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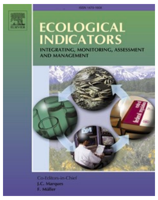

Original Articles

Estimating the economic value of green water as an approach to foster the virtual green-water trade

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ABSTRACT

Green water – precipitation that is stored in the soil as moisture and consumed in the production of biomass – provides the main source of water for crop cultivation, pasturelands, forestry, and terrestrial ecosystems. At a local level, green water is land-bound and cannot be easily allocated between uses. However, at the global level, agricultural commodities and their embodied virtual water are traded between countries. This trade typically sees the cultivation of crops in water abundant rainfed locations exported to regions that would otherwise have employed local irrigation resources. The result is a global saving of irrigation water and the negative environmental externalities associated with irrigation. In addition, scarce blue water resources are freed up for other (often higher valued) uses.

Here we assess whether there is an economic rationale for the virtual green-water trade and the increased and intentional allocation of crop cultivation to water abundant rainfed locations. We model a realistic case study of maize cultivation on representative farms in 16 major maize producing regions (across four continents) and provide the first spatially variable estimates of the economic value of the green water employed. These economic values are contrasted with the economic value of blue water used for irrigation. We find that the volume of green water employed in the cultivation of maize varies between 409 m^3/tonne and 1547 m^3/tonne; the estimated economic value of green water varies between $ −0.04 m^3 and $0.12 m^3. We demonstrate how these economic value estimates can inform crop allocation decisions in favour of green water-based cultivation and inform decisions regarding the intensification and horizontal expansion of rainfed agriculture. In so doing, we aim to provide a further rationale for the green water-based measures that have been identified in the literature as the principal means of providing the additional fresh water needed to address pressing global challenges beyond the case study.

1. Introduction

Green water ($Green_W$) is precipitation stored in the soil as moisture and directly consumed by plants and forestry during biomass production when it is evapotranspired by and incorporated into a plant or wood. The consumption of $Green_w$ supports crop cultivation, pasturelands, forestry, and terrestrial ecosystems (Savenije, 2000; Hoekstra et al., 2011).

Approximately three-fifths of global precipitation over land ends up as $Green_w$ (Oki and Kanae, 2006). Moreover, Hoekstra and Mekonnen (2012) estimate that ~ 90% of the water physically consumed in crop production, which itself accounts for ~ 90% of global consumptive water use, is $Green_w$ (equivalent to 5,771 Gm^3/year), and other authors have reported similar findings (Rost et al., 2008; Liu et al., 2009; Siebert and Döll, 2010; Liu and Yang, 2010; Fader et al., 2011).

Even though the critical importance of $Green_w$ has been increasingly recognised since Falkenmark (1995) first introduced the concept, as multiple authors have noted (Savenije, 2000; Rockström, 2001;

Abbreviations: CNR, Change in Net Rents; CWU, Crop Water Use; EU, European Union; EWP, Economic Water Productivity; FAO, Food and Agriculture Organisation; IS, Irrigation Schedule; MJ, Megajoule; QR, Quasi-rents; RVM, Residual Value Method; TR, Total Revenue; TVC, Total Variable Costs; VMP, Value Marginal Product; WF, Water Footprint; USA, United States of America; USD, United States Dollar.

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Rockström and Gordon, 2001; Falkenmark et al., 2003; Rijsberman, 2006; Rost et al., 2008; Liu et al., 2009; Liu and Yang, 2010; Schyns et al., 2015; Liu et al.,2017; Schyns et al., 2019), research and debate have been principally focused on blue water (Blue$_w$) (e.g. Vörösmarty et al., 2000; Alcamo et al., 2003; Arnell et al., 2004; Wada et al., 2011; Wada et al., 2014). Blue$_w$ resides in rivers, lakes and aquifers and can be withdrawn for agricultural, industrial and municipal uses.

However, according to Rockström et al. (2007) and Rockström et al. (2009), because of limited options to expand irrigation, Blue$_w$ will only be able to play a limited role in delivering the substantial volumes of additional fresh water that will be needed to address major global challenges such as rapid population growth and the alleviation of hunger in developing countries. Instead, most of the additional water required for these crucial purposes will need to originate from Green$_w$. The options for sourcing this additional water are: (a) improvements to the productivity of rainfed agriculture, (b) horizontal expansion of cropland, and (c) the import of crops and their embodied virtual water from elsewhere (*Ibid*). Virtual water refers to the volume of water employed to produce a commodity or service.

Regarding the last option, Green$_w$ dominates the virtual water associated with the international export of agricultural commodities (Yang et al., 2006; Liu et al., 2009; Siebert and Döll, 2010; Fader et al., 2011; Hoekstra and Mekonnen, 2012). For example, Fader et al. (2011) suggest that ~ 94% of the virtual water associated with the international export of agricultural commodities is Green$_w$. As Aldaya et al. (2010) state, these exports tend to move from water abundant rainfed locations to regions that would otherwise have employed local irrigation resources. In so doing, the result of this 'virtual green-water trade' is that Green$_w$ in one country is substituted for Blue$_w$ in another and, from a global perspective, there is a reduction in global usage of irrigation water. This reduction provides two principal benefits: (a) the negative environmental externalities associated with Blue$_w$, such as salinisation and the over-exploitation of groundwater, are reduced, and (b) given that Blue$_w$ has a higher opportunity cost than Green$_w$, Blue$_w$ is freed up for other higher-valued uses (Yang et al., 2006; Aldaya et al., 2010; Hoekstra et al., 2011). Blue$_w$ has a higher opportunity cost because it can be more easily used for a wider variety of purposes than Green$_w$; this cost is increasing because of climatic and demographic changes that contribute to increased Blue$_w$ scarcity (Vörösmarty et al., 2000; Ercin and Hoekstra; 2014).

In this global context, the principle of economically efficient water allocation is not, as conventionally understood, only about how a single unit of water is utilised in a single catchment (e.g. Creel and Loomis, 1992; Loomis and McTernan, 2014). Instead, efficient allocation of scarce resources can involve trade-offs between dissimilar resources (Green$_w$ or Blue$_w$), the burdens of which may occur in geographically diverse locations (Hoekstra et al., 2011; Hoekstra, 2014). Whilst different in focus, this choice is nonetheless still an economic problem of resource allocation.

