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Is water consumption embedded in crop prices? A global data-driven analysis

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Abstract

Agricultural production exploits about 70% of all water withdrawals around the globe, but to date, it is not clear if and how this water consumption is taken into consideration in the price of the agricultural primary goods. To shed light on this point, we analyze the farm gate prices of twelve representative crops in the period 1991-2016, considering data from 162 countries in total. The crop price dependence on the water footprint is investigated, also accounting for the country's water scarcity as a possible additional determinant of the price, and of the land footprint as a possible confounding factor. We find that prices of staple crops (e.g. wheat, maize, soybeans, and potatoes) typically embed the amount of water used for their production. Differently, food products that do not contribute in an essential way to the human diet and whose production is more export-oriented (e.g. coffee, cocoa beans, tea, vanilla) exhibit weaker or negligible water-price links. These variations may be ascribable to specific market dynamics related to the two product groups. Staple crops are often produced in markets where many producers have more space for price setting and may have an incentive to include also the value of water in the final crop price. In contrast, cash crops are cultivated in situations where few producers are 'price takers' with respect to the international market. This mechanism may decrease the influence of the water used on crop farm gate price composition. The understanding of different water impacts on crop prices may be useful for increasing efficiency in water allocation and governance decisions, with the aim of improved environmental sustainability in this domain.

1. Introduction

In recent years the concept of water availability has changed: for long time water was considered an infinite resource due to its renewability, but, due to an increased awareness of the scarcity of this resource (in a usable form) in many areas of the world, this perception is not reasonable anymore [12, 45, 54].

Water is fundamental for all human activities but agriculture consumes 70% of all freshwater withdrawals over the globe [20]. Most of the water used in agriculture derives directly from rainfall [51] and it is named *green* water. However, the volume of water extracted from rivers, lakes, and aquifers for irrigation purposes (*blue* water) also plays a fundamental role: even if the amount of irrigated land represents just 20% of the total land dedicated to agriculture, the food resources that it provides sums up to 40% of the global agricultural production [37][16].

Every increase in the world population drives an increment in the demand for agricultural goods, which in turn requires water in order to be produced [26]. By 2050 the world's population will increase by approximately one fourth with respect to the current figure [59]. At the same time, an increase of one Celsius degree in global warming has been estimated to reduce the renewable water resource availability by 20% for almost 7% of the global population [34]. Furthermore, the consumption of livestock products, whose production is significantly water-intensive, is growing as a result of higher incomes and urbanization processes that reshape people's diets [41]. Consistently to these projections, despite the improvement of technologies, water withdrawals are expected to constantly increase over time. In the main food production areas of the world, water withdrawals from rivers, lakes, and aquifers, are significantly reducing the freshwater reserves. This results in a quick and continuous deterioration of the water ecosystems, which are degrading at an

even faster rate than other threatened environments [36][60][53][6][17].

In this picture of growing environmental stress due to over-exploitation of water resources, there has been an enduring debate of the possibility to attribute a price to water [63][33][40][44][49]. Some studies argue that assigning an economic value to water would improve the efficiency in the allocation of this resource, shifting its consumption towards more sustainable habits [56][50][24][61][64]. In this case, water would be treated as a private good where the price is decided by the interactions of different subjects on a competitive market. On the opposite side, other researches argue that water should not be considered as a private good because it is a fundamental human need. According to this view, the allocation of this scarce resource should occur without involving necessarily monetary transactions, and it should generate benefits for the whole society [52][7][46][55][38].

Other studies do not enter this discussion but declare that one reason for the absence of economic value of water in agriculture is due to its direct link with the land in which it is embedded [5][8][31]. According to this point of view, the value of water would be implicit in the value of cultivable areas. Land with higher water availability, in fact, has a greater opportunity cost than arid land [43]. Its opportunity cost is in fact determined by its possible alternative uses.

In the framework of this debate, some authors claim that agricultural product prices do not reflect correctly the amount of water used for their production [31][29][1]. In this general debate, however, there is a lack of large scale data-driven analyses. On a regional, single-crop scale, recent research [22] has investigated the total impact of water for almond production units in California showing that there is a correlation between high prices of goods and high water content. Although the objective of this analysis is different from our aim, it provides an interesting indication of the correlation between crop water footprint and market prices of products. Global-scale multi-crop analyses are still lacking.

We aim to fill this gap by investigating the relationship between farm gate prices - i.e. the prices assigned to the agricultural goods that leave the farm and reach the first point of sale - and two environmental resources used for their production: water and harvested area, where the latter is considered to address its possible role as a factor confounding the price-water relation. We consider the water component both in terms of quantity utilized for each crop (crop water footprint) and of water scarcity per capita at a country level (according to the Falkenmark Water Stress Indicator [19]). The scale is global, with a country-scale resolution, and the period investigated is from 1991 to 2016.

2. Data and methods

2.1. Data

The data used in this study fall into six categories: agricultural production (in *tons*), farm gate price (in current *US*$), water footprint ($m^3/ton$), hectares harvested of each crop (ha/ton), evapotranspiration (mm/ha), and total per capita renewable water resource (m^3/pc).

All data we use are at the country scale and refer to annual values in the period from 1991 to 2016. All data except total water resource are also crop specific. The data-set includes 162 countries, covering all nations where data are available. Table 1 summarizes the main characteristics of the data sources used in this work.

