local to global scales. Identifying and quantifying these impacts is essential to focus and coordinate policies for sustainability. In this context, this study develops a methodology to estimate the pressures of a regional economy on global water resources. Unlike previous studies, which have focused mainly on the regional and national blue water footprint (WF) of consumption, the proposed framework integrates in an innovative way: i) an estimation of the global green, blue and grey WF, ii) a comparison between production and consumption-based approaches, iii) a spatial disaggregation, and iv) a scarcity-based assessment. Specifically, a regional input-output (IO) model and a global multiregional IO model are used, which allows identifying the origin and quantifying the water incorporated in imports. The Tuscany region in Italy is considered as a case study, where the domestic WF has been studied, but global impacts on water resources are unknown. The results show that, although 42.7 % of Tuscany's imports come from outside Italy, the pressures on water resources exerted abroad represent 81.2 % (production) and 73.4 % (consumption) of total. This result is amplified when only water incorporated under scarcity conditions is considered, reaching 96.3 % (production) and 94.6 % (consumption). The proposed approach allows characterizing the most significant impacts, which could guide policies to promote the consumption and import of products with low water incorporated under stress conditions.

1. Introduction

In recent decades, there has been a significant increase in pressure on global water resources, mainly due to increased water consumption and pollution from economic activities, as well as the accelerated effects of climate change on water availability (IPCC, 2022). Given the severe water stress in many regions, it is increasingly important to have a local and global accounting of water demand and supply, as well as to identify the economic activities that generate most pressure on water bodies (Lenzen et al., 2013; White et al., 2015). Pressures exerted by economic activities are not limited to domestic impacts. The current deep trade integration generates a close interconnection between local and global scales, through which local economies produce global environmental impacts (Arto et al., 2016). Consequently, evaluating how water pressures are transferred to other regions of the planet poses a challenge for the sustainable management of the resource.

The most common concept to measure economic pressures on water resources is the water footprint (WF) (Hoekstra and Hung, 2002). However, it is important to differentiate water incorporated under scarcity and abundance conditions. The concept of scarce water footprint (SWF) has been proposed to measure the water that actually generates pressures (Pfister et al., 2009; Ridoutt and Pfister, 2010). Weighing impacts by stress levels in producing countries allows for a better understanding of the actual environmental pressures.

Regional economies are interconnected with other regions and countries through exports and imports of goods and services. This connection involves virtual water flows, that is, flows of water implicitly incorporated into traded products (Allan, 1993; Hoekstra and Chapagain, 2007). Regional economies generate local water pressures through the production of their industries and external water pressures through final and intermediate imports. Thus, water pressures of a region can be classified into domestic and external pressures depending on the geographical location of the impacts, and quantified in total water volume (WF) and water volume extracted under stress conditions (SWF).

Water pressures can be also classified based on the economic operation that generates them: production or consumption (Peters, 2008). Production are generally associated with pressures on local resources

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Nomenclature

Acronyms

CFIIW	water embodied in foreign intermediate imports to meet regional final consumption
CNIIW	water embodied in national intermediate imports to meet regional final consumption
CWF	Consumption-based water footprint
DCWF	domestic consumption water footprint
DPWF	domestic production water footprint
EPWF	external production water footprint
FFIW	water embodied in foreign final imports
FIIW	water embodied in foreign intermediate imports
IO	input-output
NFIW	water embodied in national final imports
NIIW	water embodied in national intermediate imports
MRIO	multi-regional input-output
PWF	production-system water footprint
SCWF	scarce consumption-based water footprint
SPWF	scarce production-system water footprint
WRI	water requirements index
WSI	water stress index

Symbols

A	matrix of technical coefficients
H_z	matrix of virtual water flows between countries, required to produce the z vector of goods
L	Leontief inverse matrix
v	vector of water use coefficients by industry and country
W^r	vector of total water uses by country, required to meet the final demand of region r
W_z	matrix of virtual water flows between industries and countries, required to produce the z vector of goods
y^r	vector of final demand of region r
φ^z	vector of total water uses by country, required to produce the z vector of goods

(production-based approach), however, this study incorporates also its external component (imported inputs). The impacts of consumption are transmitted through the goods and services required to satisfy the demand of the inhabitants of a region, that is, they generate local and external impacts (consumption-based approach). Estimating both footprints allows targeting incentive policies for the acquisition/importation of less water-intensive goods.

Furthermore, water pressures can be classified based on the type of water considered: green, blue or grey (Hoekstra et al., 2011). Given that water stress is fundamentally defined in terms of blue and grey water (Ridoutt and Pfister, 2010), considering these two types of water is coherent for a study that aims at evaluating water pressures. However, a complete analysis should also include also green water.

Regarding the methodology to perform WF calculations, it is essential to use approaches capable of estimating direct and indirect pressures. The input-output (IO) approach makes it possible to adequately map and quantify intersectoral and interregional economic relationships (Miller and Blair, 2009).

Until now, the external WF of regional economies has been estimated based on subnational multiregional input-output (MRIO) models, identifying the pressures that regional economic activities exert on other regions (Zhang et al., 2011; Feng et al., 2014; Distefano et al., 2022). In some cases, the aggregate pressures on the rest of the world have been estimated (Cazcarro et al., 2013). Few of the studies consider grey water and scarcity weighting. In short, no specific methodologies have been proposed to estimate a comprehensive WF of a single regional economy, in the terms specified in the previous paragraphs.

The present study seeks to close this gap, developing an innovative analytical framework to comprehensively study the water pressures generated by a regional economy. This framework includes the green, blue and grey WF of consumption and production, its spatial disaggregation and its impact weighted according to the stress exerted on water resources. Methodologically, the study combines a regional IO model, to estimate domestic pressures, with a global MRIO model, to quantify water incorporated in imports.

The proposed methodology is empirically tested in the Italian region of Tuscany. For this region, WF has been estimated at a regional and subregional scale (Rocchi and Sturla, 2021; Rocchi and Sturla, 2022). Nevertheless, to have a broader picture of the pressures exerted by the region's productive system and the consumption of its inhabitants, it is essential to estimate also the impacts on the rest of Italy and on the other countries. These estimates could allow a better design of policies encouraging the acquisition of products with less water incorporated under scarcity conditions. Other aspects that reinforce Tuscany as a compelling case study correspond to the availability of regional IO tables and the existence of country-disaggregated data on intermediate and final imports.

Section 2 presents the literature review. In Section 3 are exposed the methodology, the case study and some descriptive statistics. In Section 4 the results are presented for Tuscany. Section 5 includes a discussion of the results. Finally, Section 6 presents the conclusions of the study.

2. Literature review

There are two fairly widespread approaches to study global water uses: the production-based approach and the consumption-based approach. Both have been developed to allocate responsibilities among countries (Peters, 2008; Wood, 2017; Ramos et al., 2022). The production-based approach refers to all water consumed in a region to produce goods for domestic final consumption and exports. The consumption-based approach refers to all water embodied in the final goods consumed in a region (Hoekstra and Hung, 2002). The production-based approach usually does not take into account external pressures, thus avoiding double counting in global reallocation (Peters, 2008; Wood, 2017). However, it is a fact that the production system needs also water from other regions to work. The first difference of our study with respect to the existing literature is that we are interested in assessing local and external pressures of the production system. Since the objective is not to globally reallocate water uses, double counting is not an issue. We call this approach the production system water footprint (PWF).

As mentioned in the introduction, the concept of WF has suffered some criticism (Wichelns, 2017; Yang et al., 2013; Ridoutt and Hung, 2012). We consider also the scarcity measure of water footprint (White et al., 2015; Ridoutt et al., 2018; Lenzen et al., 2013), according to which the volumetric measure is weighted by the water stress index (WSI) developed by Pfister et al. (2009). We follow the approach of Sturla et al. (2023) which includes grey water in WSI calculation.

Input-output (IO) models have been widely used to quantify virtual water flows and water footprints at national scales (Kim et al., 2001; Velazquez, 2006; Guan and Hubacek, 2008) and global scale (Feng et al., 2011; Duarte et al., 2016; Arto et al., 2016), given their ability to trace both direct and indirect water requirements by considering intersectoral and inter-regional economic linkages. IO models have also been used to evaluate the grey water component of footprint, as in a recent study carried out for China (Liao et al., 2021).