Consequently, as Lowe et al. (2018) highlight, there is a role for environmental valuation (the practice of assigning welfare values to the goods and services provided by the natural environment) in allocating water resources at a *global scale* and, as part of this, to assigning an economic value to Green$_w$. Green$_w$ is a non-market resource and, as such, does not have a readily identifiable economic value through which its scarcity can be communicated. With limited exceptions (Albersen et al., 2003; Hoekstra et al., 2003; Grammatikopoulou et al., 2019), this is not something that has been addressed. This omission no doubt arises because Green$_w$ is land-bound and therefore cannot be easily diverted for other uses. Nonetheless, Green$_w$ is not an exogenous variable; it is a limited resource, which, if used for one purpose locally, will be unavailable for another (Schyns et al., 2019). In addition, Green$_w$ traded internationally in virtual form has the potential to displace Blue$_w$ in spatially disaggregated locations.

Therefore, this study's primary aim is: *to demonstrate how estimating the economic value of Green$_w$ consumed during crop cultivation could foster the virtual green-water trade,* i.e. *the allocation of agricultural production in favour of water abundant rainfed conditions and thus the substitution of Green$_w$ for Blue$_w$.* To achieve this, a traditional economic valuation approach – the residual value method – has been adapted and updated for this purpose. Given the international nature of virtual water flows, this method is illustrated using a case study design that is global in scope encompassing 16 farm locations across four continents. The case study allows us to provide the first spatially variable estimates of the economic value of Green$_w$ and, crucially, reflect on the signals that these estimates provide when interpreted in an international setting. In addition, the case study also allows us to address a secondary aim, namely how the economic value of Green$_w$ could inform the horizontal expansion and intensification of rainfed agriculture. Finally, the policy prescriptions that flow from the analysis here - regarding the global allocation of virtual water and local horizontal expansion and intensification - are also contrasted with those from traditional water productivity indicators, including the water footprint and the economic water footprint.

The paper proceeds as follows: Section 2 introduces the methodological and empirical framework and data and assumptions. It should be stressed that whilst the residual value method presented in Section 2 traditionally has a narrow focus on water use in agriculture, as ultimately utilised here, this method facilitates the broader aims of this paper regarding the allocation of virtual water flows. Section 3 outlines the international case study (the agricultural crop chosen to test Green$_w$ consumption and the locations where this is cultivated). Section 4 presents the results from the analysis, which are then discussed in Section 5. Finally, Section 6 concludes and outlines avenues for further research.

2. Materials and methods

2.1. Methodological and empirical framework

The methodological and empirical framework comprises three elements: (a) the method used to estimate the volumes of Green$_w$ and Blue$_w$ that are consumed during crop cultivation in the case study locations, (b) the approach used to assign an economic value to these water volumes and how this has been tailored to address Green$_w$ specifically, and (c) the case study design.

2.1.1. Estimating the volumes of Green$_w$ and Blue$_w$ consumed in crop cultivation

Green$_w$ and Blue$_w$ use during crop growth were estimated using the *CROPWAT 8.0* model from the Department of Land and Water Resources at the Food and Agriculture Organisation (FAO) (FAO, 2009). The *CROPWAT 8.0* model – a Windows-based computer program – is based on FAO Irrigation and Drainage Paper 56 and utilises the Penman-Monteith method to estimate reference evapotranspiration (Allen et al., 1998). Specifically, the Irrigation Schedule (IS) option within *CROPWAT* was selected as it is the most accurate approach offered by the model (Hoekstra et al., 2011). The IS option estimates crop evapotranspiration (ET$_a$, mm/day) using a daily soil water balance approach. This approach allows for non-optimal conditions and the effects of water stress.

The precise method used to estimate crop evapotranspiration under irrigated conditions is in line with that adopted by Mekonnen and Hoekstra (2011). This involved running two scenarios in the *CROPWAT* model: in the first scenario, it was assumed that there was no irrigation (i.e. solely rainfed agriculture); in the second scenario, it was assumed that irrigation is present and sufficient to meet any additional irrigation

Table 1
Residual value applications in the literature.

Source	Approach	(1) 'With' and 'without' scenarios reported	(2) Green$_w$ included in denominator	(3) Value of Green$_w$/rainfall isolated
Bakker et al. (1999)	RVM	×	✓	×
Brown et al. (1990)	RVM	×	×	×
Chang and Griffin (1992)	RVM	✓	×	×
Duffield et al. (1992)	CNR	✓	N/A	×
El Chami et al. (2015)	CNR	✓	N/A	×
Esmaeili and Vazirzadeh (2009)	RVM	×	×	×
Hellegers and Perry (2004)	RVM	×	✓	×
Kadigi et al. (2008)	CNR	✓	N/A	Partially
Kiprop et al. (2015)	RVM	×	×	×
Knox et al. (2000)	CNR	×	N/A	×
Kulshreshtha and Brown (1990)	CNR	✓	N/A	×
Martínez-Paz and Perni (2011)	CNR	✓	N/A	×
Naeser and Bennett (1998)	Both	✓	×	×
Renwick (2001)	RVM	×	×	×
Rodgers and Hellegers (2005)	RVM	×	✓	×
Rogers et al. (1998)	CNR	✓	N/A	×
Samarawickrema and Kulshreshtha (2008)	CNR	✓	N/A	×
Shulstad et al. (1982)	RVM	×	×	×
Yokwe (2005)	RVM	✓	×	×

Note: RVM = Residual Value; CNR = Change in Net Rents. Column 1 indicates whether 'with' and 'without' scenarios were present during the application of the residual value approach. Column 2 indicates those residual value approaches that recognised Green$_w$/rainfall in the denominator in Eq. (4) (i.e. XW). Column 3 indicates whether the value of Green$_w$/rainfall was isolated.

requirement (i.e. optimal irrigation). Green$_w$ evapotranspiration (ET$_{green}$, mm/day) is assumed equal to the evapotranspiration over the growing cycle in the first scenario, whereas Blue$_w$ evapotranspiration (ET$_{blue}$, mm/day) is equal to the total evapotranspiration in the second scenario minus the green evapotranspiration in the first scenario. This assumes that irrigation is only applied when prior rainfall has been evapotranspired. For those crops grown under rainfed conditions, only the first scenario is required.

