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Measuring economic water scarcity in agriculture: a cross-country empirical investigation

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ABSTRACT

High water availability enhances agricultural performance and food security. However, many countries where water is abundant according to hydrological indicators face difficulties in the utilization of water in agriculture, being in a situation of economic water scarcity (EWS), due to lack of institutional and material means for water management and governance. EWS faces a stronger challenge of measurability, if compared to physical water scarcity. Since the Sustainable Development Goal Indicator on Integrated management of domestic and trans-boundary water resources (IWRM) is a unique attempt to quantify information on water management at a national level, we explore whether it can represent a valid metric for EWS measurement. We first show that a high level of water management is neither necessarily associated to high economic power of the country nor to low physical water availability. Then, we analyze whether the indicator can predict typical EWS situations such as low agricultural productivity and inefficient water use. Although the importance of water institutions for agriculture is well known through case studies at the local level, we make the first attempt to quantify the strengths of this relation at a global scale for different crops in climatic diverse countries. We detect a positive and significant association between IWRM level and yield, and consequently a negative and equally significant association between the IWRM level and the crop water footprint. Statistical significance holds also when potentially confounding variables are included in a multiple regression analysis. We infer from this analysis that good water management, as detectable through the IWRM indicator, improves land productivity and water saving, in turn mitigating EWS. Our findings pave the way toward the use of the IWRM indicator as a valuable tool for measuring EWS in agriculture, bridging the measurability gap of economic water scarcity, with straightforward policy implications in favour of investments in water management as a lever for enhancing food security and development.

1. Introduction

While food production is keeping pace of population growth globally and food prices have declined, poverty and malnutrition persist in many regions including Asia, Sub-Saharan Africa, and parts of Latin America (FAO, IFAD, UNICEF, WFP & WHO 2020). Clearly, the benefits of increased agricultural production have been unequally distributed, possibly also due to inequality in access to water resources, in particular in agricultural production (Carr et al. 2015). Water abundance is in fact among the main factors that enhance land productivity, agricultural performance, and consequently food security. Therefore, it is crucial to understand where (and why) water is lacking for human consumption and agricultural production (Molden 2007). The answer is not always a trivial one, since many countries have a high level of water availability according to the main hydrological indicators, but still face severe difficulties in the use of water resources for human activities. This may occur for a wide spectrum of complex reasons, from the lack of infrastructures to institutional inefficiencies (Marson and Savin 2015). Some scholars and international organizations, among which the FAO (2012), define this concept as economic water scarcity (EWS) (Sullivan 2002, Molle and Mollinga 2003, Molden 2007). The issue is relevant for many regions of the world.[1] For example, in the central African region water stress is inexistent according to current hydrological definitions, but indicators on water use and agricultural performance have low values

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[1] Individuals are water insecure when they lack secure access to safe and affordable water to consistently satisfy their needs for drinking, washing, food production, and livelihoods (Molden, 2007). About 1.2 billion people live in areas of physical water scarcity, while another 1.6 billion people live in basins that face economic water scarcity. Poor people suffer the most from symptoms of water scarcity (UNDP 2006: 48).

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(FAO 2019a, FAO 2019b, Tamea et al. 1961-2016). Central Asian countries are classified as water abundant in hydrological terms, and in fact figures on water use in irrigation per hectare are comparatively higher than elsewhere, but these countries faced economic losses in agriculture due to the disinvestment in the irrigation infrastructure and consequent waste of water resources (UNDP 2006). Underinvestment in water infrastructures and institutions, and the lack of robust water governance processes may not only lead to physical water scarcity for immediate consumption, but they may also have a negative impact on agricultural yields. These factors can generate inefficiencies in water use in this field, with the consequence of a disproportionally high water footprint.[2]

Data driven studies are essential to quantify the impact that water availability and access have on agriculture. While multiple indexes of physical water availability and scarcity are available (e.g. Schyns et al. 2015, Liu et al., 2016, Kummu et al. 2016, Liu et al. 2017, Greve et al. 2018), the challenge affecting the concept of economic water scarcity is linked to its measurability. Recent work on the Sustainable Development Goal Indicator 6.5.1 on the degree of implementation of Integrated Water Resource Management (IWRM) could help filling this knowledge gap. The IWRM indicator covers information on legislative, managerial and financial environment for water management, on the presence of agreements for the management of transboundary watersheds and rivers and on stakeholders participation processes. The IWRM indicator is a unique attempt to quantify information on water management at a national level covering more than 90% of the countries, but it has not yet been used as a measure for the quantification of potential economic water scarcity. With this work we aim to understand whether the IWRM index could be a useful indicator for this phenomenon. In this sense, we aim to utilize the indicator for a wider scope with respect to the one for which it has been created. We perform the following steps. We first set the conceptual bases for our reasoning on economic water scarcity and water management indicators, by summarizing the wide literature on these topics and by providing empirical evidence of the possible role of the IWRM in this field. Before addressing potential impacts of IWRM on EWS in agriculture, we aim to understand whether the information brought by the indicator overlaps with other common measures of countries wealth and geography. Therefore, we investigate the relation of the IWRM indicator with selected macroeconomic and hydrological indicator, such as the Gross Domestic Product (GDP) per capita, the Human Development Index and the Falkenmark Indicator on water stress. We detect that the IWRM indicator brings new information with respect to the other indicators considered. Subsequently, we explore whether the indicator brings along useful information for describing typical effects of EWS in agriculture: low yield, or excessive use of water for agriculture due to inefficient infrastructures and management schemes.

This research aims at providing advances in different streams of academic literature. On the one hand, it contributes to studies on water availability and water footprint, and, on the other hand, to researches on the role of good water-related institutions for development, by bridging the gap between physical and economic water scarcity concepts. Regarding the first stream, we aim to complement the extensive amount of studies on water scarcity, water footprint and the consequent virtual water trade that focus instead on water availability from a physical and hydrological point of view (among others Rijsberman 2006, Lenzen et al. 2013, Antonelli and Sartori 2015, Tuninetti et al. 2019, Rosa et al. 2019). The multidimensionality of water security is well recognized in the wider literature on water resources (Vörösmarty et al., 2010, Gain et al. 2016, Brauman et al. 2016, Dell'Angelo et al. 2018, Varis and Kummu 2019), while it is less considered by scholars in the field of water footprint and virtual water, with some recent pivotal exception (Rosa et al. 2020). We aspire to extend the debates of these fields into the domain of EWS. Regarding the second stream, rural development scholars recognize that good institutions for water governance at different levels represent a way to improve access to water and therefore to reduce EWS. Qualitative studies on water-related governance schemes (among others Biggs et al. 2013, Dell'Angelo et al. 2016, Yu et al. 2016,), or quantitative research on local case studies (among others Ostrom et al. 1992, Stein et al. 2011) are abundant, while theoretical contributions are also consistent (Fish et al., 2010). However, comprehensive cross-country studies with data-driven approach on water management are scarce, given that measuring EWS represents a methodological challenge. We make the first attempts to identify appropriate measures for EWS, also by quantifying the strengths of the relation between EWS, agricultural performance and water use efficiency at a global scale.

2. ECONOMIC WATER SCARCITY AND INTEGRATED WATER RESOURCE MANAGEMENT INDICATOR

The concept of economic water scarcity has been approached by academic scholars and international organizations, on the one hand with the aim of defining the concept and on the other hand with the objective of creating appropriate indicators for its measurement and quantification. Lawrence et al. (2002) and Sullivan (2002) worked on the construction of a water-poverty-index that aims to link "…physical estimates of water availability with socioeconomic variables that reflect poverty" (*ibid.*). Critiques to this index were mainly related to the difficulty of accounting for water supply fluctuations and to having combined very different kinds of information with low clarity on the impact of the respective weights (Molle and Mollinga 2003, Komnenic et al. 2009). Forouzani and Karami (2011) created an index extension more focused on agriculture, with an application to Iran. However, no attempt has been made for applying the original or modified indexes at a global scale. De Fraiture (2005) worked on the actual-potential irrigation gap in the river basins of Sub-Saharan Africa, estimating that water scarcity stems from the lack of water infrastructure rather than physical shortage. Despite the usefulness of this gap concept, it contains the limitation of being focused only on infrastructure development, whereas economic water scarcity should be tackled by a wider range of means. Through qualitative research, Noemdoe et al. (2006) and Anand (2004) found that high water scarcity subjective perception by local communities in South Africa and India is not simply due to lack of infrastructure but also to diffuse political and social inequality. These authors improved the understanding of the lack of water access, but they do not provide instruments to quantify it. The World Bank (2007) and the FAO (2012) focused on improving the concept of water scarcity, by considering organizational issues, political accountability, infrastructure and institutions for water access, beside physical water availability. These two reports helped the conceptualization of EWS but did not develop indexes for quantitative use. Gain et al. (2016) created a multidimensional global water security index (GWSI) including four criteria: water availability, accessibility, safety and management. Due to its grid scale, one can explore the transboundary dimension of water availability and access. However, this index presents two shortcomings with respect to our purposes. First, the criteria related to water management consider only transboundary legal frameworks, without addressing the more articulated dimensions of water governance at the national level. Second, the criteria related to water access are limited to drinking water and sanitation, and they exclude the agricultural domain, which is nevertheless crucial for our study. More recently Rosa et al. (2020) engaged with a quantification of economic agricultural water scarcity at a global scale. They calculated the amount of agricultural land that suffers from scarcity of rain water but owns sufficient renewable surface and groundwater (blue water). The authors