Regarding the study of the water footprint at the regional scale, some studies have calculated it at the sub-national scale using the multiregional input-output (MRIO) approach. Zhang et al. (2011) calculate Beijing's water footprint using the Chinese multi-regional input-output table, consisting of 30 Chinese regions (26 provinces and 4 city-regions), considering blue water only. Feng et al. (2012) use a MRIO model to calculate the water footprint of the Yellow River basin in China considering 48 sectors divided by 9 provinces in China, considering blue and green water. Cazcarro et al. (2013) calculate the Spanish water footprint with an MRIO table for 40 economic sectors and 19 Spanish regions, the European countries and Rest of the World, considering blue and green water. Distefano et al. (2022) estimates the virtual water flows for the 32 administrative departments of Colombia based on a MRIO model, considering blue water. White et al. (2015) build an MRIO model for China considering blue water and, unlike the previous ones, considers an evaluation of water pressures based on stress in the producing regions.

Table 1 presents a summary of these studies indicating the country, the scale of analysis, the number of regions, whether they use the production- or consumption-based approach, the type of water, whether or not they consider the global component of the WF and whether or not they consider a scarcity weight.

The above-mentioned studies use national[1] MRIO tables to assess the pressures exerted by a regional economy on the other regions of the country and, in some cases, to estimate the pressures on aggregated regions of the world (Cazcarro et al., 2013). Nevertheless, none of these studies consider a broad disaggregation of the external WF, a comparison between production and consumption pressures, nor include the grey water component of water demand; and only one of them adopt a scarcity weighting. To our best knowledge, there are no models that estimate the WF of a regional economy jointly incorporating all the aforementioned elements.

Given the limitation of national MRIO models to estimate disaggregated global WF, an alternative is to nest a national MRIO with a global MRIO, in order to study the spatial structure of external pressures in the rest of the world (Fry et al., 2022). However, this is an expensive methodology and national MRIO tables are not available for most countries. A second alternative corresponds to using a global MRIO to quantify the water incorporated in the region's imports. Although some light assumptions must be made to distinguish the regional economy from the national economy, this approach allows a comprehensive analysis of the WF for a large number of regional economies, since national MRIO models are not required, nor is it necessary to individualize the country into the global MRIO. In this work we use this second approach.

A regional IO model and a global MRIO model are built to estimate the disaggregated internal and external WF of production and consumption of a regional economy. Both models are used in their water extended version, that is, the intensities of water use are considered (Feng et al., 2011; Wood, 2017).

Regarding to Tuscany, chosen as a case study, the domestic water footprint has been estimated at a regional (Rocchi and Sturla, 2021) and subregional scale (Rocchi and Sturla, 2022), however, the external water pressures have not been estimated. Rocchi and Sturla (2021) estimated an extended water exploitation index (EWEI) for the region, obtaining a value of 19 % (low water scarcity), which means that only a small part of the local pressures are likely to generate an impact. This changes when the analysis is carried out at the subregional level, where about 30 % of the subregional systems show moderate or high water stress (Rocchi and Sturla, 2022); nevertheless, the water incorporated under conditions of scarcity remains a minor part of the total.

3. Methods

3.1. Overview

Fig. 1 shows a graphical scheme of the proposed methodology, indicating the data required, the models to be developed and the results to be obtained.

The environmentally extended Global MRIO model (hereinafter "Global MRIO model") is constructed from the global IO tables, the water satellite accounts, and the intermediate and final imports. The latter with a disaggregation compatible with the Global MRIO to be used (Economic sectors matching). An adjustment is considered to estimate the water incorporated in intermediate imports associated with final domestic consumption (sector shares of domestic consumption). This allows determining the external WF of production and consumption, and its spatial structure.

To determine the domestic WF an environmentally extended regional IO model (hereafter "Regional IO model") is used, which requires the regional IO table and the water use coefficients.

Based on water availability, satellite accounts and domestic water use estimates (from the Regional IO model), the water requirement (WRI) and water stress index (WSI) are estimated and subsequently the SWF is calculated.

3.2. MRIO model

Global MRIO Models have generally been employed to calculate the WF of a country (Feng et al., 2011; Wood, 2017; Arto et al., 2016). Here, we propose a generic methodology to estimate the global water pressures (through its intermediate and final imports) and the local water pressures (through its productive activities) exerted by a regional economy, calculating the PWF and the CFW, both spatially disaggregated and weighted by scarcity.

Let us consider n countries and m industries. The Leontief matrix of the global economic system is:

$$L = (I - A)^{-1} \tag{1}$$

where A is the $(nm \times nm)$ matrix of direct requirement coefficients for the n countries in the m industries. A single element of each submatrix A^{rs} is calculated as follows:

$$a_{ij}^{rs} = \frac{h_{ij}^{rs}}{x_i^s} \tag{2}$$

where h_{ij}^{rs} is the trade from industry i in country r to industry j in country s and x_i^s is the total output of industry i in country s. Note that the diagonal blocks of this matrix correspond to intersectoral flows within each country.

To calculate the disaggregated WF (by country and industry) of country r, we considered the $(nm \times 1)$ vector y^r, which corresponds to the final demand of country r from all countries and industries. The total water footprint $(nm \times 1)$ vector W^r of country r is:

$$W^r = \widehat{v} \cdot L \cdot y^r \tag{3}$$

where v is the $(nm \times 1)$ vector of water use intensity by country and industry (green, blue and grey water use intensity), and the symbol ˆ indicates the diagonalization of this vector.

3.3. Water embodied in any vector of goods

More generally, to calculate the water needed to produce the goods contained in any $(nm \times 1)$ vector z (e.g., a vector of regional imports), it is possible to calculate a $(nm \times nm)$ matrix W_z:

$$W_z = \widehat{v} \cdot L \cdot \widehat{z} \tag{4}$$

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[1] We use the term "national MRIO" to refer to the MRIO table that considers the entire economy of a country on a regional scale, and the term "global MRIO" to refer to the MRIO table that considers the entire world economy on a country scale.

Table 1
Water footprint studies in regional economies using MRIO models.

Author	Country	Scale	N° of regions	Consumption- or production-based	Types of water	Global water footprint	Stress weighting
Zhang et al. (2011)	China	National	26 provinces, 4 city-regions	Consumption-based	Blue	No	No
Feng et al. (2012)	China	National	9 provinces	Consumption-based	Blue and green	No	No
Cazcarro et al. (2013)	Spain	National-global	17 regions, 2 others	Consumption-based	Blue and green	Europe, rest of the world	No
White et al. (2015)	China	National	26 provinces, 4 city-regions	Consumption-based	Blue	No	Yes
Distefano et al. (2022)	Colombia	National	32 administrative departments	Consumption-based	Blue	No	No

(Source: Own elaborations.)

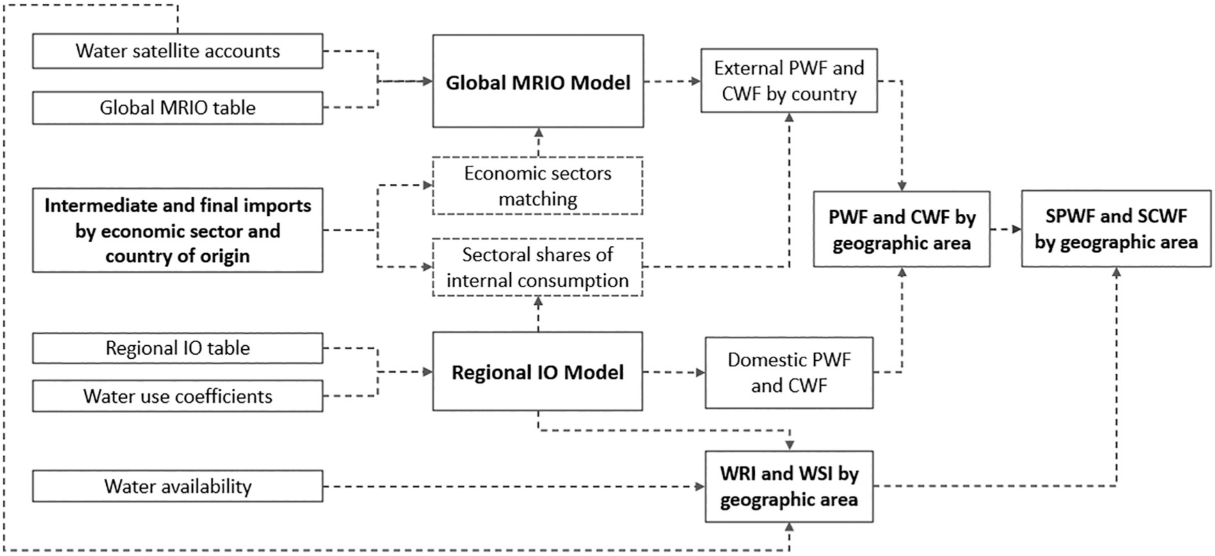

Fig. 1. Graphical scheme of the methodology[2].
[2]In this study we use the term "Geographic area" when referring jointly to countries, the study region, the rest of the country and the rest of the world (in the case of empirical application).
(Source: Own elaborations.)