Total Green$_w$ and Blue$_w$ are estimated by summing daily evapotranspiration (Crop Water Use or CWU) from the day of seeding to the day of harvest (Eq.1,2).

$$\mathrm{Green_w} = 10 \times \sum_{d=1}^{lgp} \mathrm{ET_{green}} \tag{1}$$

$$\mathrm{Blue_w} = 10 \times \sum_{d=1}^{lgp} \mathrm{ET_{blue}} \tag{2}$$

Where factor 10 is used to convert estimated crop evapotranspiration in mm to m^3/ha, and *lgp* denotes the length of the growing period in days.

2.1.2. Estimating the economic value of Green$_w$ and Blue$_w$

2.1.2.1. The residual value method. The residual value method (RVM) draws on the neoclassical theory of the firm and two possible conceptual frameworks: Wicksteed's *product exhaustion theorem*, and the theory of economic rents and quasi-rents.

The product exhaustion theorem is summarised by Young and Loomis (2014, p.57) as follows in their guide to the economic valuation of water:

> *"If firms operating under competitive market conditions optimize by selecting input quantities such that VMP [Value Marginal Product] of each input is equated with its corresponding marginal factor cost, the sum of the VMPs, each weighted by the amount of the corresponding input, will, in long-run equilibrium, exactly equal TVP [Total Value Product]."*

This is shown in Eq. (3) (note: equations 3–7 have been taken from Young and Loomis, 2014):

$$(Y \cdot P_Y) = (VMP_M \cdot X_M) + (VMP_H \cdot X_H) + (VMP_K \cdot X_K) + (VMP_L \cdot X_L) + (VMP_W \cdot X_W) \tag{3}$$

where Y · P$_Y$ is the total value of product Y; VMP$_i$ represents the VMP of resource i; X$_i$ is the quantity of the ith resource; M is purchased materials and equipment; H is labour; K is equity capital; L is other natural resources; W is water (or the residual claimant).[2]

It is assumed that producers choose the level of inputs such that VMP for each input equals the price of the input. Substituting price (P) for VMP, Eq. (4) rearranges the formula to impute a unit value (for example, in dollars per cubic metre) for the residual claimant, denoted P*w.

$$P^*_w = \frac{(Y \cdot P_y) - [(P_M \cdot X_M) + (P_H \cdot X_H) + (P_K \cdot X_K) + (P_L \cdot X_L)]}{X_w} \tag{4}$$

The theory of economic rents is the second conceptual approach to deducing the residual value of water Eq. (5).

$$TR = TVC + QR + R^W + R^{NW} \tag{5}$$

where total revenue (TR) equals the sum of total variable costs (TVC), normal quasi-rents (QR), water-related rents R^W, and non-water related rents R^{NW} (*Ibid*, p.65). Eq. (5) can be solved for R^W Eq. (6).

$$R^W = TR - TVC - QR - R^{NW} \tag{6}$$

As Young and Loomis (2014, p.65) note, "in applied contexts, R^W [Eq.(6)] and P$_{*W}$ [Eq.(4)] are [both] calculated by subtracting all estimated non-water costs of production (including non-water rents as payments to owners of scarce resources) from estimated total revenues." In practice, the RVM is solved using the well-known process of preparing farm crop budgets. Specifically, the RVM requires the compilation of two budgets – one including, and one excluding, the policy or project under analysis (so-called 'with' and 'without' scenarios).

The RVM was selected as part of the analysis here because its practicality, when compared to other economic valuation methods (Young and Loomis, 2014), means that it provides a realistic way of comparing

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[2] Young and Loomis (2014) do not explicitly recognise borrowed capital as distinct from equity capital. However, in what follows, a definition of capital that includes both is utilised.

the economic value of water across multiple (disparate) regions, at the same point in time, and at a reasonable spatial scale. However, the robustness of the estimates provided by the RVM are heavily dependent on access to an encompassing data set that does not omit any variables in the underlying production function. So-called 'omitted variable bias' occurs when the productivity of an omitted input is incorrectly attributed to the residual. In addition, when applied in an international setting, as here, the need for a consistent data collection approach across settings to ensure comparability of the economic values is also paramount. Section 2.2. details how the unique data set that underpins the analysis here directly addresses these points, both in terms of data collection and data treatment.

A variation of the basic RVM is what Young and Loomis (2014) label the *change in net rents* method (CNR). Rather than estimating Willingness to Pay for the optimally applied increment of water holding other inputs constant, the CNR approach focuses on "discrete increments and decrements of water" and thus assumes that other inputs can vary (*Ibid*, p.79). Eq. (7) illustrates the change in net rents approach.

$$\Delta Z \Big/ \Delta W = \frac{\left[\left(Y_1 \cdot P_Y\right) - \sum_{J=1}^{n}(X_{J1} \cdot P_{XJ})\right] - \left[\left(Y_0 \cdot P_Y\right) - \sum_{J=1}^{n}(X_{J0} \cdot P_{XJ})\right]}{\Delta W} \tag{7}$$

where ΔZ is the change in net rent; P_Y is the product price; P_{XJ} is the price of the j^{th} input (X_J); the subscripts 1 and 0 refer to the with and without policy scenarios.