The data regarding the production of goods and the harvested area are provided by the Food and Agriculture Organization of the United Nations' database [21]. For each crop, the database provides the quantity of tons ($Q_{cp}(t)$) and the amount of harvested hectares ($A_{cp}(t)$) of product p corresponding to the country c in the year t. The ratio between the harvested area and the tons produced allows us to consider an indicator called land footprint ($L_{cp}(t)$)[32], which is the reverse of the yield (*ton/ha*).

The economic value of agricultural production ($V_{cp}(t)$) in current *US*$ is given by FAOSTAT and it refers to the price attributed to a ton of product when it leaves the farm and arrives at the first point of sale. It is called *Farm Gate Price*. The prices of goods widely vary among countries. To compare the prices of goods produced in different national markets that present distinct living standards and whose national currencies are subject to fluctuations of exchange rates, it is necessary to convert them into a common currency. In order to obtain a comparable price on the global market, we have divided the prices in current US dollars by the price level ratio[1] (plr_{ct}, in *US*$/*Int*$, see [62]). This conversion allows us to obtain a hypothetical currency that allows global comparison of prices, the PPP International Dollar ($P_{cp}(t)$), where PPP means *Purchasing Power Parity*. Finally, we deflated the international prices in PPP using the GDP deflator $defl_t^c$, published by FAOSTAT. Since the price level ratio already accounts for the country-wise fluctuations of inflation, we consider the USA deflator calculated by taking 2010 as the reference year ($defl_t^{USA}$). In this way, we obtain the prices deflated for every year and for each product ($P_{cp}^{(d)}(t)$), with reference to the year 2010, according to

$$P_{cp}^{(d)}(t) = \frac{P_{cp}(t)}{defl_t^{USA}} \qquad t = 1991,..2016. \qquad (1)$$

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[1]The ratio indicates the number of dollars needed to buy a bundle of goods in a given country, compared to what would be necessary for buying the same bundle in the USA.

The water footprint of an agricultural product is the amount of water used to produce one ton of that crop [39]. Water footprint data are available as a time average from 1996-2005 on WaterStat[2][39]. These data change in space but not overtime. In order to take into account the time dependence of the crop water footprint $F_{cp}(t)$, we use the data-set obtained through the so-called Fast Track approach [58] which transforms the above-mentioned data of the crop water footprint from constant to time-varying considering changes in agricultural yields. The data set is presented in [57].

Data of evapotranspiration (in *mm/ha*) would be available from many different sources in terms of potential evapotransporation. However, we are interested in actual evapotranspiration data, that we obtain through the relationship between the crop water footprint (in m^3/ton) and the land footprint (in ha/ton) as [30]

$$ET_{cp}(t) = \frac{1}{10} \frac{F_{cp}(t)}{L_{cp}(t)} \qquad (2)$$

where the numerical factor 1/10 is introduced to obtain evapotranspiration expressed in mm.

In order to consider the overall water scarcity at a country level, we take into account the total renewable water resources WR_c) [2], that is defined as the sum of the internal renewable water resources (IRWR) and of the external renewable water resources (ERWR). According to the Falkenmark Water Stress Indicator [19], we divide WR_c for the annual population $Pop_c(t)$ for each country obtaining the per capita water availability ($W_c(t)$). With the aim of considering an indicator that highlights the per capita water shortage instead of water abundance, we take the difference from the global maximum water availability. This water deficiency indicator ($D_c(t)$) is therefore obtained as:

$$D_c(t) = \max_c [W_c(t)] - W_c(t). \qquad (3)$$

A heterogeneous set of agricultural products is selected: wheat, maize, rice paddy, soybeans, potatoes, apples, avocados, cocoa beans, green coffee, cottonseed, tea, and vanilla (see table 2). Four goods are staple crops (wheat, maize, rice paddy and soy beans) that, together with potatoes, cover roughly 60% of the global calorie intake [15]. Besides, we add other goods such as cocoa, cottonseed, tea, green coffee and vanilla whose large-scale cultivation is more oriented for export (commonly known as cash crops), and two fruit items (avocados and apples) characteristic of tropical and temperate areas, respectively. The selected crops exhibit wide variability in average water footprint and price (see table 2). Also, the coefficients of variation of the water footprint and the

prices (ratio of the standard deviation to the mean, both weighted upon production) span a wide range of values implying a large spatial and temporal heterogeneity for each crop.

The average of the economic water productivity (*EWP*), defined as the economic return of each product per unit of water used [42] (in *Int$/m³*), is obtained as the sum of the deflated global price of each product (in international dollars) for all years in all countries, divided by the total water footprint in all countries for each product over time. If we calculate an average of the *EWP* for each of the two groups, staple and cash crops, we do not notice a relevant difference[3]. The interesting element to consider is that, although in the *EWP* clear patterns between the two groups of products do not emerge, different trends can be observed in our analysis investigating the relationship between crop prices and water used, as we will show throughout the paper. The per-capita production size for each crop was obtained through the sum for all years and all countries, of the total tons produced by each country for that crop, divided by the respective population. We notice that production in per capita terms is highly variable, spamming from more than 112 kg per capita for maize to 0.001 kg per capita for vanilla. The total amount of water actually used for each crop is of course given by the interplay between the water footprint and the production per capita. For example, in the case of vanilla, its enormous water footprint does not translate into large total volumes of water consumed due to low production, and consequently, per capita consumption, compared to other crops.