W_z matrix is composed by elements $w^z_{sj,ri}$, representing the water used in country s and industry j to produce the goods of industry i in country r included in the vector z. Based on W_z, the origin (country and industry) of all the water required for the production of the goods of vector z can be determined.

Let us define the $(n \times n)$ matrix H_z as the aggregation by country of the matrix W_z, that is, each element $h^z_{s,r}$ of the matrix H_z represents the water used in country s to produce all goods in country r of vector z.

$$h^z_{s,r} = \sum_{j=1}^{m} \sum_{i=1}^{m} w^z_{sj,ri} \tag{5}$$

In this way, we can construct the $(n \times 1)$ vector φ^z, corresponding to the water used in the n countries to produce all the goods of vector z.

$$\varphi^z = H_z \cdot \iota_n \tag{6}$$

where ι_n corresponds to a $(n \times 1)$ vector of ones.

The methodology presented is quite powerful since it allows us to determine the origin of the water contained in any (nm × 1) vector of goods. For the case of the water footprint of a regional economy, vector z represents the intermediate and final imports.

3.4. Water footprint and its spatial structure

3.4.1. Production-system water footprint

Based on the above methodology the Production-system water footprint (*PWF*) of a regional economy can be calculated. Since we always refer to only one regional economy, sub-indices are omitted. The PWF is estimated as:

$$PWF = DPWF + NIIW + FIIW \tag{7}$$

DPWF corresponds to the domestic[2] production water footprint (all regional water used by the production system), *NIIW* is the water embodied in national intermediate imports, and *FIIW* is the water embodied in foreign intermediate imports. The second and third terms of the right side of Eq. (7) represent the external water footprint of the production system ($EPWF = NIIW + FIIW$). All of these magnitudes are scalars.

Eqs. (4) to (6) are used to calculate the $(n \times 1)$ vectors φ^{NII} and φ^{FII} with values by country for the national and foreign intermediate imports, respectively. In the case of φ^{NII} a correction is made for the country to which the region belongs to avoid double counting. *Supplementary Information A.1* provides the procedure details.

The IO table of the regional economy is used to calculate the *DPWF*:

$$DPWF = v'_{RE} \cdot L^d_{RE} \cdot y^d_{RE} \tag{8}$$

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[2] We use the term "domestic" to refer to the regional economy, in the case of imports (or exports) from the rest of the country we use "national", in order not to create confusion.

where v'_{RE} is the *(1 × m)* transposed vector of water use intensity coefficients. L^{d}_{RE} corresponds to the Leontief inverse *(m × m)* matrix and y^{d}_{RE} is the part of final demand *(m × 1)* vector (including exports), supplied by domestic produced goods. Since the matrix of technical coefficients usually does not distinguish between local (regional) and imported products (United Nations, 1993), a new matrix of input output for only domestic production is estimated (see *Supplementary Information A.1*).

3.4.2. Consumption-based water footprint

In the case of the Consumption-based water footprint *CWF*, what is of interest are the water pressures exerted locally and abroad (national and foreign) due to final consumption in the regional economy:

$$CWF = DCWF + CNIIW + CFIIW + NFIW + FFIW \tag{9}$$

where *DCWF* corresponds to the domestic consumption water footprint (which does not include local waters used to produce national and foreign exports), *CNIIW* is the water embodied in national intermediate imports to meet regional final consumption, *CFIIW* is the water embodied in foreign intermediate imports to meet regional final consumption, *NFIW* is the water embodied in national final imports and *FFIW* is the water embodied in foreign final imports. The external water footprint of the regional consumption is also defined ($ECWF = CNIIW + CFIIW + NFIW + FFIW$). All these magnitudes are scalars.

Eqs. (4) to (6) are used to calculate the *(n × 1)* vectors φ^{NFI} and φ^{FII} with values disaggregated by country for the national and foreign intermediate imports, respectively. In the case of φ^{NII} a correction is made for the country to which the region belongs to avoid double counting. *Supplementary Information A.2* provides the procedure details.

To calculate *CNIIW* and *CFIIW* we consider also the share of final domestic consumption (excluding final imports) and total final domestic consumption (sector shares of domestic consumption). The methodology is detailed in *Supplementary Information A.2.*

The input-output (IO) table of the regional economy can be used to calculate the *CPWF*, considering the internal final demand $\left(y^{q}_{RE}\right)$. (See *Supplementary Information A.2).*

$$DCWF = v'_{RE} \cdot L^{d}_{RE} \cdot y^{q}_{RE} \tag{10}$$

3.5. Scarcity measure of water footprint

To assess the scarcity structure of PWF and CWF of a regional economy, we consider the weighting of water volumes used in each country by the Water Stress Index (WSI). The index, developed by Pfister et al. (2009), takes values between 0 (no water stress) and 1 (maximum stress). White et al. (2015) call the measures of WF weighted by WSI as scarce water footprint (SWF), arguing that only a fraction of the water abstracted generates impact in terms of *water deprivation* which is potentially available for other uses.

To calculate the WSI, Pfister et al. (2009) consider the ratio of total annual freshwater withdrawals to hydrological availability (Withdrawal to Availability ratio, WTA). For this study, we consider the Water Requirement Index (WRI) proposed by Sturla et al. (2023), which corresponds to the ratio of blue and grey water to the feasible long-term water availability (average runoff plus average groundwater recharge, minus ecological flow). Grey water is included to consider also the water quality expressed in terms of volumes. The WRI index is calculated as[3]:

$$WRI = \frac{Blue\ Water + Grey\ Water}{Feasible\ Supply} \tag{11}$$

The WSI has a minimal water stress of 0.01 as any water consumption has at least a marginal local impact (Pfister et al., 2009),[4] and is calculated based on the WRI,[5] as follows:

$$WSI = \frac{1}{1 + e^{-6{,}4 \cdot WRI} \cdot \left(\frac{1}{0{,}01} - 1\right)} \tag{12}$$

The production-system *scarce* water footprint (SPWF) and consumption-based *scarce* water footprint (SCWF) are composed by the domestic components (domestic PWF and CWF multiplicated by the regional WSI) and the external components. The *s* component of the *(n × 1)* vectors π^{EPWF}_{s} and π^{ECWF}_{s} represents the scarce WF associated to each country *s*.

$$\pi^{EPWF}_{s} = \varphi^{EPWF}_{s} \cdot WSI_{s} \tag{13}$$

$$\pi^{ECWF}_{s} = \varphi^{ECWF}_{s} \cdot WSI_{s} \tag{14}$$

Note that the country in which the regional economy is located is included in the *n* countries.

3.6. Case study

To illustrate the methodology, we choose the regional economy of Tuscany, Italy. In this region, IO tables are available with a significant level of disaggregation (56 industries), together with disaggregated information for both intermediate and final imports, which can be adequately compared with the industries of the global IO databases.

Table 2 summarizes the main input data used to build the model. The description of this information, the procedure used for handling the data and the assumptions considered are detailed below.

To build the global MRIO model we use the World Input-Output Database (WIOD) for the year 2014 (WIOD, 2016). The WIOD provides information for 56 economic sectors in 43 countries (30 European, 13 non-European) and the rest of the world (RoW) (Timmer et al., 2012; Timmer et al., 2016). This dataset contains water environmental satellite accounts (Hoekstra and Mekonnen, 2012), which provide information for 35 industries in 40 countries (27 European, 13 non-European). To make the satellite accounts information consistent with WIOD, we use the procedure described by Sturla et al. (2023).

To quantify Tuscan imports, the dataset of the Regional Institute for Economic Programming (IRPET) of Tuscany for the year 2018 is used (IRPET, 2022). The database provides intermediate and final imports of Tuscany, for 32 economic sectors and from 43 countries and the RoW

Table 2

Input information for the model.