[2] We use the water footprint as an indicator of use of freshwater resources for the production of goods (Hoekstra et al. 2012). In this work we refer to the production of agricultural goods. In section 3, we explain in detail how this indicator is calculated.

identified EWS with lack of irrigation due to insufficient economic and institutional effort in areas where renewable blue water would be available. Although their work produces a significant advancement in water scarcity research, we consider essential to include a broader range of domains in the EWS concept, beyond irrigation.

We aim to utilize the Integrated Water Resource Management (IWRM) indicator as a proxy for mapping economic water scarcity at a quantitative level. The indicator has been developed by UN-Water (UN Environment, 2018) in the framework of the Sustainable Development Goals definition, and it measures the SDG 6.5.1. It is available at the country level, and officially it declares to provide a framework to assess whether water resources are developed, managed and used in an equitable, sustainable, and efficient manner, reflecting the diverse dimensions of integrated water management and some aspects of water governance (Fig. S1 in the Supplementary Material). It is based on a set of questions organized in four pillars of water management: enabling environment, institutions and participation, management instruments and financing.

It is important to distinguish the concepts of water governance and water management. Teisman et al. (2013) argued that the concept of Integrated Water Resource Management belongs to the class of 'holistic approaches' to water issues, like adaptive management and co-management, and that such approaches can be viewed as 'forerunners' of the water governance concept. However, they feared that the IWRM approach tends to reduce the complex water issues only to the level of managerial issues, which are supposed to be solved by implementing universal management principles (*ibid.*, Zwarteveen et al. 2017). They highlighted that water governance addresses the complex and intertwined aspects of water issues that require consideration and action through a multi-actor and multi-level perspective. Therefore, they claimed that water governance is placed at a higher scale with respect to water management and it concerns the interactions among numerous heterogeneous actors within structural arrangements, that in turn impact water systems features. It also implies the interdependence of levels and institutions (Gupta and Pahl-Wostl 2013). Finally, water governance is influenced by governance of others domains of the society, in which many challenges of water issue may actually lie (Teisman et al. 2013). Woodhouse and Muller (2017) also defined water governance as the "overarching framework which sets objectives, guides the strategies for their achievement and monitors outcomes" and, recalled that the OECD (2015), p. 5, defines it as "the range of political, institutional and administrative rules, practices and processes (formal and informal) through which decisions are taken and implemented, stakeholders can articulate their interests and have their concerns considered, and decision-makers are held accountable for water management". Consequently, according to them, the expression of water management should be restricted to the operational steps of monitoring and regulating the use of water resources and the planning and construction of water infrastructures. In this vein, water management appears as one of the instruments to operationalize a wider water governance vision (Bertule et al. 2018). Zwarteveen et al. (2017) provided a more politically situated definition of water governance, by conceptualizing it as "the practices of coordination and decision making between different actors around contested water distributions" (ibid., p. 3). According to these scholars, water distribution may become 'contested' because of scarcity, but also as result of policies designed according only to technical principles, pursuing goals such as use efficiency or sustainability. Such view is supported also by Bertule et al. (2018), who includes in water governance also the systems in which water decisions are taken and the dynamics by which stakeholders engage within those systems.

The institutions in which the SDG indicator 6.5.1 on Integrated Water Resource Management has been created acknowledge the conceptual difference between water governance and water management, by arguing that a robust water governance is a prerequisite for an effective water management implementation (UN Environment, 2018). They also argue that, since there are not perfect indicators of water governance, the IWRM indicator, by containing different dimensions, provides at least useful feedback for informing good water management. Nevertheless, Bertule et al. (2018) claim that the IWRM indicator can be utilized as a measure of water governance. According to them, it provides insights not only on the enabling environment for sustainable water use, but also on the instruments for the operationalization of improved water governance at diverse levels, especially regarding financing and involvement of diverse institutions and stakeholders. The indicator construction methodology addresses the three water governance assessment areas presented in the OECD framework, which are effectiveness, efficiency, trust and engagement (OECD, 2015). Considering the OECD (2015), p. 5 definition of water governance, we argue that the IWRM indicator partially captures some water governance dimensions, especially in the pillars on enabling environment and institutions and participation. Moreover, the different scales and levels of water governance are included. However, Bertule et al. (2018) highlights that some among the OECD principles are not covered by the survey questions for the IWRM indicator, in particular 8 (Promotion of innovative water governance across diverse stakeholders), 9 (Transparency, accountability and integrity), Principle 11 (Managing trade-offs across water users, areas, and generations), and 12 (Promote regular evaluation of water policy and governance, share the results with the public). Furthermore, the IWRM indicator does not provide information on actual equity, sustainability and efficiency in water use derived from the existence of given institutional, legislative and managerial tools (Guppy et al., 2019). Finally, we observe that the SDG 6.5.1 is normative, by considering the IWRM as a successful universal blueprint to be implemented, without taking into account the adequacy of all principles to local specificities. Instead, a water governance perspective would allow a wider range of possibilities for rules and institutions regulating water use. In summary, the IWRM indicator is able to partially quantifies some water governance aspects since it provides information on the complex multi-level, multi-agent water issue and on the systems in which water decisions are taken. However, it does not collect information on the dynamics by which stakeholders engage within those systems and on the decision making processes. Finally, it does not consider final outcomes in water distribution across stakeholders, although those data can be partially monitored by other indicators of the SDG 6. Therefore, we would rather name it 'water management indicator' instead of 'water governance indicator'.

2.1. Empirical evidence of the potential role of the IWRM indicator for the quantification of economic water scarcity

Molden (2007) developed an economic water scarcity map with data at river basin level (Fig. 1, panel A). However, the original dataset is not available, which allows for qualitative analyses only. In particular, we compare the spatial distribution of the IWRM indicator with the one provided by Molden (2007) on the so called economic scarcity map. In panel B of Fig. 1 each country owns its IWRM indicator value, according to the degree of Integrated Water Management implementation. Although officially the IWRM values are divided into six categories, from" very low" to "very high" (UN Environment, 2018), we subdivided them into four groups, in order to compare panels A and B. For the same reason, in panel B we reproduced the same colors utilized by Molden (2007). We note that many areas that have been classified as economic water scarce also have a low value of IWRM indicator, such as for example Congo and a large region in Sub-Saharan Africa. Possible exceptions are Burkina Faso, Mali, Senegal, and Benin in in the Western Sub-Saharan Africa, and Tanzania, Kenya, Uganda and Mozambique in East Africa. These countries are considered as economic water scarce but present a relatively high value of IWRM indicator. A positive association between economic water scarcity and low IWRM indicator holds also for areas of central and southern America and South East Asia. Substantial similarity is to be observed also between the map on the IWRM indicator (panel B) and the map of the distribution of