Finally, the crops are distinguished by the geographical distribution of their production (see figure 1).

2.2. Methods

In order to investigate whether the water component is reflected in the market price of the basket of selected goods, we perform multivariate regressions, considering both all 12 crops together (all-product analysis) and each crop separately (single-product analysis). The deflated International dollar PPP ($P_{cp}^{(d)}(t)$) is considered as the dependent variable, and a set of different indicators are the explanatory variables (X_i). We consider a power-law relation between the dependent and the independent variables, that translates into a linear form upon log-transformation, namely

$$\log_{10} P_{cp}^{(d)}(t) = \beta_0 + \sum_{i=1}^{m} \beta_i \log_{10} X_i(t) + \epsilon \qquad (4)$$

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[3]It can be deduced that from the point of view of economic water productivity it seems convenient to grow crops products with low water footprint and higher economic value (such as apples and potatoes), although in reality, many more variables influence the decisions on crops selection.

Table 1. Variables and data sources considered in this work. The time interval reports the period available in the datasets. Links to the open source databases are reported.
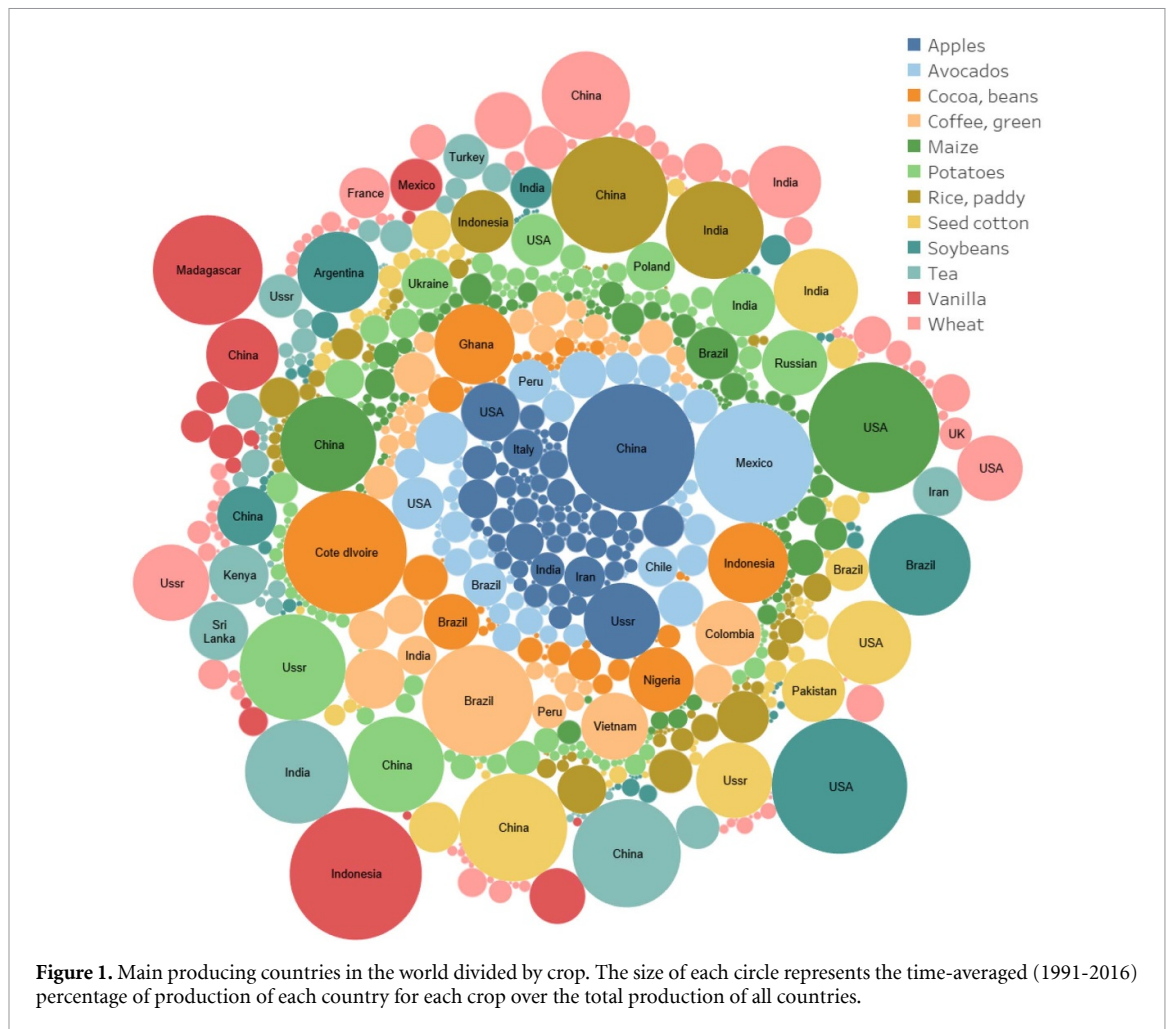
Variable	Description	Source	n. Countries	Time interval
$V_{cp}(t)$	Value of agricultural production in current prices ($US\$/ton$)	FAOSTAT[a] (http://www.fao.org/faostat/en/#data/QV)	around 245	1991-2016
$Q_{cp}(t)$	Production quantity ($tons/yr$)	FAOSTAT[a] (http://www.fao.org/faostat/en/#data/QC)	around 245	1961-2017
$A_{cp}(t)$	Area harvested (ha)	FAOSTAT[a] (http://www.fao.org/faostat/en/#data/QC)	around 245	1961-2017
$Pop_c(t)$	Annual population	FAOSTAT[a] (http://www.fao.org/faostat/en/#data/OA)	around 240	1950-2017
$F_{cp}(t)$	Crop water footprint (m^3/ton)	[58] (https://watertofood.org/data/)	255	1961-2016
WR_c	Total annual renewable water resource (10^9 m$^3/yr$)	AQUASTAT[b] (http://www.fao.org/nr/water/aquastat/data/query/index.html?lang = en)	200	1958-2017
prl_{ct}	Price level ratio of PPP conversion factor to the market exchange ($US\$Int\$$)	World Bank (https://data.worldbank.org/indicator/PA.NUS.PPP)	264	1990-2017
$defl_t^c$	GDP deflator (base year varies by country)	FAOSTAT (http://www.fao.org/faostat/en/#data/PD)	around 212	1970-2017