2.1.2.2. Applications of the residual value approach (and variants) in an agricultural water context. Lowe et al. (2020) conducted a comprehensive review of the water valuation literature. This review suggested that the RVM (and its variants) have not focused on the economic value of Green$_w$/rainfall. Specifically, neither P_{*W}/R^W nor ΔZ/ΔW have been estimated for Green$_w$/rainfall directly. Moreover, X_W (Eq.4) has not been represented by Green$_w$/rainfall. Indeed, only four approaches had taken any account of Green$_w$/rainfall (Bakker et al., 1999; Hellegers and Perry, 2004; Rodgers and Hellegers, 2005; Kadigi et al., 2008). In the first three of these (which were traditional applications of the RVM), X_W (Eq.4) consisted of both rainfall *and* irrigation and did not isolate the contribution of the former. The final source – Kadigi et al., 2008 – utilised a CNR approach to value water in rainfed and irrigated agriculture. However, whilst they reported a value for water in rainfed agriculture, the approach used does not appear to have isolated the contribution of rainfall in the presence of artificial irrigation. In addition, the focus of Kadigi et al. (2008) was artificial irrigation and not rainfall, and the authors did not comment on the economic value of rainfall deduced, and the implication of this.

In addition to ignoring the value of Green$_w$/rainfall, in practice, many residual value applications also appear to ignore the presence of Green$_w$/rainfall. This omission has implications for the correct estimation of irrigation water values. Specifically, the 'without' irrigation scenario often does not appear to have been estimated (or at least reported), the implication being that an inflated economic value will, therefore, be imputed to irrigation. Table 1 summarises the 19 residual value applications found in Lowe et al. (2020).

2.1.2.3. Refining the residual value method. Eq. (8) presents an adapted form of the traditional RVM that will be used in this study to deduce the economic value of Green$_w$; a 'without' scenario is not necessary when focusing on Green$_w$ as there are no water-based interventions.

$$\text{Value of Greenw} = \frac{\left(Y_{\ rainfed} \cdot P_{\mathrm{Y}\ rainfed}\right) - \left[\left(P_{\mathrm{M}\ rainfed} \cdot X_{\mathrm{M}\ rainfed}\right) + \left(P_{\mathrm{H}\ rainfed} \cdot X_{\mathrm{H}\ rainfed}\right) + \left(P_{\mathrm{K}\ rainfed} \cdot X_{K\ rainfed}\right) + \left(P_{\mathrm{L}\ rainfed} \cdot X_{\mathrm{L}\ rainfed}\right)\right]}{X_{\mathrm{Greenw}}} \tag{8}$$

where X $_{\mathrm{Greenw}}$ is the volume of Green$_w$ consumed, and all variables are denoted with the subscript *rainfed* to indicate that prices and quantities of all inputs are those associated with rainfed agriculture only.

An example of the farm crop budget template that was used to solve Eq.8, populated with dummy data, is shown in Table 2. Part Five (Column A) calculates the residual value (or return over total costs) under rainfed conditions (Line 34) and integrates the volumes of Green$_w$ (Line 36). This residual value is used to derive the economic value of Green$_w$ per cubic metre (Line 37) separately to any consideration of the value of Blue$_w$.[3]

To estimate the value of Blue$_w$ in this study, Eq. (9) presents a traditional CNR approach, the exception being that the 'with' and 'without' scenarios now refer to *separate* rainfed or irrigated production sites.

$$\text{Value of Bluew} = \frac{\left[\left(Y_{\ Irrigated} \cdot P_{\mathrm{Y}\ Irrigated}\right) - \sum_{J=1}^{n}\left(X_{\mathrm{J}\ irrigated} \cdot P_{\mathrm{XJ}\ irrigated}\right)\right] - \left[\left(Y_{rainfed} \cdot P_{\mathrm{Y}\ rainfed}\right) - \sum_{J=1}^{n}\left(X_{\mathrm{J}\ rainfed} \cdot P_{\mathrm{XJ}\ rainfed}\right)\right]}{\Delta_{\mathrm{Bluew}}} \tag{9}$$

where ΔBlue$_w$ refers to the volume of Blue$_w$ consumed to supplement naturally occurring Green$_w$, and variables are denoted with the subscripts *rainfed* or *irrigated* to indicate whether prices and quantities of inputs are those associated with rainfed or irrigated agriculture.

Referring to Table 2, the valuation of Blue$_w$ is derived from the *change in net income* (Line 38), which measures the *additional* return over total costs that is attributable to irrigation water. This additional return is divided by the volumes of Blue$_w$ (Line 39) to deduce the economic value of Blue$_w$ per cubic metre (Line 40). As will be expanded on in the description of the case study that follows, this revised approach indicates why we have sought to include representative farms that simultaneously, but *separately*, cultivate the same crop on both rainfed and irrigated production sites i.e. it is necessary to recognise the prior contribution of rainfall (from the rainfed production site) and then only

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[3] As mentioned in the previous section, this is a different approach to that taken by Bakker et al. (1999), Hellegers and Perry (2004), and Rodgers and Hellegers (2005). In these studies, the total residual value under Column B appears to have been divided by the total volume of rainfall and irrigation employed, instead of focusing on what proportion of this value was attributable to rainfall.

Table 2
Residual value template populated with dummy data.

Part One		(A)	(B)
	Revenues per hectare	Rainfed/Green$_w$ (USD)	Irrigated/Blue$_w$ (USD)
1	Yield (tonnes/hectare)	7	12
2	Price (tonne)	140	140
3	Revenue/hectare (1 × 2)	980	1,680
Part Two	Direct costs per hectare		
4	Seeds	150	150
5	Fertiliser	125	220
6	Pesticides	125	200
7	Dry energy cost	0	0
8	Crop insurance net cost	30	60
9	Other direct cost	10	10
10	Finance cost field inventory	8	14
11	Total direct costs (4–10)	448	654
Part Three	Operating costs per hectare		
12	Hired labour	12	12
13	Family labour	40	50
14	Contractor	0	30
15	Machinery depreciation cost	120	180
16	Machinery finance	20	30
17	Machinery repairs	30	40
18	Diesel	20	30
19	Other energy	5	10
20	Total operating costs (12–19)	247	382
Part Four	Additional costs per hectare		
21	Buildings depreciation	20	20
22	Buildings finance cost	4	4
23	Building repairs	10	10
24	Land improvement	0	10
25	Farm tax (related to inventory)	15	15
26	Farm insurance (related to inventory)	15	15
27	Farm insurance (related to activities)	0	0
28	Farm advisory cost	5	5
29	Farm accounting cost	0	0
30	Farm office cost	10	10
31	Other farm cost	6	6
32	Total additional costs (21–31)	85	95
33	Total costs (11 + 20 + 32)	780	1,131
Part Five	Return over costs/residual value		
34	Return over costs/hectare Green$_w$ (3–33)	200	
35	Return over variable cost/ hectare Blue$_w$ (3–33)		549
36	Volume of Green$_w$ (m^3/ha)	2,000	
37	**Net benefit per unit of Green$_w$ (\$/m^3) (34/36)**	**0.1**	
38	Change in net income (35–34)		349
39	Volume of Blue$_w$ (m^{3}ha)		1,000
40	**Net benefit per unit of Blue$_w$ (\$/m^3) (38/39)_**		**0.349**