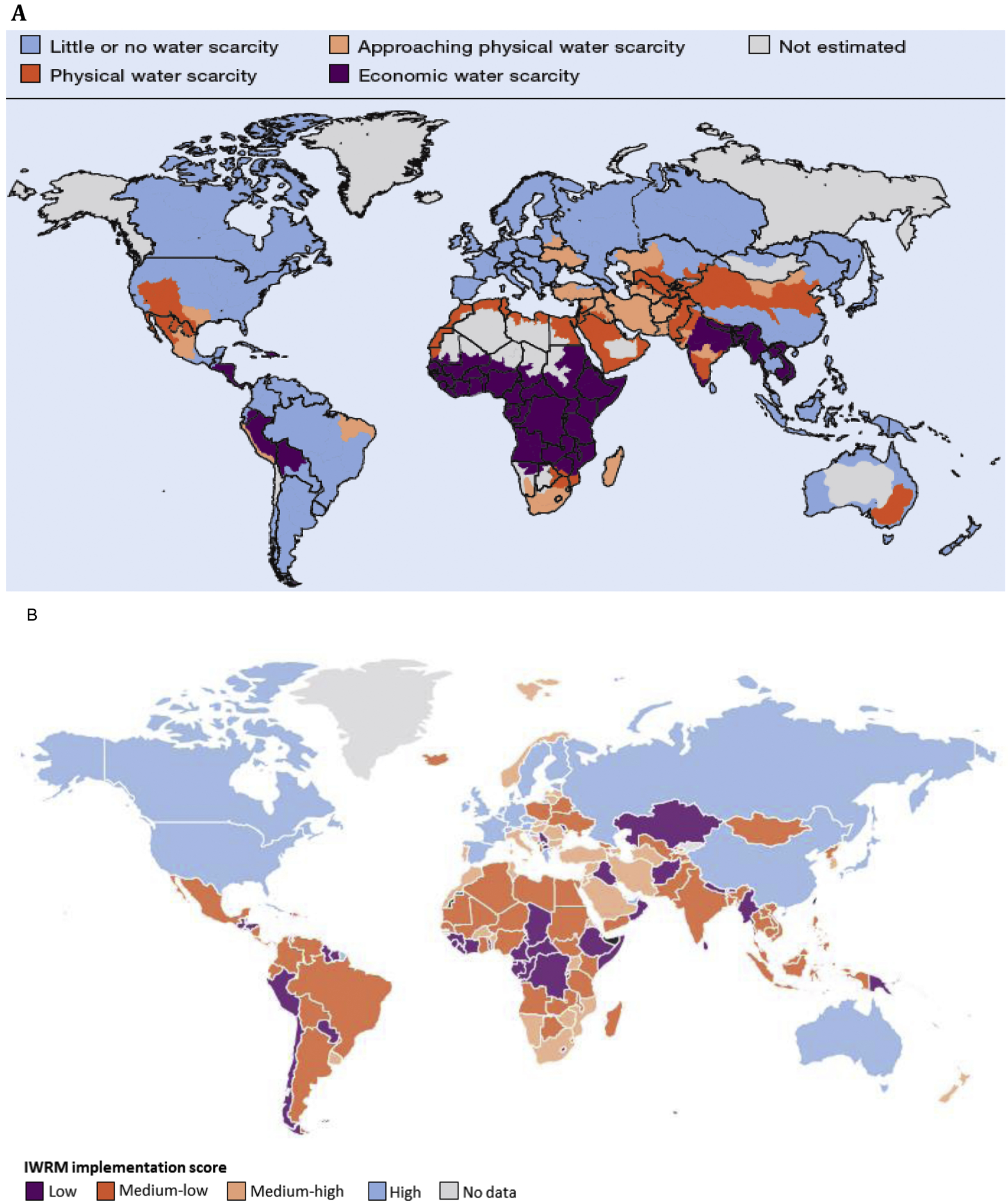


Fig. 1. A) Areas of physical-economic water scarcity (Molden 2007, pag. 11); B) IWRM indicator from 2018, 2001, and 2007 surveys (authors' elaboration from UN-Environment).

agricultural EWS in Rosa et al. (2020). Interestingly, many of the countries that have been inserted in the EWS category present high value of physical water availability. Summarizing, the IWRM indicator can be interpreted as a good proxy for economic water scarcity, although the two dimensions are not perfectly overlapping in every geographical area. Further analyses are needed to support this claim, and are provided in the following sections.

3. DATA AND METHODS

3.1. Data

The data utilized in this work stem from different sources. As we presented above, the SDG indicator 6.5.1 on Integrated Water Resource Management (IWRM) has been developed and made available by UN-

Water (UN Environment, 2018).[3] It is measured at the country level, on a scale from zero to 100, representing the degree of IWRM implementation. It is calculated on the basis of the responses to 33 questions in a country self-assessment questionnaire, submitted in 2017-2018 worldwide.[4] We calculated missing scores for 2018 from the information in similar surveys that have been conducted in 2007 and 2011.[5] These calculations were conducted for the following countries: Canada, Eritrea, Gijibouti, India, Lao PDR, Nauru, Nicaragua, Palau, Syrian Arab Republic, Tajikistan, Thailand, Turkmenistan, USA, Uruguay, and Venezuela.

Data on the Gross Domestic Product per capita are from The World Bank and expressed in current US dollars (WB 2019). Data on renewable water resources per capita are retrieved from the AQUASTAT database (FAO 2019b). This metric corresponds to the well-known Falkenmark indicator (Falkenmark et al. 1989), which calculates the amount of cubic meters available for every individual in a given country in a given year.

In each specific analysis we considered the number of countries indicated in column 4 of Table 1, depending on data availability. In Table 2 we report the number of countries considered for each crop, utilizing available data on crop yield and water footprint.[6]

We perform the analysis on ten crops that are crucial for nutrition both worldwide and in areas of economic water scarcity: wheat, maize, soya, rice, potatoes, cassava, sweet potatoes, millet, sorghum, and sugarcane (D'Odorico et al. 2014, de Fraiture 2005, FAO 2019a, Molden 2007, Table S5 in Supplementary Material). For each crop, we consider all the countries in which it was cultivated in 2016. From the Food and Agricultural Organization database (FAO 2019a), we retrieved data on crops yield for 2016 (*ton/ha*). Regarding the crop water footprints (WF), we utilized data from the CWASI database[7], described in Tamea et al. (1961-2016). For crops, the unit WF (*uWF*) is the ratio between the water consumed by the crop during the growing season and lost through evapotranspiration (*ET,* in mm), and the crop yield, *Y* (in *ton/ha*), i.e.

$$uWF = 10 \cdot ET/Y \tag{1}$$

where the factor 10 converts the units of *uWF* into $^{m^3}/_{ha}$. The *uWF* is an inverse measure of efficiency, since the lower is the value, the more efficient is the use of water resources in the crop production. The water evapotranspired could be originated from rainfall (green water), or from irrigation (blue water), which in turn may be originated from surface or groundwater (Hoekstra et al. 2012). In the present analysis we consider the sum of blue and green WF. Yield and WF are crop and country specific. In order to account for the temporal variability, Tamea et al. (1961-2016) developed the CWASI database, by applying the method proposed and verified in Tuninetti et al. (2017) for the computation of time variant *uWF* for each crop in each country over the period 1961-2016.[8] Information on data utilized in this study and their respective sources is summarized in Table 1.

3.2. Methods

In order to compare different cultivations, we computed a normalized yield for each of them in every country. For each crop (z) we performed the following calculations. First, we computed the global average yield weighted for the production of each country (i), by calculating the ratio between the total produced tons (t) and the total harvested hectares (ha) for that crop worldwide,

$$WAY_z = \sum\nolimits_{i=1}^{n} t_{z,i} / \sum\nolimits_{i=1}^{n} ha_{z,i} \tag{2}$$

where *WAY* is the weighted average yield for crop z, and n is the total number of countries. Subsequently, we divided the yield (Y) for that crop in each country by the global weighted mean yield, i.e.

$$NY_{z,i} = Y_{z,i}/WAY_z \tag{3}$$

Normalized yield (*NY*) values around one imply that the yield of the given crop in the given country is close to the world weighted average yield for that crop.

In order to investigate the potential impact of the water management dimension on agricultural production and water footprint, we conduct different regression analysis, both with standard and logarithmic values. We first perform the regressions taking the normalized yield as the dependent variable. The complete regression model with actual values of the dependent and explanatory variables is

$$NY_{z,i} = \beta_0 + \beta_1 IWRM_i + \beta_2 GDPpc_i + \beta_3 W_i + \varepsilon_{z,i} \tag{4}$$

where $NY_{z,i}$ denotes the normalized yield of crop z in country i, and W_i indicates a country's total renewable water resources per capita (i.e. the Falkenmark indicator). ε represents the error term, which estimates the difference between the actual and the predicted values of the dependent variable. We explored different combinations of explanatory variables. In the case (I), we considered the regression with the IWRM indicator as a single independent variable. In the case (II) we used the GDP per capita as single independent variable. In the case (III) we considered the IWRM indicator and the GDP per capita as explanatory variables and in the case (IV) we added the variable on renewable water per capita to the last two.