[a] For the FAOSTAT database the number of countries changes according to the crop.
[b] For the Total Annual Renewable Water Resource, AQUASTAT provides data as a mean every 4 years.

Table 2. Basket of the products considered in this work. Columns report the global average crop water footprint (weighted on production) throughout the time period considered (1991-2016) and the global average price per ton (weighted on production), expressed both in International dollars and in US dollars (in parenthesis coefficients of variation CV_w across both countries and years are reported). The size of production in per capita terms is expressed as a global average between countries and years for each crop (kg/pc). The economic water productivity (EWP, in $Int\$/m^3$) shows the economic return of one cubic meter of water, different for each crop. The last column reports the number of producing countries within our dataset for each crop in 2016.

Product Description (n.FAOSTAT)	Water Footprint (m^3/ton)	Avg price (Int$)	Avg price (US $)	Avg Prod pc (kg/pc)	Avg EWP (Int$/m^3$)	Num. Countries 2016
Apples (**515**)	646 (0.85)	1175 (0.67)	658 (0.56)	9.76	1.75	79
Avocados (**572**)	1112 (0.80)	1461 (0.53)	958 (0.64)	0.52	1.23	45
Cocoa, beans (**661**)	21711 (0.41)	3497 (0.56)	1535 (0.48)	0.58	0.15	34
Green coffee (**656**)	14739 (0.67)	3737 (0.64)	1865 (0.57)	1.16	0.23	46
Cottonseed (**328**)	3259 (0.62)	2016 (0.69)	972 (0.60)	9.78	0.55	57
Maize (**56**)	957(0.71)	374 (0.83)	216 (0.53)	112.73	0.38	125
Potatoes (**116**)	212 (0.46)	484 (0.64)	264 (0.59)	49.91	2.16	120
Rice, paddy (**27**)	2282 (0.53)	948 (0.53)	413 (0.96)	98.15	0.39	88
Soybeans (**236**)	2074(0.36)	545 (0.72)	369 (0.43)	31.23	0.27	73
Tea(**667**)	8409 (0.73)	4419 (0.89)	2178 (1.57)	0.61	0.47	33
Vanilla (**692**)	155587 (1)	12167 (1.6)	4348 (1.42)	0.001	0.07	5
Wheat (**15**)	1552 (0.46)	481 (0.72)	248 (0.39)	97.05	0.30	99

Figure 1. Main producing countries in the world divided by crop. The size of each circle represents the time-averaged (1991-2016) percentage of production of each country for each crop over the total production of all countries.

where c runs over all 162 countries and t runs from 1991 to 2016, as explained in section 2.1. The set of explanatory variables (X_i), used alone $(m = 1)$ or in multiple combinations $(m \neq 1)$, includes the crop water footprint $(F_{cp}(t))$, the land footprint $(L_{cp}(t))$, the evapotranspiration $(ET_{cp}(t))$, and the per capita water deficiency indicator $(D_c(t))$. We include each explanatory variable step-wise in the model, keeping all the others constant, in order to detect the respective contribution in explaining the variance of the crop prices. The use of a logarithmic scale is justified by the fact that the quantities span different orders of magnitude. The regression coefficients are estimated with the weighted least square method. We run the regressions minimizing the sum of squared residuals weighted by the percentage of production for each country in every year with respect to the total tons produced by all the countries considered in the same year. In this way, we assign greater importance to the largest producers worldwide for each product. The statistically significant coefficients are identified by applying a Student's t-test with a 5% significance level.

The same regressions are performed also at an intra-product level in order to explore, for each crop, the associations between deflated price and the role

of water, detached from the land, in terms of both quantity and scarcity. To explore the temporal stability of associations between variables, for each product we run 26 multivariate regressions across countries, one for each year taken into consideration in this study.

In order to compare the results of the different models we use the adjusted coefficient of determination (R^2_{adj})[4].