Model stage	Information	References
MRIO model	Tuscany intermediate and final imports	IRPET (2022)
	World input-output database	WIOD (2016)
	Environmental satellite accounts	Hoekstra and Mekonnen (2012)
IO model	Tuscany IO table	IRPET (2021)
	Tuscany coefficients of water use	Rocchi and Sturla (2021)
Scarcity weighting	Water demand by country	WIOD (2016), Hoekstra and Mekonnen (2012)
	Indicator 6.4.2 SDGs (water availability estimation)	(FAO, 2022)

(Source: Own elaborations.)

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[3] Blue and grey water are considered on a net basis, i.e. withdrawals minus discharges to the hydrological system.

[4] The curve was calibrated by (Pfister et al., 2009) to result in a WSI of 0.5 for a WTA of 0.4, which is the threshold between moderate and severe water stress.

[5] In this formula the WRI should be multiplicated by 100 (it is not used in percentage terms).

(the same countries as in the WIOD table). Euro-dollar exchange rates and inflation have been taken into account, because the IRPET table is expressed in Euros, while the WIOD table flows are in US dollars.

The industries represented in the WIOD were combined and aggregated with those from IRPET to provide a panel with homogeneous classifications. Once the two datasets were matched, the imports of the industries were further disaggregated into the 56 WIOD sectors by reallocating the Tuscan imports values from the IRPET table according to the Italian WIOD proportions. For example, the IRPET sector of Agriculture, forestry and fishing is divided into 3 categories in the WIOD (Plant and animal production, hunting and related service activities; Forestry and logging; Fishing and aquaculture). The value of Tuscan imports of Agriculture, forestry and fisheries, in the IRPET table, has been divided according to the weight of the three sub-sectors in the WIOD.

For the domestic WF, we use the IO table for 2017 (IRPET, 2021), containing 56 economic sectors, and the water use intensity coefficients estimated by Rocchi and Sturla (2021). For the internal analysis of domestic WF, we use the IO table for 2017 (IRPET, 2021) and water use intensity coefficients (Rocchi and Sturla, 2021).

Data limitations for 2018 imply that the results are based on some assumptions. When considering the year 2017 for the IO model, we are assuming the same domestic WF for 2018 and that the sector allocation of domestic and total consumption is maintained. Both assumptions are not strong, due to the few changes in one year. When considering the global MRIO model for 2014, we assume that the global production structure of the goods composing the import vector is maintained. This assumption might seem stronger, however, global production structures do not change that much in four years. These changes are of the order of magnitude of the data uncertainty (WIOD, 2016).

For the WRI calculations, the uses of the WIOD satellite account and SDG indicator 6.4.2 for the year 2018 are considered (FAO, 2022; Dickens et al., 2019). In the long term, the feasible supply (WRI) coincides with the SDG availability indicator (Sturla et al., 2023).

The fact that the rest of Italy is considered in the global MRIO model leads to double counting of Tuscany's water. The extent of the error is not known exactly, since there is no national MRIO model for Italy. However, the proposed methodology apply a correction, weighting the water associated with Italy at 94.5 % (Braca et al., 2021; Rossi and Benedini, 2020), to exclude Tuscany (5.5 %). In any case, the volume of water involved in double counting does not exceed 1.2 % of Tuscany's total water footprint. Regarding the WSI for the rest of Italy, it has been calculated by subtracting the water demand and the feasible supply of water for Tuscany (FAO, 2022; Rocchi and Sturla, 2021).

3.7. Descriptive statistics

This section presents some important data on imports, water use intensity and water stress, for Tuscany, Italy, 41 WIOD countries and the rest of the world (RoW).

Imports of Tuscany total 63,106 million US dollars (MM US$), of which 39,903 MM US$ correspond to intermediate imports and 23,203 MM US$ to final imports. The vast majority of these imports, 94.4 % of intermediate and 96.4 % of final imports, come from the rest of Italy and the 42 WIOD countries (Fig. 2).

As Fig. 2 shows, imports from the RoW are only a minor part of the total, however, this does not allow affirming that an insignificant part of Tuscany's water impacts will be generated in this region. This is mainly due to indirect effects and the differences in water use intensity among countries, the latter being greater in the RoW (Fig. 3).

Fig. 3 shows that the intensity of water use in Italy and Tuscany is much lower than the average value of the 42 WIOD and RoW countries. Therefore, it is expected that external impacts will be much more concentrated outside Italy than the imports generating them.

Regarding production and consumption impacts, given that most of the imports are intermediate (63.2 % of total), a greater impact could be expected from production, however, this also will depend the intermediate imports used to produce final domestic goods. Regarding the spatial structure, consumption pressures should be more concentrated within Italy than production pressures, given the origin of final imports (Fig. 2).

To evaluate the water incorporated under water stress conditions, the WSI is used (Fig. 4). The aggregate WSI of the 42 WIOD countries and the RoW has been estimated based on the average of the WRI (linear) and subsequent calculation of the WSI (non-linear). The higher value in the RoW and in the 42 WIOD countries makes the spatial structure of the scarcity-weighted impacts more concentrated outside Italy. The application of the proposed methodological framework allows quantifying all the differences.

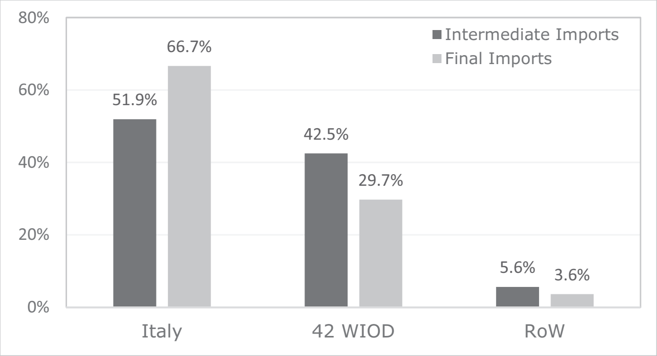

Fig. 2. Spatial structure of Tuscan intermediate and final imports.
(Source: Own elaborations.)

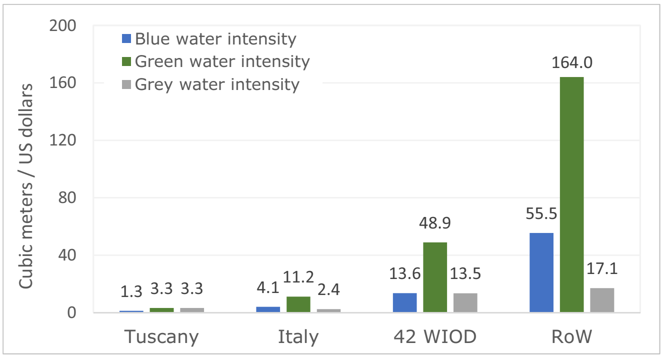

Fig. 3. Water use intensity by geographic area.
(Source: Own elaboration.)

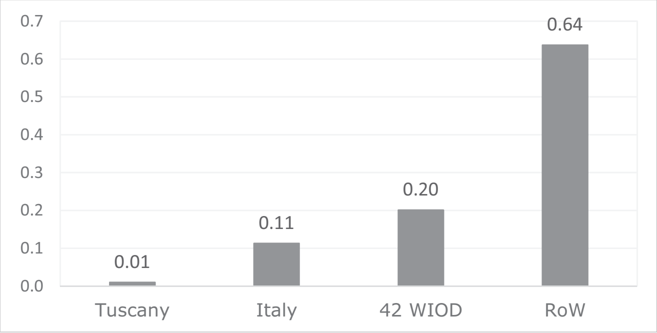

Fig. 4. Water stress index by geographic area.
(Source: Own elaborations.)

4. Results

4.1. *Domestic water and virtual water embodied in imports*

First, we present the PWF and CWF results disaggregated by domestic and virtual water embodied in the different components of imports, considering the three types of water (blue, green and grey) separately. All import components include virtual water from all over the world, including the rest of Italy region.

Table 3 presents the results of the PWF. The total WF of the Tuscan production corresponds to 7710 Mm^3, the domestic component representing a share of 29 %: the external water pressures of the regional production system (71 % of the PWF) are 2.4 times higher than the pressures exerted on Tuscan water resources. The most important component is the virtual water embodied in foreign intermediate imports (FIIW), which represents 49 % of the PWF. Blue WF represents 25 % of the total PWF, green WF 56 % and grey WF 19 %.

Table 4 presents the results for the CWF. The total WF of the Tuscan consumptions corresponds to 7179 Mm^3, which is quite similar to the PWF. However, in this case the external water pressures are much higher (89 % of the total). The water embodied in national and foreign final imports (NFIW and FFIW) represents 56 %, i.e., Tuscan final consumptions exert their greatest pressure through final goods and services that are not produced in Tuscany. The blue WF represents 22 % of the total CWF, the green 62 % and the grey 16 %, a composition similar to that of the PWF.