The power-law regression model is

$$NY_{z,i} = \beta_0 * IWRM_i^{\beta_1} * GDPpc_i^{\beta_2} * W_i^{\beta_3} * \varepsilon_{zt} \tag{5}$$

where the coefficients are estimated recurring to a logarithmic transformation.. Also in this case we explored the influence of different combinations of explanatory variables on the normalized yield, by applying the cases from (I) to (IV), as explained above.

Considering the unit water footprint dimension, we notice that it differs for each product and each country. Therefore, we followed the same procedure utilized for the yield, as explained in Equations 2 and 3, in order to compare the water footprint of different crops. We computed a weighted average of unit water footprint for each crop worldwide. We then normalized the actual water footprint (NWF) of each crop for each nation for this value. As we explained for the yield, values below one imply a crop water footprint for the given country lower than the world weighted average for the same crop.

Considering the normalized water footprint, the models in their most extended case (IV) are expressed in actual values and in logarithmic values, as

$$NWF_{z,i} = \beta_0 + \beta_1 IWRM_i + \beta_2 GDPpc_i + \beta_3 W_i + \varepsilon_{zt} \tag{6}$$

$$NWF_{z,i} = \beta_0 * IWRM_i^{\beta_1} * GDPpc_i^{\beta_2} * W_i^{\beta_3} * \varepsilon_{zt} \tag{7}$$

4. IWRM, MACROECONOMIC INDICATORS AND WATER AVAILABILITY

Before turning to the exploration of the association of the water

[3] Detailed information can also be found at http://iwrmdataportal.unepdhi.org/

[4] More details on the IWRM index are to be found in the Supplementary Material of this paper.

[5] In the Supplementary Material we provide more details on the merging of information among 2007, 2011 and 2017 surveys.

[6] Due to constraints in data availability on water resources per capita (FAO 2019b), in cases in which this variable is included in the analysis, a lower number of countries is considered for each crop (see section 5).

[7] Database available at: https://watertofood.org/data/

[8] The original WaterStat database (Mekonnen & Hoekstra 2010a, b) provides a time constant *uWF*, which reports green and blue uWF of many crops in every country, averaged over the period 1996-2005. However, the unit water footprint of crops changes in time due to climatic and anthropic factors, such as technical innovations, mechanization, and fertilization.

Table 1
Input data and sources.

Variable	Year	Source	N. of countries
IWRM indicator [range 1-100]	2017-2018	UN-Environment	187
GDP per capita [USD]	2017	The World Bank	187
Renewable water resources per capita [m^3/inhab./year]	2017	FAO - AQUASTAT	163
Yield for 10 crops [ton/ha]	2016	FAO - FAOSTAT	Dependent on the crop (Table 2)
Water Footprint for 10 crops [m^3 /ha]	2016	Tamea et al. (1961-2016)	Dependent on the crop (Table 2)

Table 2
Data on single crops (FAO 2019a)

Crop	FAO CODE	N. of countries of production	N. of countries included in the analysis
Maize	56	170	150
Potatoes	116	162	148
Wheat	15	126	118
Rice	27	124	106
Sweet potatoes	122	120	99
Sorghum	83	115	104
Sugarcane	156	113	92
Cassava	125	104	87
Soybeans	236	104	91
Millet	79	89	82

management level to given performances in agriculture and in water use, in this section we observe the interdependencies between the IWRM indicator and some macroeconomic and hydrological indicators: in other words, we try to understand whether the level of engagement in water management in a country simply reflects its wealth and water availability. Data from UN Environment (2018) show that country IWRM scores ranges from very low to very high, with a global average value of 49. Roughly 40 per cent of the countries belong to the medium-high category or above; a similar percentage belongs to the medium low category, while 19 per cent of the countries present low or very low levels of IWRM implementation. Latin America, Central and Southern Asia, Oceania and Sub-Saharan Africa have the lowest average scores, although there is a large range of values within each region. Subnational, basin and transboundary IWRM scores present lower values with respect to national implementation levels in most of comparable instances (Bertule et al. 2018).

We plot in Fig. 2 the relation between the IWRM indicator and the GDP per capita. A positive correlation coefficient is found between these two variables (Pearson correlation 0.56) and between the country rankings (Spearman correlation 0.53).[9] The relation is weaker for countries with low IWRM indicator, as countries with very different levels of income per capita fall in this range. For very high IWRM indicator values the relation with the GDP per capita is stronger, as all the countries having an indicator above 80 have also a relatively high income (> 13,000 USD per capita). The only country having the indicator equal to 80 and not belonging to the high income country group is Cuba. If we apply the official threshold of 70 for high IWRM indicator, all countries above this level present high income, with the remarkable exceptions of China, Eritrea, Romania and Russian Federation. However, the opposite does not hold, not all high income countries present a high IWRM indicator, but some of them reach also low peaks. The points in Fig. 2 are indeed rather scattered, with several exceptions to the intuitive relation high income-good water management. For example, Chile, Oman, Brazil and Italy are in a range of medium-high GDP per capita but present only a medium-low IWRM indicator. Exceptions on the other side of the expected relation are some Sub-Saharan African countries such as Burkina Faso, Benin, Cape Verde and Zimbabwe, that have a very low GDP per capita but a water management indicator around 60, which is relatively high for this class of income. Burkina Faso shows a better performance of the IWRM indicator with respect to India, despite its income per capita is one third of the Indian one. The Syrian Arab Republic and Eritrea, still placed among low income countries, reach indicator levels around 70, which is classified as medium-high. This denotes an engagement of the country in investing in water management despite difficult economic conditions. We repeated this analysis for each of the four IWRM pillars separately, obtaining very similar results, demonstrating that economic wealth is only one of the facets of water resources management. In Fig. 3 it is possible to observe the low correlation between the country positions in the rankings for GDP per capita and for the IWRM indicator.

Concerning the relation between the IWRM indicator and the Human Development Index (HDI), again a positive but not perfect correlation is observable (Fig, S3 in Supplementary material, from (2018)). Of the countries in the very high HDI group, 87 % present a IWRM indicator from medium-high to very high. In the rest of the other HDI groups, less than 25 % of nations have a very high level of integrated water management. However, a group of countries (among which Burkina Faso and Zimbabwe) presents a more advanced IWRM level compared to the average of countries with similar low HDI levels, demonstrating that the foundations for integrated and possibly sustainable management of water resources can be established even in an adverse economic context, and that political will must have played a role. Another country group is observable, having a high HDI, yet a medium-low IWRM indicator. Although capacity and resources are theoretically present in these countries, integrated water management has not been fully implemented (UN Environment, 2018).

Regarding physical water availability, we consider the Falkenmark Indicator, which calculates the total renewable water per capita per year (expressed in cubic meters), where the total is composed by the external plus the internal water resources of the country, considering both surface and groundwater (Falkenmark et al. 1989). Fig. 4 shows a tendency of negative association, although the correlation is weak (-0.17): for countries with low water availability, less water is associated to high IWRM indicator values. Differently, there is no correlation between the country rankings for water per capita and for IWRM indicator (Fig. S4 in the Supplementary Material). The dimension of GDP per capita suggests which countries have a low water management indicator probably because of water abundance (such as for example Iceland) and which ones probably because of a less developed economy, such as Bhutan and Guyana. For countries with severe physical water scarcity, it seems that a necessary condition for having a high IWRM indicator is having also a high GDP per capita. This is evident for Kuwait, United Arab Emirates and Qatar. As we already observed in the previous figure, countries with low GDP per capita are in any case well distributed among the water management indicator, and for them it is stronger the relation between water scarcity and relatively higher IWRM indicator. Nations with high GDP per capita have generally higher values of IWRM, even if they do not face water scarcity.

The general outcome of this section is that, despite the clear association between high economic power and high IWRM indicator, the GDP is not the only crucial driver for investments in water governance,

[9] The Pearson correlation measures linear relationships, while the Spearman correlation evaluates monotonic relationships.