3. Results

3.1. All-product analysis

Our analysis starts focusing on the relation between crop prices and crop water footprints. Figure 2 shows the scatter plot of these two variables considering all the products and all the years together. Different colors correspond to distinct crops and the size of the points represents the percentage of production of

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[4]The adjusted coefficient of determination (R^2_{adj}) quantifies the measure to which the regressor describes the variation of the dependent variable and considers both the number of independent variables and the sample size. Given the large sample size, however, its value is very similar to the standard R^2.

each country in every year referred to the global production of the same crop in the same year. The R^2_{adj} obtained from this first regression is 0.50.

The slope of the regression line is equal to 0.50 and significantly different from zero (p-value ≤ 0.05). If we convert the logarithmic values to an arithmetic scale we obtain

$$P_{cp}^{(d)} \propto F_{cp}^{0.50} \qquad (5)$$

implying that the crop water footprint impacts the price, but the effect becomes smaller as the monetary value of the crops increases. This trend recalls the law of diminishing returns which argues that the additional profit obtainable from the increasing use of one production factor (keeping all the others constant) tends to progressively decrease [35].

The results in figure 2 would suggest that water has a significant impact on pricing behavior. However, as mentioned, many studies claim that the value of water is implicitly included in the value of arable land [5][13]. To disentangle the roles of water and land, we investigate the possible relation between the hectares used to produce a ton of good and the respective amount of water needed. As it is shown in figure 3, the two variables are strictly and positively correlated with a R^2_{adj} equal to 0.95.

As a consequence, it is questioned how much of the relationship previously found between deflated prices in PPP and crop water footprint is actually ascribable to the water component. For this reason, we analyze the association between the deflated price in PPP and the land footprint by applying the weighted regression framework of equation (4), with $m = 1$ and $X_1(t) = L_{cp}(t)$. Also in this case, the slope of the regression line is positive ($\beta_1 = 0.53$) and significantly different from zero. Converting the value to an arithmetic scale (i.e. $P_{cp}^{(d)} \propto L_{cp}^{0.53}$), the curve takes on the same diminishing return trend observed for the previous model. Therefore, one could hypothesize that the water footprint follows the behavior described in equation (5) because of its embeddedness in the land variable. Since land is an input of production with an existing market it is expected to follow a law of diminishing returns more than water, which is often not regulated by markets.

Nevertheless the R^2_{adj} of the law $P_{cp}^{(d)} \propto L_{cp}^{0.53}$ is equal to 0.40, which is significantly lower than the coefficient of determination found for the regression with the crop water footprint as an explanatory variable (as shown in table 3). This lower value suggests that a part of the variance of the dependent variable could depend directly on the water component (see the Supplementary Material for a deeper investigation on the relation between the land footprint and the price, in figure S1).

In order to extract the information on the role of the water component alone on deflated prices, we partition the water footprint into its two components, as derivable from equation (2): land footprint and evapotranspiration. We perform the multivariate regression in equation (4) with $m = 2$, $X_1(t) = L_{cp}(t)$ and $X_2(t) = ET_{cp}(t)$. The coefficient of determination is higher than those of the two previous models ($R^2_{adj} = 0.53$) and the overall relation reads

$$P_{cp}^{(d)} \propto L_{cp}^{0.37} * ET_{cp}^{1.04}. \qquad (6)$$

The result reported in equation (6) indicates that keeping the cultivated land per ton constant, the deflated prices increase almost linearly with evapotranspiration, underlining a well distinguishable role of the water component in terms of volume used during the production of a given crop.

Finally, we investigate whether water scarcity at the country level has an influence in determining the price behavior. In order to investigate the role of water shortage, the regression is performed by adding water deficiency as a third explanatory variable beyond land and evapotranspiration. The result, as shown in table 3, indicates that water deficiency ($D_c(t)$) is positively and significantly correlated to price. This suggests that keeping the other variables unchanged, the deflated price tends to raise in the presence of greater per capita water scarcity. The value of the coefficient of determination R^2_{adj} is larger than the one of the models which do not consider water deficiency (0.56). Also, in this case, the slope of evapotranspiration ($\beta_2 = 1.03$) remains stable compared to the previous regressions and still with almost-unitary value, confirming the linear relationship between the deflated prices and the volume of water used in production.

3.2. Single-crop analyses

Regression analyses are also performed at the intra-product and intra-year level. By considering individual crops in single years, we examine the possible dependence of country-level crop price on the set of dependent variables considered in the all-product analysis. For each crop, we run 26 multivariate regressions, one for each considered year.

We describe in detail two illustrative examples for each product category: wheat and potatoes for staple crops, green coffee, and avocado for cash crops. The behavior of all 12 crops is summarized in table 4.