4.2. *Spatial structure of the total water footprint*

In this section we consider the spatial disaggregation of Tuscany's WF, with an emphasis on total WF. In the following section, we will focus on blue and grey WF, which correspond to the resources that generate a more direct impact on the water balance of the geographic areas.

As for the spatial structure of the PWF (Fig. 5), 42.6 % of the total water required directly and indirectly by the Tuscan production system comes from Italy (29.3 % Tuscany and 13.3 % Rest of Italy), while the remaining 57.4 % corresponds to water pressures exerted outside the country. Specifically, the share of the 41 WIOD countries (see *Supplementary Information B*) is equal to 22.8 %, while the share of the countries included in the RoW group is 23.4 %. China alone accounts for 11.3 %. *Supplementary Information C* provides the results for all geographic areas.

Considering the CWF (Fig. 5) 65.4 % of the pressures are external to national borders. In this case, however, the pressures on the rest of Italy (23.6 %) are higher than in Tuscany (11.0 %). The share of the 41 WIOD countries is equal to 26.4 %, while the share of the countries in the RoW group is 28.4 %. China accounts for 11.6 %, a share similar to that recorded for the PWF and equivalent to the value of domestic water used. CWF in China is largely consisting of grey water. *Supplementary Information C* shows the results for all the geographic areas.

When considering total WF, a relevant difference between PWF and CWF emerges in the composition of external pressures. Tuscan *consumptions* (1693 Mm^3) have a much more significant impact on Italy's water resources than the Tuscan production (1094 Mm^3). However, the difference becomes smaller when foreign countries are considered, with the pressure from consumption (4697 Mm^3) slightly higher than that of the production system (4430 Mm3).

Table 3
Production-system WF (PWF) of Tuscany (WF in millions of cubic meters).

Variable	Green	Blue	Grey	Total	% Total
Domestic production (DPWF)	1070	789	395	2255	29 %
National intermediate imports water (NIIW)	1100	346	273	1721	22 %
Foreign intermediate imports water (FIIW)	2143	788	800	3733	48 %
Production-system (PWF)	4314	1925	1470	7710	100 %
% Total	56 %	25 %	19 %	100 %	

(Source: Own elaborations.)

Table 4
Consumption-based WF (CWF) of Tuscany (WF in millions of cubic meters).

Variable	Green	Blue	Grey	Total	% Total
Domestic consumption (DCWF)	278	457	52	788	11 %
Consumption national intermediate imports (CNIIW)	498	157	124	779	11 %
Consumption foreign intermediate imports (CNIIW)	970	357	362	1690	24 %
National final imports (NFIW)	1499	313	270	2083	29 %
Foreign final imports (FFIW)	1241	289	306	1836	26 %
Consumption-based (CWF)	4488	1574	1116	7179	100 %
% Total	58 %	22 %	14 %	93 %	

(Source: Own elaborations.)

The maps in Figs. 6 and 7 show the geographic distribution of global blue PWF and CWF of Tuscany. *Supplementary Information D* provides the maps for green and grey components.

4.3. *Spatial and scarcity structure of blue and grey water footprints*

In this section we analyse the blue and grey component of Tuscany's PWF and CWF, considering, in addition to their spatial structure, their scarcity weighted measure. Supplementary Information *E* contains the WSI (and WRI) of each geographic area.

Table 5 shows the blue and grey WF and scarce WF of Tuscany divided by geographic area, for both the production system and consumption-based approaches.

The SPWF[6] of Tuscany amounts to 1201 Mm^3, which represents 35.4 % of the PWF$_{BLUE+GREY}$ (3396 Mm^3), presenting a very different spatial structure (see Fig. 8). An interesting result is that the share of water pressures within Italy decrease from 45.2 % to 4.3 % of total when considering the stress on water resources. This is explained by the WSI of Tuscany (0.010, no water stress) and that of the Rest of Italy (0.113), both values much lower than those associated with foreign countries (see *Supplementary Information E*). The Tuscany scarcity-weighted water pressures are concentrated in foreign countries, where China appears as an outlier with 46.5 % of total (only 16.4 % when considering the volumetric WF approach), followed far behind by India (7.2 %); both countries have a WSI equal to 1 (severe scarcity, maximum value).

In absolute terms, SCWF is equal to 1087 Mm^3, lower than the SPWF, due to the lower blue and grey components. However, the SCWF represents 40.4 % of the CWF$_{BLUE+GREY}$ (see Fig. 9), i.e., in proportion, Tuscan consumptions generate more impact in water-stressed zones than the activity of the regional production system. The scarcity-weighted pressures in Tuscany and in the rest of Italy represents only 5.8 % of the Tuscan SCWF (37.9 % in the volumetric case), a low value, but higher than in the case of the pressures of the production system.

While the Tuscan production system is much more intense in the total blue and grey water requirements (3396 vs. 2691 Mm^3) and more concentrated within Italy than Tuscan consumptions (45.2 % vs. 37.9 %), when weighted by scarcity, the differences becomes much smaller (1201 vs. 1087 Mm^3) and the spatial structure is reversed, i.e., a higher

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[6] For the scarce water footprint of production (SPWF) consumption (SCWF) we do not place a sub-index indicating that blue and grey water are considered, as this is the way this measure is defined. However, when we refer to the *volumetric* (not weighted by scarcity) water footprint, we make it explicit that we are considering blue and grey water for both production (PWF$_{BLUE+GREY}$) and consumption (CWF$_{BLUE+GREY}$).

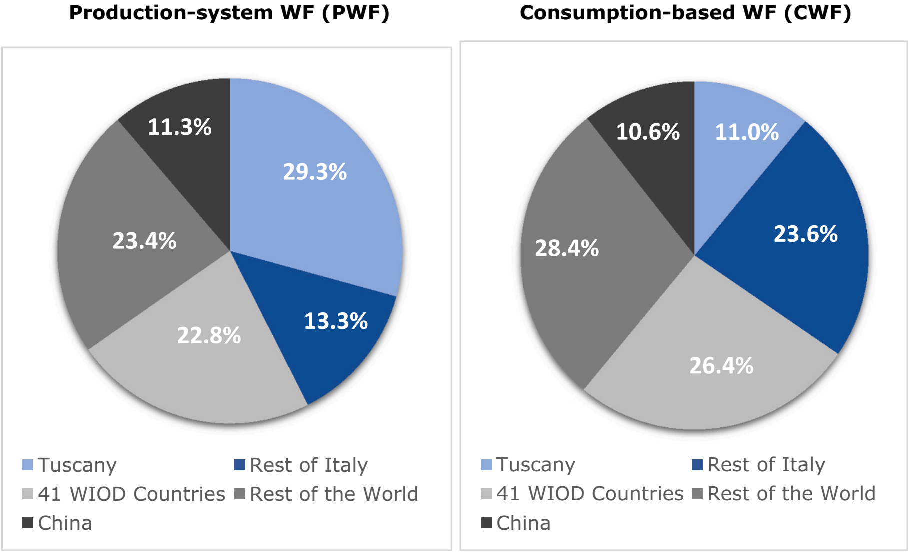

Fig. 5. Spatial structure of the Tuscan total water footprint (green, blue and grey).
(Source: Own elaborations.)