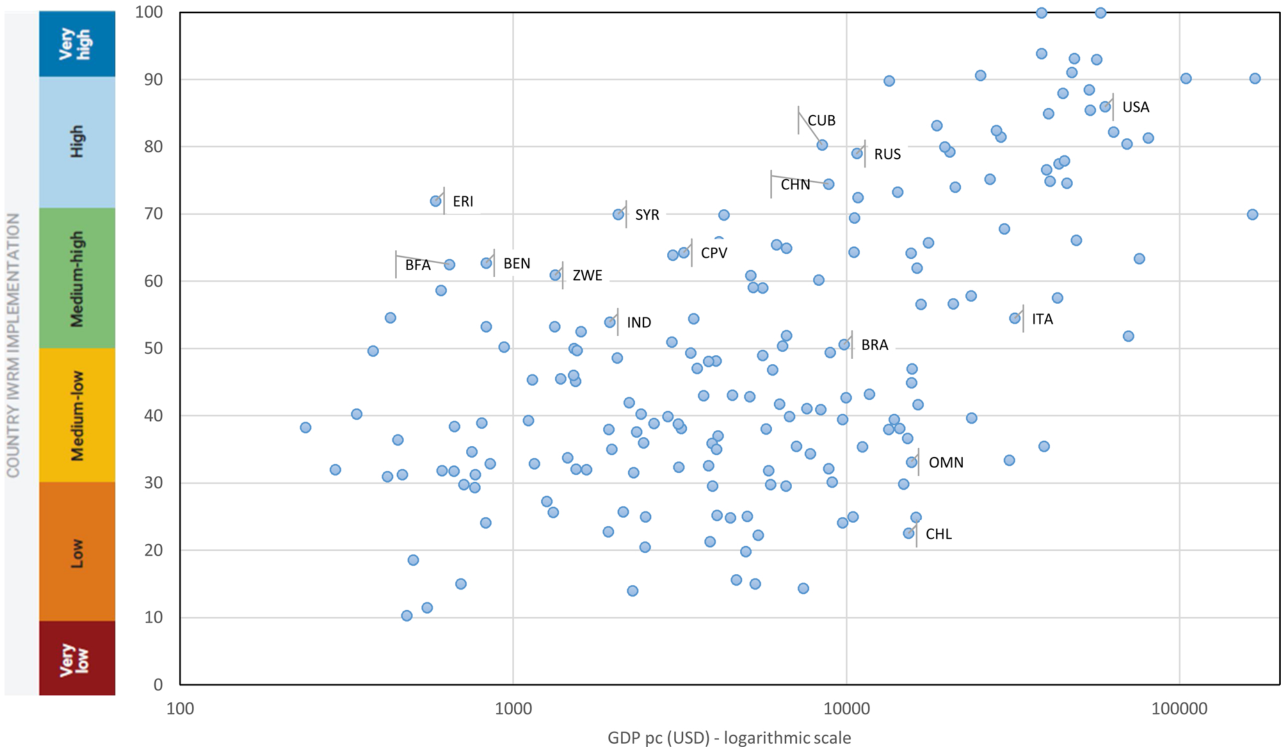


Fig. 2. Integrated Water Resource Management Indicator (IWRM) and GDP per capita in USD for 2017 for 187 countries. We inserted the codes of the countries mentioned in the text. The three letters codes correspond to the following countries. BEN: Benin, BFA: Burkina Faso, BRA: Brazil, CHL: Chile, CHN: China, CPV: Cape Verde, CUB: Cuba, ERI: Eritrea, IND: India, ITA: Italy, OMN: Oman, RUS: Russian Federation, SYR: Syrian Arab Republic, USA: United States of America, ZWE: Zimbabwe. Data are from (2018) and from (2019).

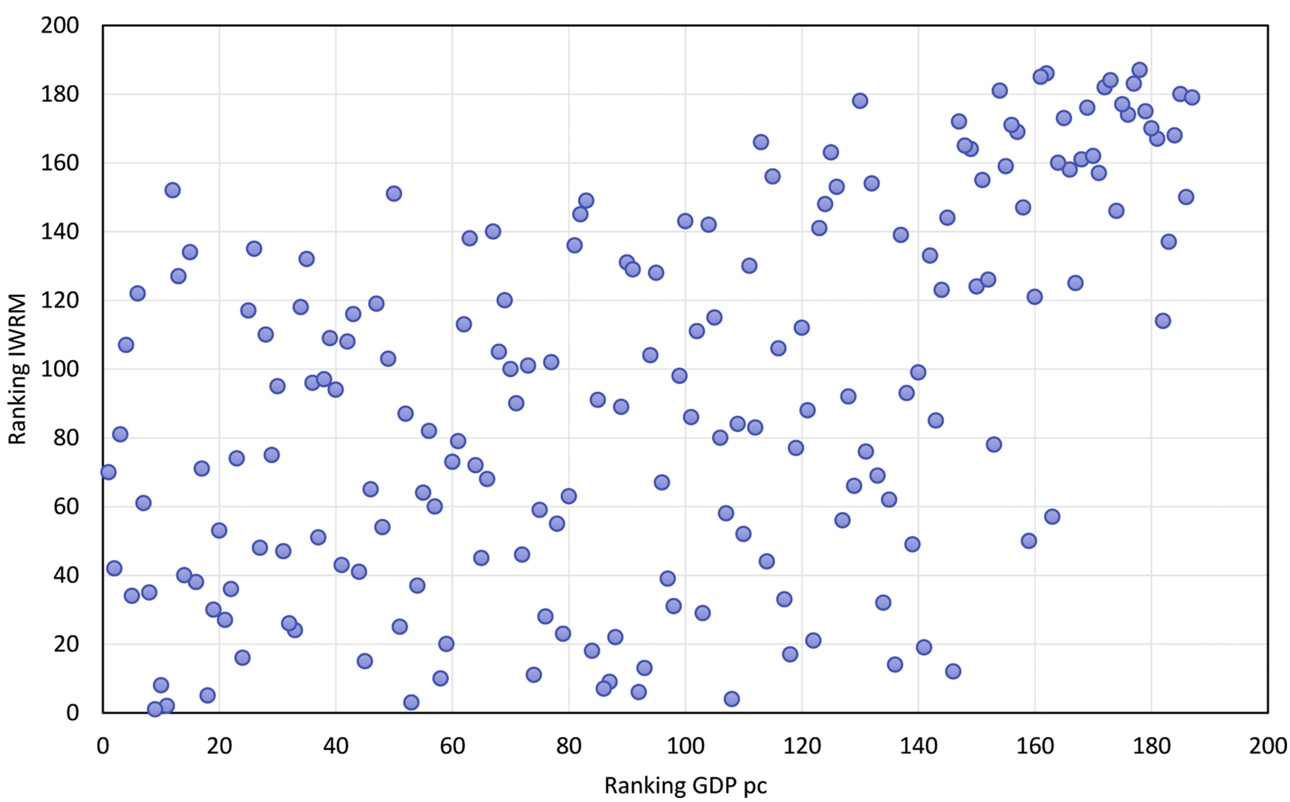


Fig. 3. Rankings of countries for GDP per capita and for IWRM indicator. The 187 countries are ranked in increasing order: small values on the axes indicate a low GDP per capita and a low IWRM indicator. Data are from (2018) and (2019).