Figure 4 shows the time variability of the regression coefficients, β_i, obtained for wheat, potatoes, green coffee, and avocados. In the case of wheat the coefficients of the land footprint and water deficiency are statistically significant throughout the time interval, indicating that, as the explanatory variables increase, the related prices increase as well. Instead, the evapotranspiration coefficients become statistically different from zero only after the year 2003. Although more specific research is needed for the understanding of changes over time in the significance of the independent variables of every crop, we
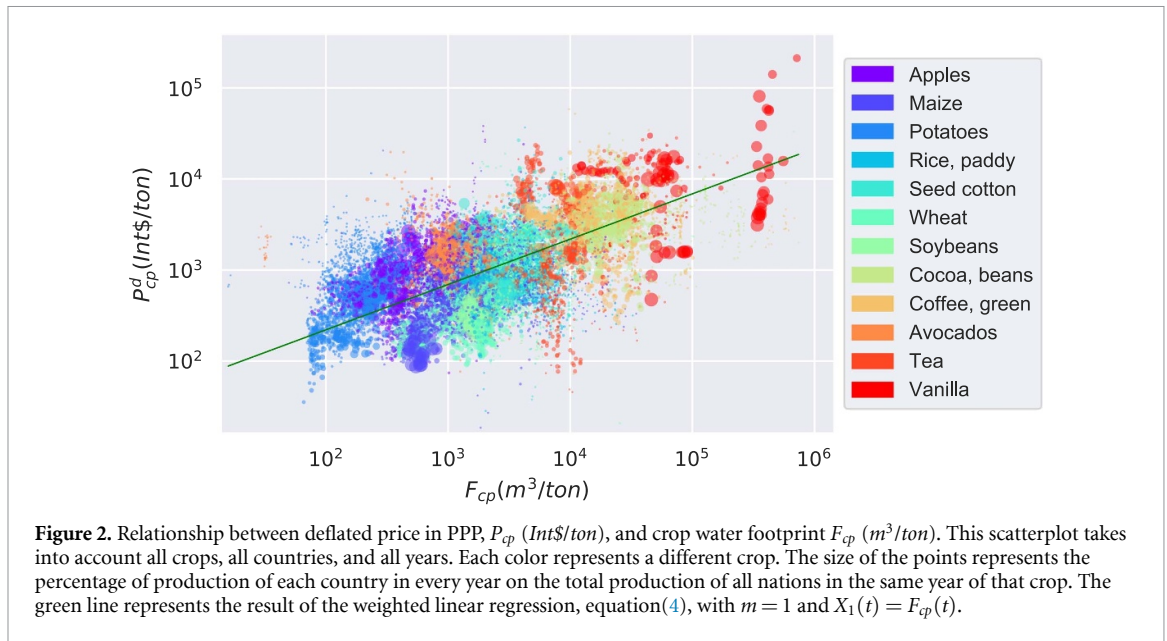
Figure 2. Relationship between deflated price in PPP, P_{cp} (*Int\$/ton*), and crop water footprint F_{cp} (*m³/ton*). This scatterplot takes into account all crops, all countries, and all years. Each color represents a different crop. The size of the points represents the percentage of production of each country in every year on the total production of all nations in the same year of that crop. The green line represents the result of the weighted linear regression, equation (4), with $m = 1$ and $X_1(t) = F_{cp}(t)$.
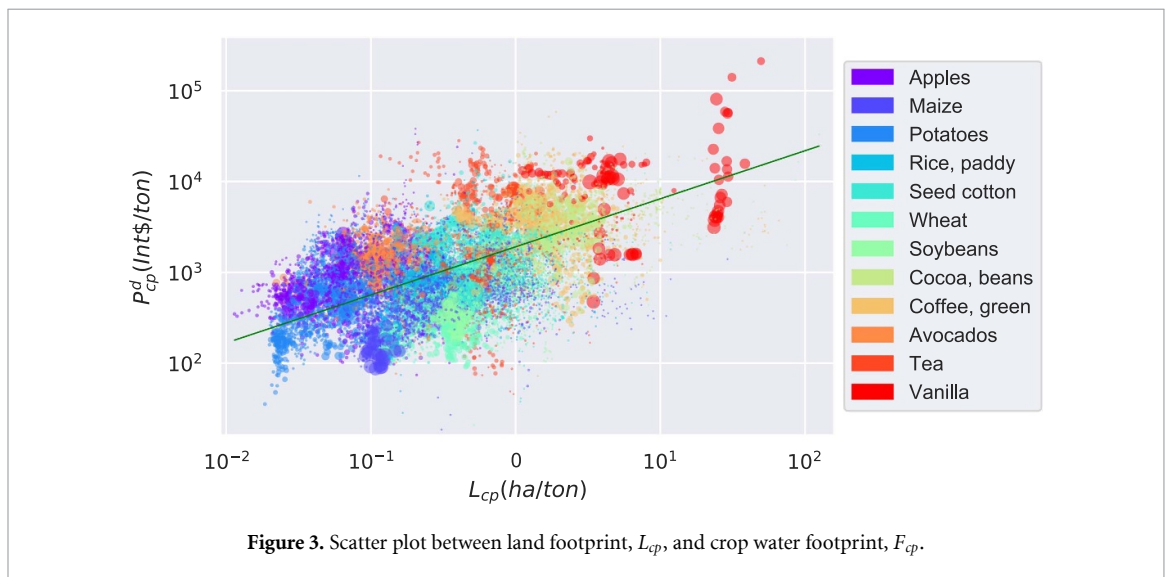

Figure 3. Scatter plot between land footprint, L_{cp}, and crop water footprint, F_{cp}.

Table 3. Results of univariate and multivariate regressions. All crops, all countries and all years are considered. The symbol (***) indicates the significant coefficients, identified by applying a Student's t-test with a 5% significance level.