Note: revenue and cost categories are defined in Appendix 1.

assign any *additional* value (generated by the irrigated production site) to Blue$_w$/irrigation.[4] As referred to previously, there are numerous examples in the literature that do not take this approach and simply assign the *total* residual value under irrigated conditions to the volume of irrigation employed. In other words, the residual value under Column B (in this case, \$549) is divided by the volume of irrigation water employed (in this case, 1,000 m^3). However, as we will show in what follows, the correct estimation procedure should utilise the change in net income between irrigated and rainfed conditions.

2.1.3. *Case study approach*

The methodological and empirical framework described above is generalisable to multiple agricultural crops and products. However, in order to *illustrate* this framework and the interventions it can prescribe, we have adopted a case study design; the intention of this design is not to construct theory and nor is it to deduce causal effects that have application beyond the respective case study contexts to a broader population. Nonetheless, the case study elaborated in Section 3 is a "revelatory case" in the sense that: (a) it has been devised to reflect a crop that accounts for large volumes of green virtual water, and (b) the locations where this crop is cultivated are representative of farms in the countries analysed, which are themselves prominent international producers. In this sense, it provides a unique opportunity to observe and analyse a phenomenon previously unavailable, which conforms to the definition provided by Yin (2003) for revelatory case studies. Therefore, whilst the external validity of the case study is qualified, it provides explanatory insight into an important example which will be of direct relevance in the context of other similar cash crops.

2.2. *Data sources and assumptions*

2.2.1. *Green$_w$ and Blue$_w$ consumption data*

The IS option in the *CROPWAT* model requires climate, rainfall, soil and crop data. Climate data for each farm location was sourced from the nearest and most representative meteorological station(s) as given by the FAO's CLIMWAT 2.0 climate database (FAO, 2006). The climate parameters used in the estimation of crop evapotranspiration are maximum and minimum temperature (°C), humidity (%), wind (km/day), sunshine (hours), latitude and longitude of climate station, and altitude of climate station. From this, the climate module in the CROPWAT model calculates radiation (MJ/m2/day) and reference evapotranspiration (ET$_0$) (mm/day). For farm locations with more than one relevant meteorological station, climate data were equally weighted (on the assumption that each station represents an equally sized crop-producing area) and used alongside the latitude, longitude and altitude of the farm location.[5]

Average monthly precipitation data between 1970 and 2000 was sourced from WorldClim Version 2 at 10-minute spatial resolution (Fick and Hijmans, 2017).

Detailed soil data for each of the locations were not available. Therefore, in line with the approach advocated by Hoekstra et al. (2011), the medium (loam) soil profile within the *CROPWAT* model was adopted. This profile assumes a maximum rain infiltration rate (40 mm/day), maximum rooting depth (900 cm) and initial soil moisture depletion (0%). It further assumes total available soil moisture; however, this was adapted for each location using FAO (2002) who provide data on maximum available soil moisture at a 5*5 arc minute resolution. The use of historic data sets for soil moisture and precipitation, whilst the best available, is addressed in Section 5.6 when the limitations of the analysis are discussed.

The crop parameters used in the model are shown in Appendix 2. These parameters include seeding and harvesting dates, crop coefficients (K$_c$), crop growth stages (initial, development, mid-season, late-season), rooting depth, critical depletion fraction, yield response factor and crop height. The pre-populated crop profile in the *CROPWAT* model provided

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[4] Of the three farms that cultivated maize under irrigated and rainfed conditions, the farms in Romania and South Africa used the same planting and harvesting dates for both conditions. However, the farm in Kansas (USA) planted and harvested their irrigated fields first followed directly by their rainfed fields. Nonetheless, we have assumed that this small time gap does not have a material impact on the relative costs or revenues associated with cultivating maize under rainfed or irrigated conditions.

[5] There were no Ukrainian climate stations in CLIMWAT. Therefore, for farms located in Ukraine, climate data were taken from multiple climate stations in contiguous countries, again weighted equally.

Table 3

Revenue and cost categories excluded from the residual analysis.

Item	Revenue or cost?	Definition	Justification
Coupled and decoupled payments	Revenue	Agricultural subsidies that may (coupled), or may not (decoupled), be linked to production volumes.	Inconsistent with the private accounting stance adopted. The inclusion of this category would have artificially inflated the value of water in any locations where these payments operated.
Variable irrigation cost	Cost	Energy costs associated with water extraction and distribution, and fees for using the water. Applicable to irrigated farms only.	Contains fees for using water that will account for some of the value of water that we are looking to deduce. The costs associated with the energy used to extract and distribute water were not available separately. Therefore, by also excluding these costs, the value of Blue$_w$ deduced represents the at-site value of irrigation.
Other revenue	Revenue	Includes monies received for providing environmental services, leasing land for grazing etc	No link to crop cultivation.
Overhead water costs	Cost	Water used elsewhere on the farm for cleaning machines etc.	No link to crop cultivation.

Fig. 1. Locations of 16 farms considered in this study.

these parameters except for the seeding and harvesting dates that were adapted based on local data.[6,7] Furthermore, based on these dates, the crop growth stages were horizontally adjusted using the procedure set out in Henggeler et al. (2020). As advocated by Hoekstra et al. (2011), the irrigation parameters selected in the IS option were irrigate at critical depletion (timing) and refill soil to capacity (application) with a field efficiency of 70%.