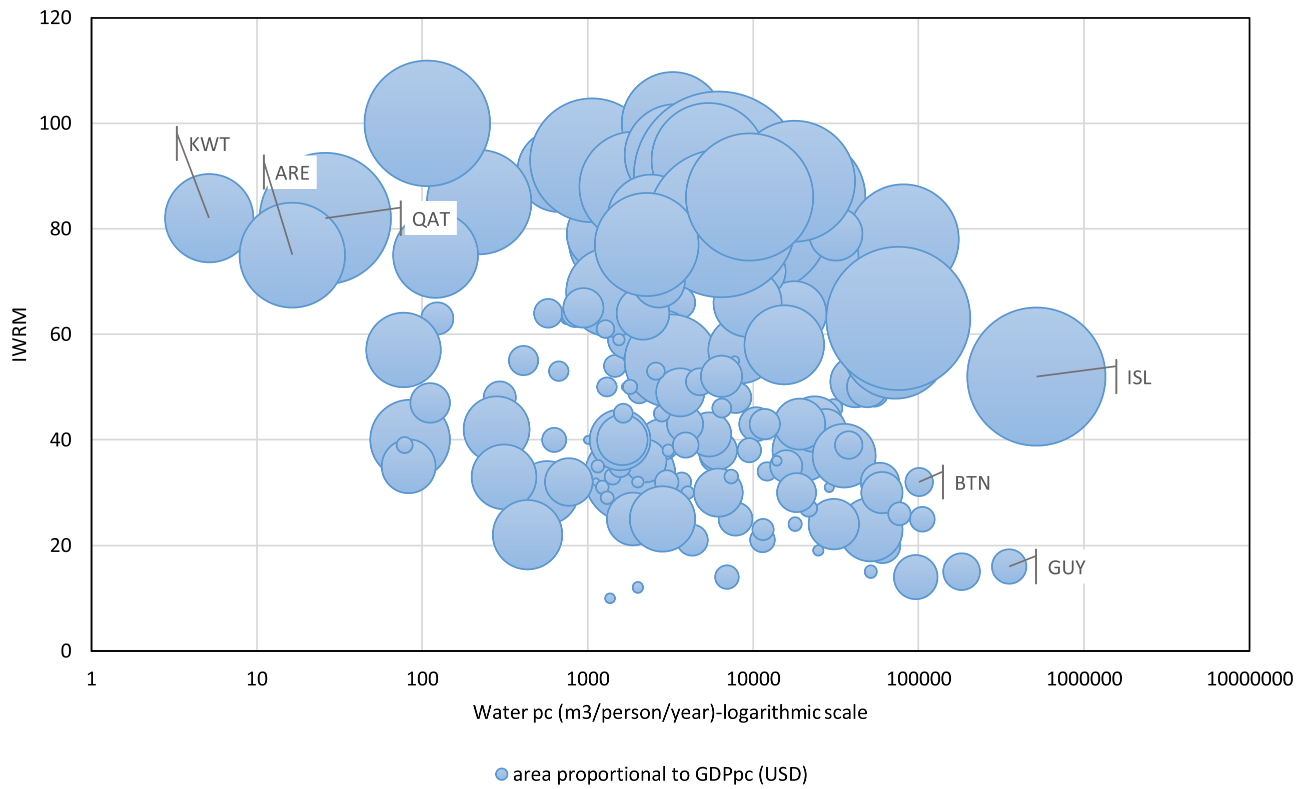


Fig. 4. IWRM (2017) and renewable water availability per capita (average 2013-2017) for 163 countries. The point area is proportional to the GDP per capita in USD (2017). We inserted the codes of the countries mentioned in the text. The three letters codes correspond to the following countries. ARE: United Arab Emirates, BTN: Bhutan, GUY: Guyana, ISL: Iceland, KWT: Kuwait, QAT: Qatar. Data are from UN Environment (2018), The World Bank (2019) and FAO (2019b).

since we often find extreme variability in the IWRM indicator for similar ranges of economic size. Moreover, water availability loosely influences the water governance level, leading to assume that policies for integrated water management are determined more by political and economic considerations, than by actual abundance or scarcity of the resource itself. This is especially important, because it points toward an efficient separation between physical and economic water scarcity.

5. IWRM AND AGRICULTURAL PRODUCTION

In the previous section we formulated hypotheses on the reasons related to the physical water availability and to the economic strengths of the countries that lead to given investment levels in water management. In this section, instead, assuming that economic water scarcity generates inefficiencies in agricultural production, we utilize the IWRM indicator as an explanatory variable to predict yields and water-use conditions, in order to understand whether the indicator can act as a sign of EWS.

Table 3 displays the results on the coefficients of the explanatory variables for the normalized yield (first horizontal panel, Equations 4 and 5 in the “Method” section) and for the normalized water footprint (second horizontal panel, Equations 6 and 7). The left part shows results of the regression models with actual values, while the right part displays results from regressions with logarithmic values. For each of the two parts, the columns show results for cases from I to IV, as explained in the "Methods" section. The coefficients indicate the magnitude of the estimated impact of the chosen explanatory variable on the dependent variable (either yield or water footprint). We indicate which of the coefficients denote a relation between explanatory and dependent variable that contains a significance from a statistical point of view.

In Fig. 5 we observe the association between the IWRM indicator and the normalized yield of the ten selected crops. A positive association is detected between the IWRM indicator and the yield. In order to provide statistical significance to the graphic representation of the data, we perform the linear regression model explained above. The red line in panel 5.A represents the trend of the model with actual values and it corresponds to case (I) of the Equation 4. As it is shown in Table 3-yield panel-case (I), the curve slope is equal to 0.013, therefore an increase of 10 point of the IWRM level is associated to an increase of 0.13 units of the normalized yield. That means that, should the normalized yield be initially equal to one, after the increase it would become 1.13, and it would have increased by 13%. Therefore, we observe a positive association between higher levels of water management and agricultural productivity.

In Fig. 6 we show the relation between the crop water footprint and the IWRM indicator. Considering the ten crops worldwide we note that a clear negative and statistically significant relation holds between the normalized water footprint and the IWRM indicator. This result is expected since the water footprint and the yield variables are strictly related, as we showed in Equation 1. However, the impact of the water management indicator on the water footprint appears even stronger that the one on the yield. Also in this case the red line in panel 6.A depicts the trend emerging from the linear model with standard values, as expressed in case (I) of Equation 6 (“Method” section). An increase of 10 points in the IWRM indicator is associated to a decrease of 0.2 units of the normalized water footprint (Table 3-Water Footprint panel-case (I)). Therefore, should the initial normalized water footprint be equal to one, after the change it would drop to 0.8, facing a decrease by 20%. We can assume that having a more sophisticated level of water management has a positive effect on water consumption for the production of the most important agricultural products, leading to more efficient solutions from the point of view of water footprint.

In Figs. 5 and 6 we built nonsimultaneous prediction intervals bounds at 90% level in order to take into account statistical uncertainty. Prediction intervals are an estimate of a range in which a future observation would fall, with a given probability, given what has already

Table 3
Coefficients estimated through the linear regression models (respectively standard and power law), considering normalized yield (NY) and normalized water footprint (NWF) for 10 crops. IWRM: Integrated Water Resource Management Indicator. GDPpc: Gross Domestic Product per capita (USD). W: Total renewable water per capita (m^3). In case (I), we performed the regression with the IWRM indicator as single independent variable (Figs. 5 and 6). In case (II), we substituted the indicator with the GDP per capita. In (III), we utilized the IWRM indicator and the GDP per capita jointly, and in IV we added the variable W to the variables used in case (III). The number of observations is related to yield and water footprint data on each crop in each country in 2016. Statistical significance: *p-value < 0.10; **p-value < 0.05; ***p-value < 0.01.

	Indep. Var.	Linear model (Eq. 4 and 6)				Power law model (Eq. 5 and 7)			
		I	II	III	IV	I	II	III	IV
Normalized Y	IWRM	0.013 ***		0.008 ***	0.008 ***	0.567 ***		0.272 ***	0.254 ***
	GDPpc		$1.816 \cdot 10^{-5}$ ***	$1.187 \cdot 10^{-5}$ ***	$1.238 \cdot 10^{-5}$ ***		0.246 ***	0.204 ***	0.206 ***
	W				$-8.592 \cdot 10^{-7}$				-0.005
Normalized WF	IWRM	-0.020 ***		-0.010 ***	-0.011 ***	-0.519 ***		-0.250 ***	-0.235 ***
	GDPpc		$-2.997 \cdot 10^{-5}$ ***	$-2.150 \cdot 10^{-5}$ ***	$-2.039 \cdot 10^{-5}$ ***		-0.225 ***	-0.187 ***	-0.190 ***
	W				$-1.245 \cdot 10^{-6}$				0.007
	Obs.	1094	1094	1094	1068	1094	1094	1094	1068