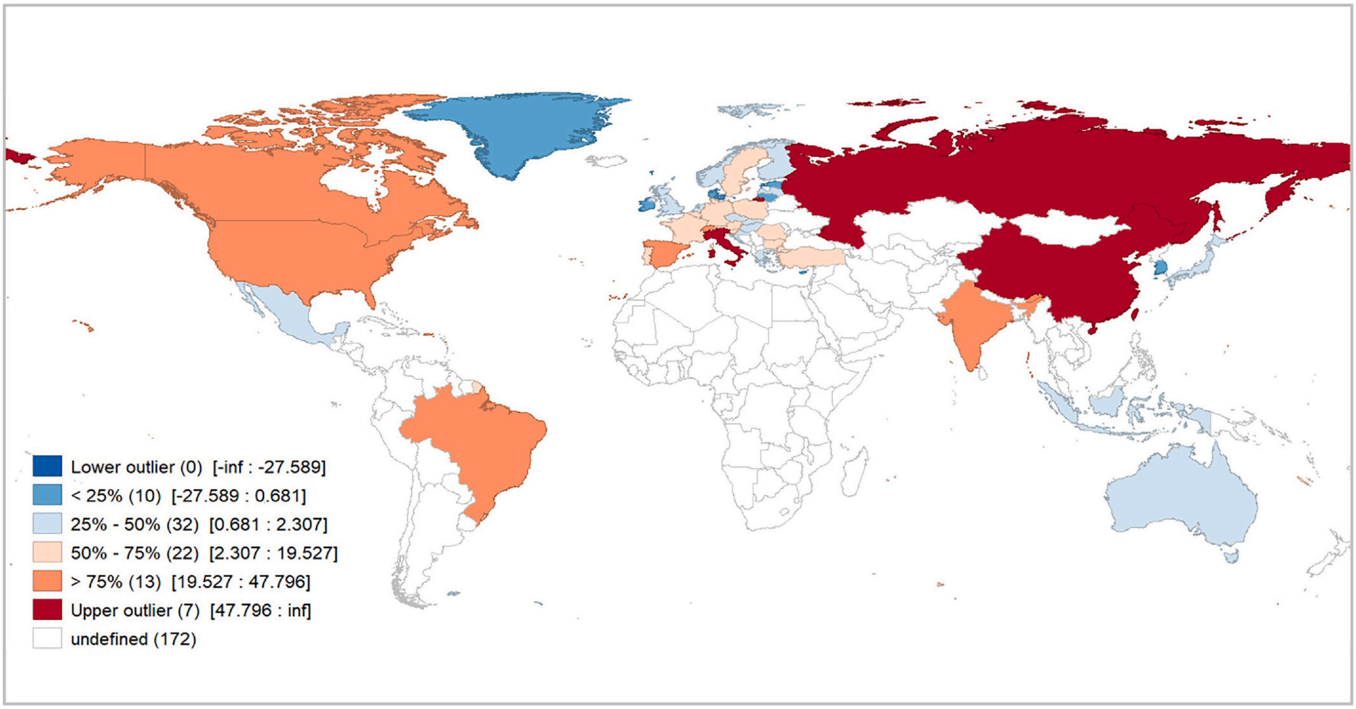

Fig. 6. Map with the spatial structure of the Production-system WF (Blue water) of Tuscany (millions of cubic meters).
**The "Undefined" category corresponds to countries which are in the Rest of the World classification of the WIOD data.*
(Source: Own elaborations using GeoDA.)

share within Italy for consumptions appears (5.8 % vs. 4.3 %).

The disaggregation of Tuscany's $\mathrm{PWF}_{\mathrm{BLUE+GREY}}$ and SPWF for all countries (*Supplementary Information F*), shows that for some geographic areas the share on the total amount increases and for others it decreases. China, the Rest of the World and India stand out as the areas where the share increases the most when WF is weighted by scarcity, rising from 36.2 % to 84.8 %. The same is true in the case of consumption, albeit somewhat less markedly, with these three geographic areas increasing from 41.7 % to 83.8 % (share of $\mathrm{PWF}_{\mathrm{BLUE+GREY}}$ and SCWF). *Supplementary Information F* contains these results for the 42 WIOD countries, Rest of the Word, Rest of Italy and Tuscany.

Finally, it is also interesting to evaluate the intensity (cubic meters per US dollar) of the SPWF and SCWF. For its estimation, the production required satisfying the needs of the Tuscan production system and consumption in each geographic area has been quantified. In the case of the production system, the three countries with the highest SWF intensity are India, China and Bulgaria. When looking at consumption, a similar situation occurs, but Bulgaria shows a higher intensity than China. The maps in Figs. 10 and 11 show the spatial distribution of SWF intensities. *Supplementary Information G* contains the results for all geographic areas.

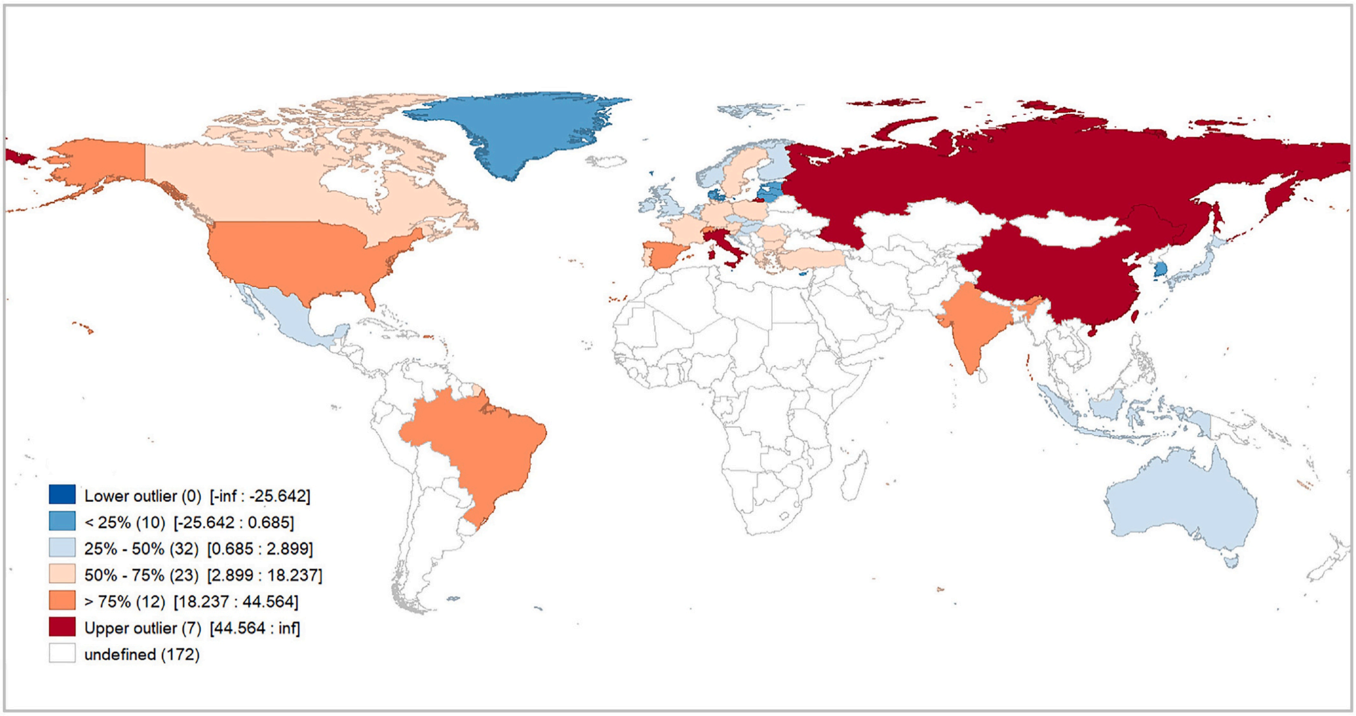

Fig. 7. Map with the spatial structure of the Consumption-based WF (Blue water) of Tuscany (millions of cubic meters).
**The "Undefined" category corresponds to countries which are in the Rest of the World classification of the WIOD data.*
(Source: Own elaborations using GeoDA.)

Table 5
WF (blue and grey) and Scarce WF of Tuscany by geographic area (Production-system and Consumption-based) (WF in millions of cubic meters).

Geographic area	$PWF_{BLUE+GREY}$	SPWF	$PWF_{BLUE+GREY}/SPWF$	$CWF_{BLUE+GREY}$	SCWF	$CWF_{BLUE+GREY}/SCWF$
TOS	1186	12	1.0 %	511	5	1.0 %
RoITA	348	39	11.3 %	509	58	11.3 %
40 WIOD	631	132	20.9 %	549	113	20.6 %
China	558	558	100 %	457	457	100 %
India	86	86	100 %	83	82	100 %
RoW	587	374	63.7 %	582	371	63.7 %
Total	3396	1201	35.4 %	2691	1087	40.4 %

(Source: Own elaborations.)