2.2.2. *Revenue and cost data for populating farm crop budgets*

Cost ($/hectare), yield (tonnes/hectare) and crop revenue ($/tonne) data associated with the case study crop were provided by *agri benchmark*, which is a global non-profit network coordinated by the Thünen Institute of Farm Economics and global networks gUG. The data provided by *agri benchmark* are for a ‘representative farm’ in each location and were collected using a standardised production system approach across all the locations under analysis, which mitigates the risks of omitting a key variable in the RVM. This standardised approach ensures that all inputs, and operations and related costs, are captured. Furthermore, this approach generates consistent data sets i.e. inputs and outputs are strictly related. agri benchmark (2015) and Chibanda et al. (2020) set out the procedure used to define a representative farm and quantify the associated data based on the approach of Nehring (2011). In brief, *agri benchmark* defined a representative farm as belonging to a class of farm that *provides the bulk of national output*. These farms are usually located in the more productive regions, and they tend to be bigger and more advanced than the simple average across all farms.

Cost, yield and revenue data were averaged over either two years (2016–2017), or, if available, three years (2015–2017). Data before 2015, or after 2017 were not available. The utilisation of multi-year average data ensures that the costs, yields and revenues are more reflective of a ‘typical’ year. The full list of data categories used in the farm budgets is shown in Table 2; the categories are defined in full in Appendix 1. The cost categories include a measure of contribution from fixed and owned assets. Therefore, the values of Green$_w$ and Blue$_w$ deduced from the residual analysis represent a long-run value (Young and Loomis, 2014).

Young and Loomis (2014) provide the most comprehensive overview of the empirical implementation of residual analysis. They advise paying attention to the “special” problem of owned (or non-contractual) inputs. These inputs are also scarce and valuable, but they do not have a readily observable market price. Therefore, they need particular treatment to avoid the omitted variable problem. Young and Loomis (2014) divide owned inputs into equity capital, management, entrepreneurship, and land.

As detailed in Appendix 1, the *agri benchmark* dataset includes the

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[6] We assumed that seeding occurs on one specified day as required by the CROPWAT model. However, in reality, seeding is a slow process which may take a few days to complete, particularly on large farms such as those included here.

[7] The two farms in Hungary had multiple maize crop rotations, each with a slightly different seeding and harvesting dates. Therefore, in these cases, we selected representative seeding and harvesting dates that either reflected the mid-point in a range of dates, or the rotation with the greatest acreage.

Table 4
Background information on each farm.

Farm (Country)	Farm (Region)	Total crop acreage 2017 (ha) [a]	Maize acreage 2017 (ha) [a]	Irrigation type
Argentina	North Buenos Aires	420	50	Rainfall
Argentina	South Buenos Aires	1,100	40	Rainfall
Argentina	West Buenos Aires	1,125	140	Rainfall
Canada	Huron County	1,550	690	Rainfall
Hungary	Tolna	1,100	440	Rainfall
Hungary	Balaton	1,500	515	Rainfall
Poland	Wielkopolskie	300	40	Rainfall
Romania	Ialomița	6,310	680	Rainfall + irrigation
Russia	Kursk Oblast	23,760	3,000	Rainfall
Russia	Labinsk, Krasnodar Krai	19,250	5,590	Rainfall
South Africa	Western Free State	1,680	930	Rainfall + irrigation
Ukraine	Khmelnytsky region	5,670	420	Rainfall
Ukraine	Poltava region	5,990	1,350	Rainfall
USA	East central North Dakota	1,300	430	Rainfall
USA	North central Iowa	730	360	Rainfall
USA	Northwest Kansas	2,240	790	Rainfall + irrigation
AVERAGE		**4,627**	**967**	

Note: [a] Source: data supplied by *agri benchmark*.

opportunity costs of equity capital used to finance field inventory and machinery. The opportunity cost of family labour is also accounted for, as is the labour input associated with management activities. Regarding entrepreneurship, the *agri benchmark* dataset is in line with Young and Loomis (2014), who suggest ignoring any measure of contribution from entrepreneurship when applying the residual method to water use in an agricultural context. Finally, regarding land, the *agri benchmark* dataset *does* provide the opportunity cost of owned arable land. However, costs associated with land are driven by a variety of factors, including, for example, direct payments from the European Union (EU) to EU-based farms, some of which are in the pool of 16 farms analysed. Therefore, we have decided to exclude all land costs, whether owned or rented. This has been done specifically to ensure that the private accounting stance that has been adopted here (i.e. to assess the costs and revenues faced by farms excluding the effects of any public interventions) is not compromised. However, the implication is that, for all locations, a share of the value of the residual claimant (i.e. water) will in fact be attributable to land. Indeed, to address additional empirical issues specific to the aims of this paper, we also excluded four further data categories from the *agri benchmark* dataset in our analysis. These data categories – together with the justification for exclusion – are set out in Table 3. However, in Section 5, sensitivity analysis is performed on the two most important of these exclusions – land costs and coupled/decoupled payments – to assess if this alters the conclusions reached.

3. Case study

3.1. Case study crop

Maize has been chosen as the case study crop because, excluding rice, it accounts for the second-largest share of the total water consumed in global crop production (Siebert and Döll, 2010; Chapagain and Hoekstra, 2004). In addition, a substantial proportion of the water burden associated with maize is imported virtual water (Fader et al., 2011).

There are four major types of maize: 1) yellow maize that is produced for feed, ethanol and starch/sugar, 2) white maize, which is a staple food in Africa and Mexico, 3) sweet maize, which is harvested half-ripe and then cooked for food, and 4) popcorn which is harvested as a grain and then used to produce popcorn. Yellow maize that is grown for feed can be further divided into (a) grain (the ears are harvested), and (b) silage (the whole plant is harvested and cut into small pieces). The *agri benchmark* data used in this paper falls into the category of yellow maize for grain. Maize off this type typically has a low economic value in the region of 100 – 190 USD/tonne, i.e. it is not a so-called *high value* (or *speciality*) crop (Young and Loomis, 2014).