N.countries: 162
N.obs: 19981

Explanatory Var. Independent Var.	$F_{cp}(t)$	$L_{cp}(t)$	$ET_{cp}(t)$	$D_c(t)$	$R^2 adj$
$P^d_{cp}(t)$	0.50(***)				0.50
		0.53(***)			0.40
		0.37(***)	1.04(***)		0.53
		0.41(***)	1.01(***)	0.19(***)	0.57

formulate some hypotheses for the interpretation of this result. The change in the statistical relationship between evapotranspiration and wheat price can be explained by the combination of strong fluctuations in wheat prices since 2003 and increased variability in wheat evapotranspiration over the same period. Regarding potatoes, the coefficients of the three variables are for the most part positive and statistically

significant, although water deficiency becomes significant only since the 2000s. This behavior could be ascribed to the fact that this indicator is gradually increasing over time because of the constant increase in the world population. As a result, the per capita water deficiency only starts to be reflected in market prices once it reaches higher values. At the same time, also the average price trend of potatoes encountered

strong changes during the 2000s, and this may have influenced the relation between water deficiency and price.

For green coffee, a different behavior is observed; prices are almost never significantly dependent on land footprint and water scarcity, and evapotranspiration exhibits only 10 positive-valued and statistically significant coefficients. The evapotranspiration coefficient for green coffee loses significance around the 2000s. Therefore, for green coffee, a clear relationship between the considered variables does not emerge. This behavior is even sharper in the case of avocados where all the coefficients except one are not significantly different from zero.

Table 4 illustrates the number of years for which the slope coefficients are positive and statistically significant for the three explanatory variables in the regression model for every crop in the sample. The main information captured from table 4 is that we can distinguish two different behaviors.

Products with lower water consumption and with a more spatial spread in the world - like wheat, potatoes, apples, and soybeans - show at least two out of three coefficients systematically significant over time. These crops are cultivated in a higher number of countries and are located in the bottom part of the data bundle in figure 2. For this group of agricultural goods, we find a positive and increasing price-water relationship at an intra-product level.

On the contrary, the same relation does not hold for the most water demanding products in terms of water footprint. This group of crops (like vanilla, green coffee, and cottonseed) are cultivated in a lower number of countries, and in this case, the price-water relations are less clear at the intra-product level. These crops are placed on the top right section of the data bundle in the figure 2 and, therefore, in the portion of the regression curve with the lower slope, if considered at an arithmetic scale.

4. Discussion and conclusion

4.1. Discussion
The literature claims that many agricultural products are placed on the national and international markets at a price that does not include the cost of the water used in production [31]. However, there is no large scale data-driven studies that analyze whether the water used for agricultural production is considered within the market prices on a global scale. Our work aims to fill this gap. We started our study focusing on the association between water footprint and crop prices, finding a statistically significant relationship, even if, as water footprint increases, crop prices tend to rise but at a progressively lower rate.

Literature claims also that the value of water is inextricably related to land [5][28]. Taking this

Table 4. Crop-specific number of coefficients β_i that are positive and statistically significant in the 26 multivariate regressions (one for each year) adopting land footprint (L_{cp}), evapotranspiration (ET_{cp}) and water deficiency (D_c) for every single crop. For example, in the case of apples, coefficients are statistically significant in 26 years for land footprint, in 23 years for evapotranspiration and in 23 years for water deficiency.

Crop	$L_{cp}(t)$ (ha/ton)	$ETcp(t)$ (mm/ha)	$D_c(t)$ ($m^3 pc$)
Apples	26	23	23
Avocados	3	0	1
Cocoa beans	12	23	8
Green coffee	1	10	5
Cottonseed	0	3	26
Maize	26	0	26
Potatoes	26	26	11
Rice Paddy	11	0	16
Soybeans	26	25	14
Tea	24	2	11
Vanilla	6	1	0
Wheat	26	14	26

connection into account, we found that land footprint and crop prices are related, but crop prices are also significantly determined by water, both in terms of quantity (evapotranspiration) and scarcity (water deficiency). Moreover, as water scarcity increases, crop prices tend to rise but progressively to a lesser extent. From an economic standpoint, this behavior corresponds to the theory of diminishing marginal returns which establishes that the additional output obtainable from the gradually increasing use of a production factor, keeping all others constant, progressively tends to decrease. Therefore, in the driest countries, water seems to behave as an asset comparable to land and, consequently, often follows the law of diminishing returns.

Studies about water use distinguish the so-called green water (i.e. rainfall) from the blue water, which is the irrigation water that is typically withdrawn from surface water bodies (rivers, lakes, etc.) and groundwater. In this study we also considered the blue water footprint isolated from the green one, analyzing its impact on price behavior. We expected blue water to be reflected in crop prices since it is the only kind of water resource where tariffs are applicable, although there exists a wide heterogeneity of situations regarding the pricing of irrigation schemes worldwide [45][11]. Nevertheless, the dependence of prices on the blue water footprint was negligible. This result could be due to the smaller quantities in terms of volumes used for agriculture with respect to green water and to less overall availability of data. In any case, additional studies are needed to better understand the performance of the blue water component [4].

We carried out the study also at single-crop level, in order to investigate the behavior of the variables considered within the production of each individual crop. The results allowed us to identify two main

Figure 4. Time behavior of the coefficients β_i of the multivariate regression analysis in equation (4) (with area per ton, evapotranspiration and water deficiency as explanatory variables) for wheat (a), potatoes (b), green coffee (c) and avocados (d). The different coefficients are identified both by colour and by a different symbol. The larger (smaller) markers identify coefficient significantly (non-significantly) different from zero at a 5% level.

behaviors, with some crops confirming the significant price-water relation, and others providing less clear results. These two behaviors can be associated with two specific crop categories, generically referred to as staple and cash crops, respectively.