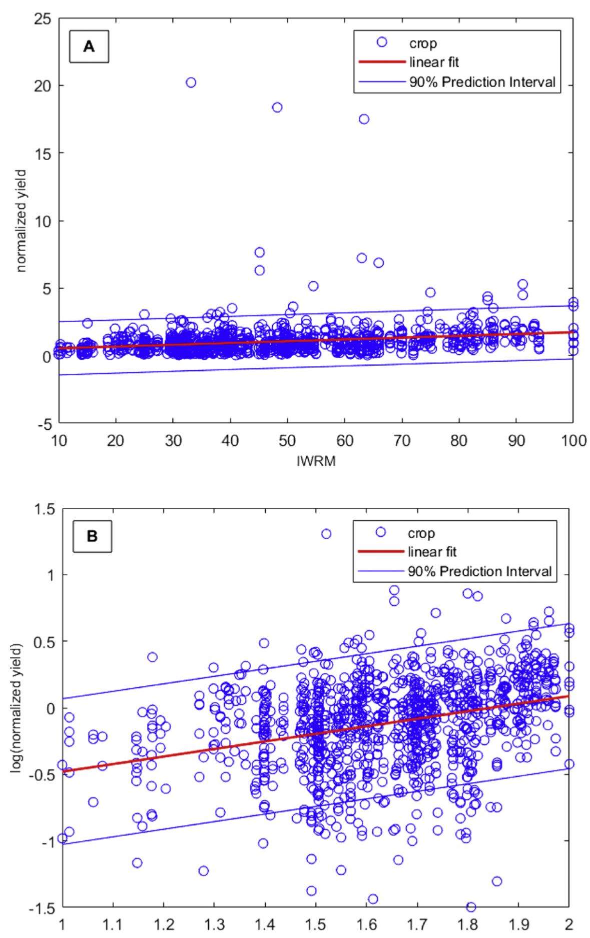


Fig. 5. IWRM indicator and normalized yield for ten selected products (2016). In panel 5.A the red line represents the trend of the linear model with actual values (Equation 4; Table 3-left upper panel-I), while in panel 5.B the red line shows the trend of the linear model with logarithmic values (Equation 5; Table 3-right upper panel-I), with IWRM as unique regressor in both cases. In both panels, the blue lines represent the upper and lower bounds of the prediction intervals at 90%. Data sources: (2018) and FAO (2019a).

been observed. They predict the spread for an individual future observation.[10] In every figure we notice that the prediction bounds are wide, which confirms the presence of noise in the data, given the wide spatial scale and the high number of variables that influence the agricultural performance and water use efficiency. Therefore, statistical uncertainty is present. However, the intervals are placed at reasonable values of the normalized yield and water footprint, and the relation between the water management dimension and the agronomical and hydrological variables holds across countries and crops.

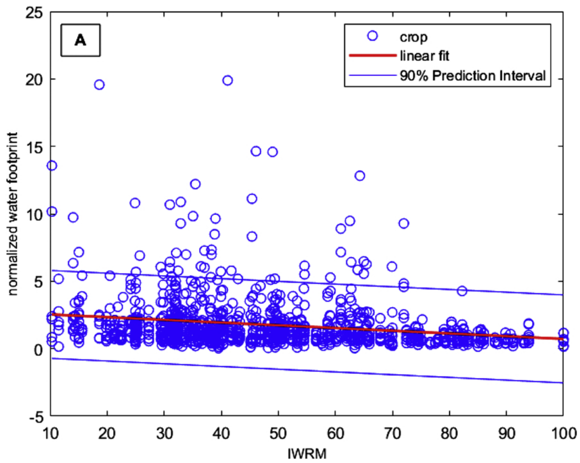
Having acknowledged that the IWRM indicator is significantly associated to the yield and water footprint trends, we investigate whether it maintains its significance also when income level and water availability per capita in the country are considered as explanatory variables.[11] In fact, economic and climatic conditions consistently influence agricultural productivity and resource use efficiency, as it is widely acknowledged in the literature (Ruttan 2002, Kaufmann and Snell 1997). Therefore, we perform multiple linear regressions including the GDP per capita expressed in USD and the renewable water availability per capita expressed in $m^3/year$ as independent variables, besides the IWRM indicator (cases II, III and IV, Equations from 4 to 7).

In all cases the IWRM indicator results statistically significant at the 0.01 level (Table 3). Results from the model with the logarithmic variables confirm the ones emerged from the model using the actual values of Equation 4, showing that the IWRM indicator maintains its statistical significance in every case (from I to IV). We can therefore deduce that, in investigating the yield trends, the water management dimension brings consistent additional information with respect to the one brought by variables related to the economic capacity of a country and to its physical water availability considered in per capita terms.

We perform the same linear regression models considering the normalized water footprint (NWF) as dependent variable (Table 3). Given the inverse relationship that occurs between the yield and the water footprint, it is straightforward that the coefficient representing the impact of the IWRM indicator on the WF has a negative sign. In this case as well, the results related to the use of the IWRM indicator as single regressor are represented in Fig. 5 above, as it has been done for the normalized yield model. In all model cases (from I to IV in Equation 6) the water management indicator keeps its statistical significance at the 0.01 level, despite the presence of the variables GDP per capita and water availability per capita. Results are confirmed in the models with logarithmic values (Equation 7)

[10] Nonsimultaneous bounds measure the confidence with whom a new observation would lie within the interval given a single predictor value. Simultaneous bounds measure the confidence for all predictor values.

[11] A specific study on the factors that determine the yield levels is beyond the scope of this paper. For reviews on crop yield determinants see, among others, Kaufmann and Snell (1997), Ruttan (2002), Barrett et al. (2010).



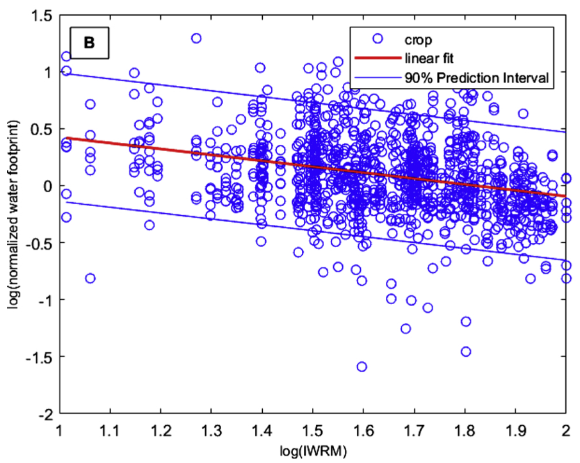


Fig. 6. IWRM and normalized water footprint of ten selected crops (2016). The red line in panel 6.A represents the trend of the linear model with actual values (Equation 6; Table 3-left bottom panel-I), while the red line in panel 6.B shows the trend of the linear model with logarithmic values (Equation 7; Table 3-right bottom panel-I), with IWRM as unique regressor in both cases. In both panels, the blue lines represent the upper and lower bounds of the prediction intervals at 90%. Data sources: UN Environment (2018) and Tamea et al. (1961-2016).

After having discussed the performance of the IWRM indicator, from Table 3 we notice that the GDP per capita, displayed in rows 4 and 7, keeps as well its statistical significance in every case, both if considered as the only regressor, and jointly with the IWRM indicator and total renewable water per capita. On the contrary, total renewable water per capita at the nation level, shown in rows 5 and 8, does not display statistical significance. This last result is counterintuitive, and it adds evidence in favour of the hypothesis that in agriculture sound water management may act as key transmission mechanism from water presence to water use. The performance of the variable on the GDP per capita is expected, since it is acknowledged in the literature that the economic conditions of a country are among the major determinant of average yield levels (Ruttan 2002). This relation is channeled mainly through higher access to technology, fertilizers, and know-how for small and large agricultural enterprises.

We performed the same regression models utilized above (i.e. Equations 4–7; cases from I to IV) considering each of the ten crop individually (i.e. the coefficients/exponents become crop specific). Table S7 in the Supplementary Material shows the regression coefficients for every crop, while graphic examples related to three products are in Fig. S6. Running the model that includes the IWRM indicator as the only regressor (case I), we observe that yield coefficient values range from 0.01 for millet to 0.1 for maize. The regressions for the water footprint give coefficients from -0.01 to -0.05. All coefficients are statistically significant. We can indeed deduce that the water management dimension provides new information beyond the most traditional measures used for the analysis of the water footprint and agricultural productivity. Having a more sophisticated level of Integrated Water Resource Management generates a positive impact on yields of important crops for human nutrition and a correspondent saving of water resources for the same cultivations. Very importantly, these trends hold across all countries despite large economic and climatic differences, both considering all products together and each of them separately.

We recall that the total water footprint figure sums green (precipitation) and blue (surface) water. We expected that a virtuous relation between water management and efficiency in water use would have emerged also for the blue water alone, which is usually associated to irrigation. Therefore, we performed single crops analysis by exploring the relation between the IWRM indicator and the blue water footprint, isolated from the green one (CWASI database, Tamea et al. 1961-2016); surprisingly, we did not detect any significant correlation. This result could be the effect of two opposite trends. On the one hand, countries with a better integrated water management system invest more in irrigation infrastructures and present higher crop blue WF. On the other hand, such countries also have a better technical know-how for modulating between green and blue water use according to specific conditions, with the aim of avoiding overuse of water for irrigation. This could entail savings of crop blue WF. Deeper investigations are needed to disentangle these relations (Rosa et al. 2020, Rosa et al. 2019, Antonelli and Sartori 2015).