3.2. Case study locations

The case study considers 16 representative farm locations in nine countries (Fig. 1). In all locations, Green$_w$ is a major input in the production function of maize (>3,500 m^3/ha). Three farms simultaneously cultivate maize on rainfed fields, as well as fields that employ supplemental irrigation (Ialomița, Romania; Free State, South Africa; Kansas, USA). As detailed in Section 2, including these three farms allows us to demonstrate the revised approach to valuing irrigation water (Blue$_w$) in crop cultivation using the residual value method. The simultaneous

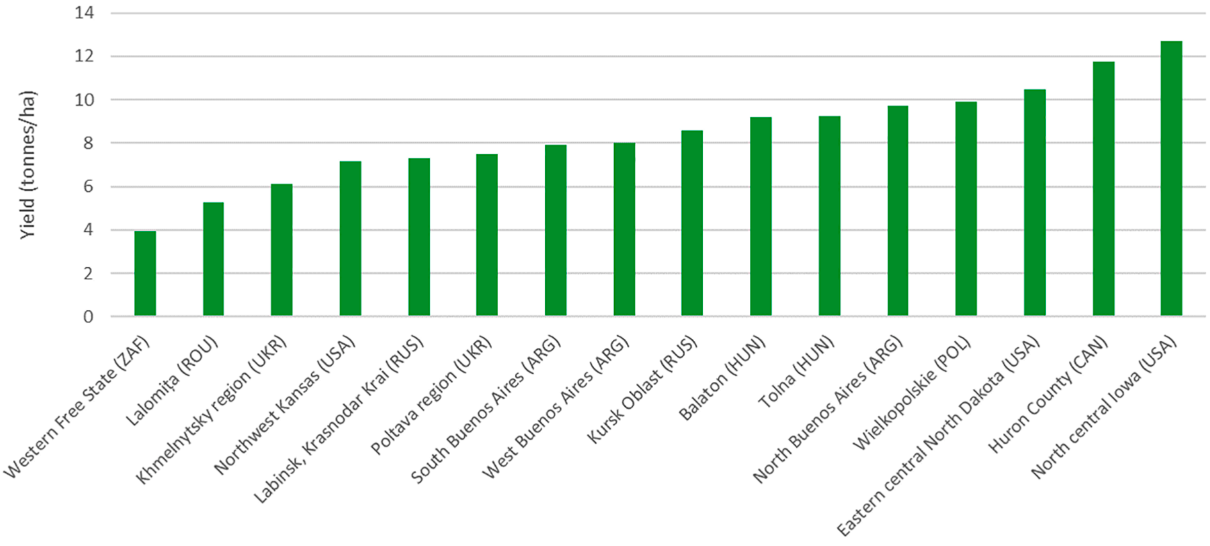

Fig. 2. Average rainfed yield at each farm location (2016 to 2017 or where available 2015 to 2017).

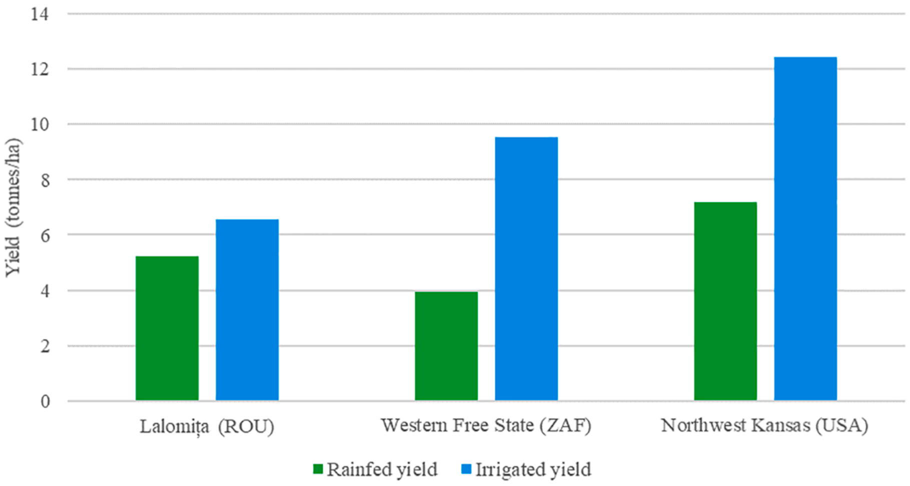

Fig. 3. Comparison of average rainfed and irrigated yields (2015 to 2017).

Table 5
Maize production in case study countries during 2017.

Country	Production 2017 (tonnes)	Global rank	Average yield
USA	370,960,390	1	11.08
Argentina	49,475,895	4	7.58
Ukraine	24,668,750	8	5.51
South Africa	16,820,000	9	6.40
Romania	14,326,100	10	5.96
Canada	14,095,300	12	10.52
Russian Federation	13,235,748	13	4.90
Hungary	6,811,337	18	6.89
Poland	4,021,592	27	7.15
Total	514,415,112		
World total	**1,134,746,667**		

Source. FAO (2019).

Table 6
Green_w volumes estimated using *CROPWAT* model – rainfed locations.

Farm (Country)	Farm (Region)	Green water (m^3/ha)	Green WF (m^3/tonne)
Argentina	North Buenos Aires	6,852	704
Argentina	South Buenos Aires	6,028	763
Argentina	West Buenos Aires	6,806	848
Canada	Huron County	5,036	428
Hungary	Tolna	4,943	534
Hungary	Balaton	4,609	500
Poland	Wielkopolskie	4,085	413
Russia	Kursk Oblast	3,621	421
Russia	Labinsk, Krasnodar Krai	4,757	651
Ukraine	Khmelnytsky region	4,631	757
Ukraine	Poltava region	3,961	530
USA	Eastern central North Dakota	5,326	509
USA	North central Iowa	6,335	499
AVERAGE		**5,153**	**580**

Note: WF = water footprint.

cultivation of maize under these two conditions arises either because of a lack of sufficient water rights to irrigate the entire maize crop, or because of a lack of equipment to source and distribute water for this purpose. The remaining 13 representative farms grow maize under rainfed conditions only.