Staple crops represent a substantial part of the caloric requirement of many diets [15] and are produced in large quantities. Wheat, maize, soybeans, rice, potatoes, and apples fall into this category. For staple crops (apart from rice), the water component is reflected in their market prices. Cash crops are more water-demanding and their production is smaller with respect to staple crops and it is concentrated in fewer countries. Literature suggests that a cash crop is a good which is grown almost exclusively for its economic value on the national and international market [3]. For this group of products, the relationship between water use (or land use) and the price seems to be weaker compared to the first category. Coffee, cocoa beans, cottonseed, tea, vanilla, and avocados, whose production is usually more oriented for export, belong to this category. If we consider the relation emerged in figure 2, expressed in arithmetic scale, we see that the marginal productivity of water seems to be reflected in the market prices for staple crops, while this does not happen for the so-called cash crops, which are located at the top right of the data bundle.

Among the reasons for this diversity we may find the different production dynamics of the two crop categories.

Rice displays a peculiar behavior since it belongs to the staple crops category but it shows a pattern similar to one of the cash crops. This may be due to different factors. Firstly, rice consumes more water than other staple crops and, therefore, it may follow the law of decreasing marginal returns, for which the additional profit obtained from the increasing use of one production factor (keeping all the others constant) tends to progressively decrease. Secondly, although the water footprint of rice documented in the Asian regions (which are among the largest producers in the world) is high, relying extensively on irrigation water, on average it does not contribute excessively to water scarcity in the region, given the abundance of water resources (despite there existing high heterogeneity within the area) [10]. This may lead to a detachment of the dynamics of water use for rice production from those linked to prices. Finally, more investigation is needed in analyzing the role of subsidies in the prices of irrigation water, that may lead to an under-representation of water in the final farm gate price of rice.

We also tentatively explored the economic water productivity intended as the monetary return

obtained from one cubic meter of water for each crop [42], (as shown in table 2). The average economic water productivity for staple crops in terms of dollars per cubic meter does not seem to differ significantly from the one obtained for cash crops. A larger water footprint per ton for cash crops does not seem to significantly affect their lower economic water productivity. The clear pattern found in the distinction of the two categories in the impact of water use on product prices does not seem to be found in the calculation of their economic productivity.

4.2. Economic interpretation

Although the distinction between cash and staple crops is subject to the context in which it applies, it is useful in this analysis as it allows us to formulate a hypothesis for the understanding of the two macro behaviors [25]. Staple crops are often produced in situations embedded in more competitive market dynamics, in which many producers, in order to maximize profits, must include to a higher extent inputs values into the final crop price, therefore taking more into account also the value of water. Differently, cash crops are often produced in situations of oligopsony and oligopoly, where the farm gate price is more influenced by few producing or trading firms that are in a "price-taker" position with respect to the international markets. In oligopsony, few companies buy cash crops from many small producers and re-sell them on the international market at a fixed price [48][47]. In an oligopoly, few corporations are directly involved in the extensive production of those crops. In both cases, large firms own the market power for setting final prices according to the incentives provided by the international trade of those crops and can afford to decouple the price creation from the cost dynamics related to some inputs, such as water. The possibility to trade the cash crop products at a global scale determines both scale and quality of the production [18]. Paradoxically this process concerns those products that require relatively more water for their cultivation if compared to the others included in this study, as shown in table 2. As an example of market concentration, 80 percent of all cocoa exported by Sierra Leone is handled by one single firm [9]. Few companies that produce cash crops have the freedom to decide the economic parameters of the commercialization processes and often agree on a common profit-maximizing strategy. This is the case of coffee, for instance, a crop that has experienced abrupt price changes over time [27]. The control on the coffee markets, in fact, is performed by a few corporate groups through a restriction of the export quotas with the aim of keeping the prices high [14][23]. In this way, companies own market power over farmers and are able to appropriate the surplus generated by the exports. In our analysis, the dependent variable of the regression, the deflated crop price, tends not to grow above a certain threshold for products defined as cash crops and this may happen because it depends less on perfect competition dynamics.

4.3. Conclusion

With the present work, we have contributed to disclose the water-price relation for agricultural goods, addressing the problem with a data-based approach with data from the whole world. Through this method, we have found that some of the controversy characterizing the literature on this issue could be ascribed to the fact that different crops behave differently during the production and commercialization process, with the price of staple crops maintaining a significant imprint of water used in their production. We believe this result could have relevant implications also in the debate on the possibility to explicitly attribute a monetary value to water used in agriculture. It lays the groundwork for future analyses of crop categories to explore in more detail the market mechanisms behind each of them. From a theoretical point of view, the result addresses the unequal consideration given to the different production inputs of crops, from which water is often excluded [1]. From a more practical standpoint, the result may help in designing targeted solutions for contexts in which a clear tendency of overuse of water is present, such as one of the cash crops.

More research focused on specific crops, their production processes, and the kind of producers involved is certainly needed. Should further results confirm the finding of the present study, we could argue that, instead of recommending blueprint solutions of water management to be applied to every cultivation, targeted policies could be designed according to the trends related to each crop category. For example, a price could be applied to water used by large enterprises involved in cash crop production and commercialization, in order to discourage the overuse of water resources that emerged from our analysis.

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