6. DISCUSSION AND CONCLUSION

In order to explore the role of water resources in contributing to a productive and sustainable agricultural sector worldwide, it is necessary to consider the dimension of economic water scarcity beside the most traditional one of physical water availability. Following a wide but somehow unorganized literature, we defined economic water scarcity as a situation in which technical and institutional capacities or financial resources are insufficient to supply adequate water quantities for human use. If physical water availability is quantifiable in different ways, economic water scarcity faces the challenge of measurability. We identified the Integrated Water Resource Management Indicator, developed by UN Environment in the framework of the construction of the indicators for the Sustainable Development Goals, as an interesting attempt to collect and organize information on legislative, managerial and financial environment related to water management at nation level. We aimed to explore whether the IWRM indicator could represent a useful proxy for measuring economic water scarcity. In this view, we used it for a wider scope with respect to the one for which it has been created.

By analyzing the relation between the IWRM indicator and social and environmental dimensions we show that socio-economic development is not the only determinant of sophisticated water management levels. From a policy perspective, it emerged that high investments in water management institutions seems to be driven by necessity only in countries of very severe water scarcity. Moreover, despite strong climatic and economic differences, some relations between the IWRM indicator and agricultural production hold across countries. Advances in IWRM levels are associated to yield increase up to 13% and to unit water footprint decrease up to 20%. These improvements may decrease the negative effects of EWS on agriculture, that usually imply low performance and high inefficiency in water use. From a statistical point of view, the IWRM indicator maintains its relevance also when we disentangle its influence on the variables of interest from the one exerted by the GDP per capita and by water presence in a country. Moreover, if considered alone, GDP per capita shows its statistical significance, as expected, but the same does not hold for volumes of water per capita alone, suggesting the presence of a gap between water availability and water use in agriculture. The relevance or the IWRM indicator is confirmed also in investigations on each of the ten crops separately. Taking into account these results, we conclude that the Integrated Water Resource Management Indicator is a good quantitative measure of economic water scarcity in agriculture.

Regarding the contribution of our work to the field, we notice that there exists a high number of qualitative studies conducted through field work, interviews and focus groups that deal with the importance of water governance and integrated water management for improving both access to water and efficiency in its use (among others Biggs et al. 2013, Dell'Angelo et al. 2016, Yu et al. 2016). There is a wide literature also on case studies conducted with a quantitative methodology based on micro-data collected in the field (among others Ostrom et al. 1992, Stein et al. 2011). More descriptive large-scale works are also available (Molden 2007). However, cross-country studies with data-based approach on water governance and management are missing, in consideration of the difficulties in measuring EWS. We produce an advancement in existing knowledge on the topic, by making the first attempt to identify indicators for measuring EWS, and by providing quantitative figures on the association between economic water scarcity, efficiency in water use and agricultural performance. Moreover, we aim to introduce the relevance of the economic water scarcity dimension into the literature on the water footprint and virtual water trade, which is currently more focused on hydrological variables for the assessment of water availability (Lenzen et al. 2013, Antonelli and Sartori 2015, Tuninetti et al. 2019, Rosa et al. 2019, D'Odorico et al. 2019). An important contribution to the field is represented by Rosa et al. (2020), who quantify EWS on agricultural land by focusing on the gap between actual and potential irrigation in rain scarce areas. By utilizing the IWRM indicator as proxy for EWS, we aim to address a wider range of aspects of the EWS, including, together with irrigation infrastructure, also governance, management, legal and institutional concerns. Moreover, we consider the impact of IWRM on both a basket of products and on specific single crops, while Rosa et al. (2020) quantify EWS for a large aggregate of crops.

In our research there are a number of sources of uncertainty, both at qualitative and quantitative level. First, the IWRM indicator is compiled at national scale, but it gives no information on how those policies may vary across internal provinces or regions, and consequently on the relation with heterogeneity in yield and water footprint within each country. Nevertheless, many water policies are decided by central governments, such as for example the strength of decentralization efforts, which makes the national level appropriate for a nation-wide consideration of the level of sound water management. Second, the construction methodology of the index translates qualitative information form the survey into quantitative scores, which produces uncertainty in measurement accuracy. Third, as we explained above, statistical uncertainty is present, as expected, given the wide spatial scale of the analysis and the high number of factors that have an impact on the water footprint and the yield. Our aim is to acknowledge the new information that does emerge from the relation among the variables of interest.

We acknowledge some limitation of this research. First of all, despite its pivotal role in quantifying Integrated Water Management elements across countries through a common methodology, the IWRM indicator itself contains some shortcoming according to scholars. Bertule et al. (2018) focus mainly on the SDG indicator 6.5.1 assessment approach. First, they highlight difficulties in objectivity and transparency in country assessments, because it is not trivial to eliminate the range of potential bias that may be brought by the responding stakeholders or by countries' wider political priorities, or by their interpretation of specific IWRM dimensions that should translate to in practice. Second, although guidance was provided, the authors warn against differences in interpretation of assessment questions and thresholds. For example, low or very low degree of implementation of a given measure may be interpreted differently by different countries, depending on the contextual needs, politics, or ambitions for such mechanisms to be in place, with negative consequences on the global comparability of the results (Zinzani and Bichsel 2018). Third, there are difficulties in comparison of results overtime. For given countries and indicator of good IWRM performance may not lie in the static indicator value, but in the progress of their indicator with respect to the past, which would indicate the establishment of a successful path (or *vice-versa*). This consideration contributes to question the feasibility and the appropriateness to set the same global targets for all nations, when countries start from very different initial situations. Guppy et al. (2019) identify a potential gap within the SDG 6 indicator framework, to which the IWRM indicator belong. The gap is about poorly understood linkages between core targets and their indicators. They question whether the IWRM indicator, by measuring the wide range of management tools, is able to capture the actual figures of equity, efficiency and sustainability in water use, that are the goals that the same indicator aims to pursue.

Second, turning to this research, we notice that it is methodologically challenging to disentangle the impact of the dimensions contained in the survey questions that compose the IWRM indicator on yield and water footprint from other important factors. We have the advantage that many agronomic variables, (e.g. fertilizers) are highly correlated with GDP per capita, which has been included in the regression analysis as potential confounding factor. However, more exact disentangling would require further research. Moreover, as we explained in the previous section, more research is also required for estimating the relation between the IWRM indicator and blue water data in agriculture. The focus on irrigation water is compelling on the one hand for scientific interest, and on the other hand because it represents the dimension on which it is more straightforward to intervene with policies, if compared to rainfall water. For these reasons, we performed analysis on blue water at country scale, consistently with the whole work, and we did not detect statistically significant relations with the IWRM indicator. Probably it would be more useful to work at smaller scales, such as provinces or cells, in order to capture associations between water management practices and efficiency in irrigation use.

Nevertheless, despite the intrinsic limitations of the IWRM indicator and the noise in the data produced by the issues explained above, we do observe that our results signal useful information deriving from the water management indicator, opening the way for a more detailed analysis on the benefits of sound water management tools for agriculture.

Further steps for this research would include an exploration of the relation between the water management indicator and within-country income inequality, in order to complement the analysis done with respect to the GDP per capita and to the Human Development Index. It would be informative also to investigate the relation of the IWRM indicator with metrics on the general quality of institutions of a country. Furthermore, the focus could be on countries grouped in regions, in order to capture specific features of given areas of the world that would affect simultaneously all the variables of interest. Analysis across regions and within regions could be conducted, and information from the different isolated sub-pillars of the indicator could be exploited. It would be also useful to have a IWRM indicator at a lower scale for provinces within countries, in order to observe territorial specificities. Should this data be available, it would be possible to investigate their relation with already existent information on yield and water footprint at cell level (Monfreda et al. 2008, Tuninetti et al. 2015). Moreover, it would be useful to study the evolution of the water management indicator overtime, by exploiting the information of the survey waves of 2007 and 2011, in order to estimate the rates of improvement for each country (UN Environment, 2018). It would be also informative to explore non-linear relations among the variables of interest. Finally, it would be interesting to study the impact of the IWRM variable on water access and use in non-agricultural fields, such as consumption in urban areas, sanitation, industrial use, and more or less industrialized food processing activities.

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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 material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.envsci.2020.07.017.

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