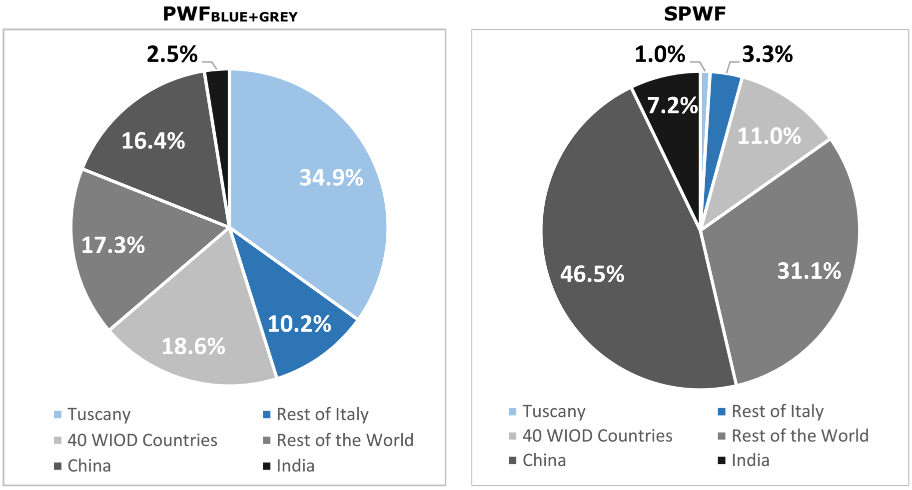

Fig. 8. Spatial structure of the Tuscan Production-system WF (Blue and Grey water) and scarce production-system WF (SPWF).
(Source: Own elaborations.)

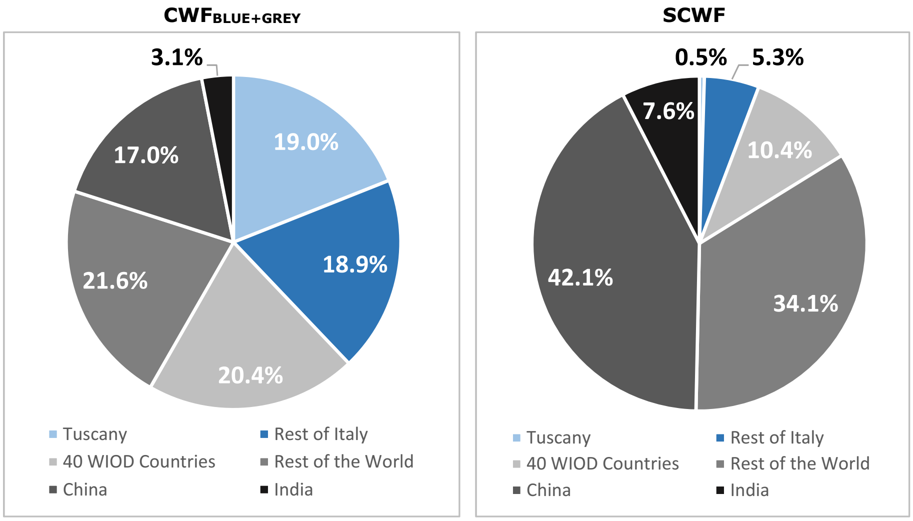

Fig. 9. Spatial structure of the Tuscan Consumption-based WF (Blue and Grey water) and scarce consumption-based WF (SCWF).
(Source: Own elaborations.)

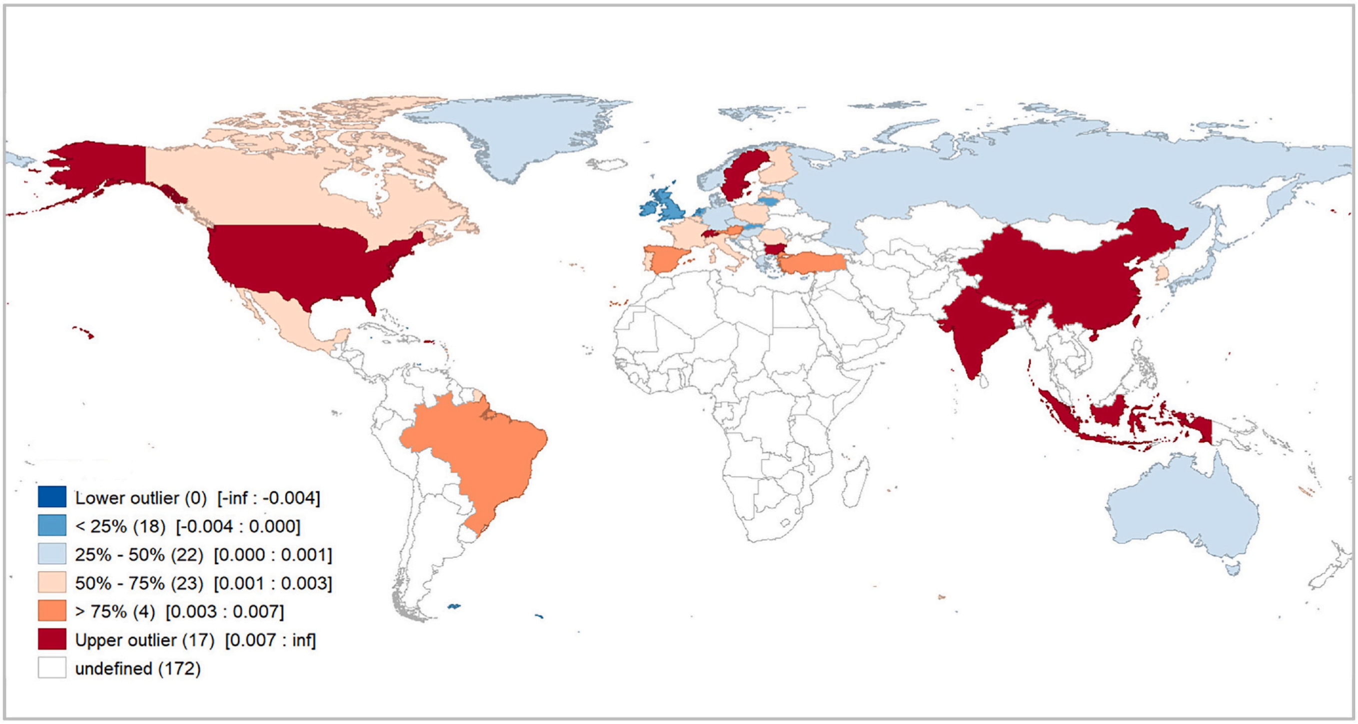

Fig. 10. Spatial structure (WIOD countries) of the SPWF Intensity (in cubic meters by US dollars).
**The "Undefined" category corresponds to countries which are in the Rest of the World classification of the WIOD data.*
(Source: Own elaborations using GeoDA.)

5. Discussion

5.1. General aspects

The proposed framework allows estimating the global WF of consumption and production of a regional economy by disaggregating external pressures by country. This disaggregation is achieved using a global MRIO model, through which the water incorporated in the region's imports is estimated. These waters are incorporated under heterogeneous stress conditions in each country, which motivates the calculation of a scarcity weighted measure of water footprint (SWF).

The proposed methodology has been empirically tested in the Tuscany region, obtaining interesting results on the spatial and scarcity structure of its global impacts Both the methodology and the data used have been useful to obtain for the first time estimates to support the analysis of the WF of Tuscany. The model and the generated information have important implications regarding the targeting of policies for sustainability. However, the methodology and data present also some limitations that must be stressed.

The rest of the paragraph discusses the case study results, limitations, and policy implications.

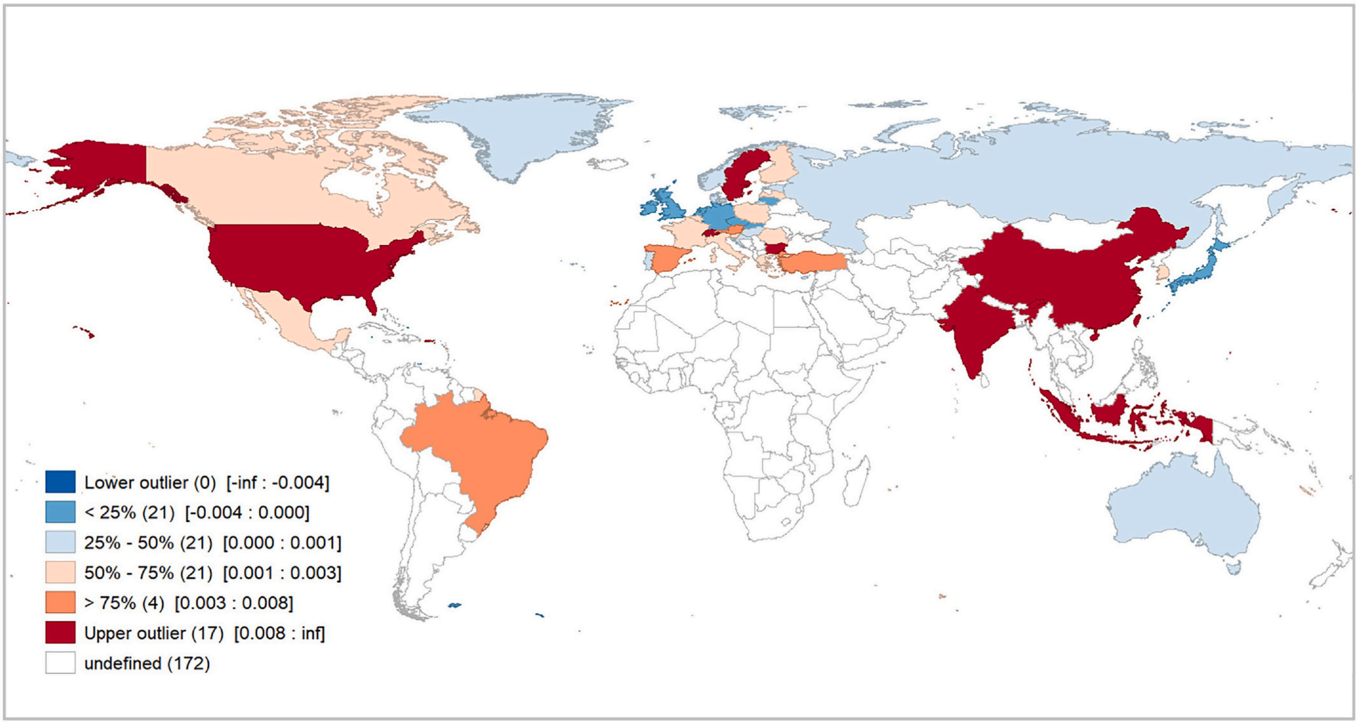

Fig. 11. Spatial structure (WIOD countries) of the SCWF Intensity (in cubic meters by US dollars).
**The "Undefined" category corresponds to countries which are in the Rest of the World classification of the WIOD data.*
(Source: Own elaborations using GeoDA.)

5.2. *Case study*

The main results show that although 42.7 % of Tuscany's imports come from outside Italy, the water pressures exerted abroad represent 81.2 % (production) and 73.4 % (consumption) of the total external pressures. This result is amplified in the case of water incorporated under scarcity conditions, reaching 96.3 % (production) and 94.6 % (consumption) respectively. Other important findings deserve some comments.

The total (volumetric) footprint of the Tuscan production system (PWF) amounts to 7710 Mm^3, of which 29 % of domestic water (production-based approach). Most of the external pressures are exerted through foreign intermediate imports (48 %). Looking at consumption, the CWF is equal to 7179 Mm^3, with only 11 % of domestic pressures, while final imports from the rest of Italy represent the higher external component of the CWF (29 %).

In the case of total WF (green, blue, and grey), foreign external water pressures dominate both according to the production system (PWF) and consumption-based (CWF) approaches. They represent 57.4 % of the PWF and 65.4 % of the CWF. The national share of external pressures (rest of Italy) show a marked difference in the two approaches (23.6 % CWF and 13.3 % PWF).

When considering blue and grey WF, the production system is much more intense in the total requirements (3396 vs. 2691 Mm3) and more concentrated within Italy compared to consumption (45.2 % vs. 37.9 %). Weighted by scarcity, however, the differences becomes much smaller in absolute terms (1201 vs. 1087 Mm3) and the spatial structure is reversed, showing a higher share within Italy for consumption (5.8 % vs. 4.3 %), in a context where more than 94 % of impacts of both approaches are abroad.

The China's share of external pressures (blue and grey) is considerable (16.4 % of the PWF and 17.0 % of the CWF) but becomes extremely relevant when the scarcity weighting is applied (46.5 % of the PWF and 42.1 % of the CWF), which is explained by the WSI in China, reaching the maximum value. Also India, reaches important values also for the scarce water footprint (7.2 % of the PWF and 7.6 % of the CWF).

These results, especially the impacts on the 42 WIOD countries and the RoW, are strongly depending by the greater water use intensity, the greater WSI and the indirect effects through the IO model. Products imported into Tuscany from Italy, in fact, require a large amount of inputs produced abroad.

5.3. *Limitations*

The limitations of the empirical application to Tuscany are mainly due to the differences in the years of available information (IO model, 2017; MRIO model, 2014; imports, 2018). This can generate distortions, especially in the case of to the MRIO model (2014). However, global production structures do not change quickly, and a lot of variability is associated with the estimate of global databases (WIOD, 2016). However, this could be improved when more recent information became available from WIOD or using other global MRIO tables.

Regarding the weighting for scarcity, the scale of analysis generates some limitations. Multiplying a country's total water volume by the national WSI assumes that all economic sectors, on average, produce the same level of water stress, which is not necessarily the case. For the case study, the use of the Tuscany-specific WSI improved the accuracy of the estimate of internal pressures. The discussion of the scale of analysis is interesting and would deserve further analysis.

The objective of the proposed methodology is not to evaluate trends and drivers of temporal evolution in WF, but to provide a global and comprehensive measure of WF of a regional economy in a particular year. Unfortunately, in the case study disaggregated data on imports from Tuscany by country and economic sector for other years were not available. Repeating the calculation for several years could shed light on dynamic aspects of the exploitation of water resources and should be addressed by future research.

One of the objectives of the present study was not to depend on the availability of MRIO tables for the country the region object of study belongs, since in practice they are available in very few cases. The proposed approach allows calculations to be done for many regional economies. There are however some limitations associated to the fact that the whole country is represented in the global MRIO. Specifically, a part of the country's virtual water flows correspond to the study region. For this analysis, an approximate methodology has been proposed to avoid this double counting, which is reasonable when the results are obtained for the aggregate of industries and the study region is only a small part of the country. This is the case of Tuscany, representing only 6 % of Italy's production.

5.4. Policy implications

The availability estimates of the global water impacts of a regional economy allow targeting incentives to reduce both the local and the global water pressures. This study has jointly incorporated several elements that allow this type of policy to be designed based on a better understanding of impacts of consumption and production activities on water resources.

Evaluating the impacts of the regional production system (not just regional consumption), including its external pressures, allows evaluating incentives to promote the use of intermediate inputs with a lower amount of blue and grey water incorporated. This translates into lower water content in domestic consumption and exports.

The disaggregation of external pressures allows to know the impacts on the different countries (42 in the case study), and to weight the WF by scarcity. These results go beyond the traditional approach to water footprint analysis, facilitating the design of policies to reduce the import of goods and products with water incorporated in conditions of scarcity.

Finally, although this study does not consider the pressures associated with single economic sectors in the study region, the proposed methodological framework would allow carrying out such an analysis. More precisely, instead of using the vector of total imports (vector z in Eq. (4)), the vector of imports for each economic sector would have considered separately. Such an analysis would provide evidence to support the design of sector policies aiming at reducing global impacts of production activities. In the case study, to date there is no information disaggregated by *importing* economic sector for Tuscany, however, this could be a valuable extension of the analysis to consider in future research.

6. Conclusions

This study develops a methodology to estimate the pressures of a regional economy on global water resources. The proposed framework integrates in an innovative way: i) an estimation of the global use of green, blue and grey water, ii) a comparison between the production-system and the consumption-based approaches, iii) a spatial disaggregation, and iv) a scarcity-based assessment of global WF. Specifically, a regional IO model and a global MRIO model are used, which allows identifying the origin and quantifying the water incorporated in regional imports.

The empirical application to Tuscany allowed identifying and quantifying in detail the regional local and global water impacts, the latter hitherto unknown. The results are fundamental to evaluate the role of local production and consumption in the sustainability of water use and to design policies to encourage the consumption and import of products with a lower amount of water incorporated under stress conditions.

Two elements make the methodology useful for calculating the global WF in a wide range of regional economies: i) the regional economy may not be within an individualized country in the global MRIO table, and ii) the analysis could be carried out also in absence of the regional IO. In the first case, the only cost would be that water pressures on the rest of the country the region belongs to could not be known. In the second case, the domestic WF could not be estimated only from the accounted uses of water, and to calculate the water incorporated in intermediate imports associated with final consumption, the sector shares of domestic consumption should be estimated from other sources at a cost of a lower precision in this WF component.

While the ideal would to move towards national MRIO models nested within global MRIO models, having an "interim" tool to perform regional water footprint analysis provides valuable advance in assessing the sustainability of regional consumption and production, and in designing policies to reduce impacts on global water resources.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2023.11.023.

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