The 16 farms range in size from 300 (Wielkopolskie, Poland) to 24,000 (Kursk Oblast, Russia) hectares (ha) (average 4,627 ha) (Table 4). The area devoted to maize cultivation ranges from 40 (South Buenos Aires, Argentina) to 5,590 (Labinsk, Russia) hectares (average 967 ha).

The representative farms in Russia and Ukraine, in particular, are well above the national average farm, both in terms of size as well as in agronomic and economic performance. This arose because a relevant share of the farm population in both countries – principally those still managed in a more Soviet-style – is still trailing in terms of know-how and technologies employed. As a result, hese farms were not accessible to *agri benchmark* and thus were excluded.

Rainfed maize yields ranged from a low of 3.93 tonnes/ha in Free State, South Africa, to a high of 12.70 tonnes/ha in Iowa, USA (average 8.40 tonnes/ha) (Fig. 2). Irrigated yields ranged from 6.58 tonnes/ha (Ialomița, Romania) to 12.42 tonnes/ha (Kansas, USA) (Fig. 3). The crop yields in Ukraine, Russia, Hungary, Poland and South Africa (irrigated) are slightly higher than average yield data for generic maize from FAOSTAT (FAO, 2019) (Table 5). This likely reflects the profile of the farms included here. Conversely, the rainfed yields in South Africa and Kansas (USA) are below those noted in FAO (2019). However, FAO (2019) does not differentiate between rainfed and irrigated crop yields and this disparity may be reflective of that.

On the three farms that grow maize under both irrigated and rainfed conditions, the largest yield gap was in Free State, South Africa (5.6 tonnes). Across these three locations, the average ratio of rainfed to irrigated yield was 0.6. This is comparable to that identified by Siebert and Döll (2010).

As presented in Table 5, the nine countries that the farms encompass are all major global producers of maize, who collectively represent ~ 45% of global maize production. Appendix 3 provides a summary of the revenues and costs at each farm location; Appendix 4 provides a summary of the climate and rainfall characteristics that were used in the modelling.

4. Results

4.1. Green_w consumed in the cultivation of maize – Rainfed conditions

Table 6 reports the volumes of Green_w consumed in the cultivation of maize in each of the 13 exclusively rainfed locations. Table 7 reports the volumes of Green_w consumed on the rainfed production sites in the three locations that employ *both* rainfed and irrigated conditions. These water volumes are reported per hectare, as well as per tonne of maize (the water footprint or WF). The green WF is estimated in rainfed agriculture by dividing $\text{CWU}_{\text{green}}$ (m^3/hectare) by the rainfed crop yield (tonnes/hectare).

Green_w consumption in rainfed agriculture ranged from 3,621 m^3/ha (Kursk Oblast, Russia) to 6,852 m^3/ha (North Buenos Aires, Argentina). This variation is largely explained by variations in reference

Table 7

$Green_w$ and $Blue_w$ volumes estimated using *CROPWAT* model – rainfed and irrigated locations.

Farm (Country)	Farm (Region)	$Green_w$ (m^3/ha)	$Blue_w$ (m^3/ha)	Total (m^3/ha)	% green	% blue	Green WF using rainfed yield (m^3/tonne)	Green WF using irrigated yield (m^3/tonne)	Blue WF (m^3/tonne)	WF (m^3/tonne) [a]
Romania	Ialomiţa	4,577	2,107	**6,684**	68	32	872	696	320	1,016
South Africa	Western Free State	6,086	1,911	**7,997**	76	24	1,549	639	201	839
USA	Northwest Kansas	4,363	4,815	**9,178**	48	52	608	351	388	739
AVERAGE		**5,009**	**2,944**	**7,953**	**64**	**36**	**1,009**	**562**	**303**	**865**

Note: WF = water footprint. [a] Calculated using green WF (irrigated yield) and blue WF.

Table 8

The economic value of $Green_w$ – rainfed locations.

Farm (Country)	Farm (Region)	$Green_w$ \$/m^3
Argentina	North Buenos Aires	0.055
Argentina	South Buenos Aires	0.063
Argentina	West Buenos Aires	0.042
Canada	Huron County	0.107
Hungary	Tolna	0.044
Hungary	Balaton	0.074
Poland	Wielkopolskie	−0.041
Russia	Kursk Oblast	0.115
Russia	Labinsk, Krasnodar Krai,	0.038
Ukraine	Khmelnytsky region	0.094
Ukraine	Poltava region	0.092
USA	Eastern central North Dakota	0.040
USA	North central Iowa	0.066
AVERAGE		**0.061**

Table 9

The economic value of $Green_w$ and $Blue_w$ – rainfed and irrigated locations.

Farm (Country)	Farm (Region)	$Green_w$ \$/m^3	$Blue_w$ \$/m^3
Romania	Ialomiţa	−0.014	0.080
South Africa	Western Free State	0.006	0.328
USA	Northwest Kansas	0.030	0.099
AVERAGE		**0.007**	**0.169**

evapotranspiration (ET_0) (Table A4); in North Buenos Aires average ET_0 is 2.95 mm/day (one of the highest of the rainfed sites), whereas in the Kursk Oblast this was 1.96 mm/day (one of the lowest levels exhibited).

The green WF in rainfed agriculture ranged from 413 m^3/tonne (Wielkopolskie, Poland), to 1,549 m^3/tonne (Free State, South Africa). This variation is attributable to the interplay between the volumes of $Green_w$ per hectare and crop yield. For example, the high green WF in South Africa is driven by relatively high $Green_w$ per hectare (6,086 m^3), coupled with the lowest rainfed yield across the locations (3.93 tonnes/ha). As a result, the volume of water per hectare is spread over fewer tonnes per hectare.

4.2. $Green_w$ and $Blue_w$ consumed in the cultivation of maize – Irrigated conditions

Three farms simultaneously (but separately) cultivated maize under both rainfed and irrigated conditions. The green WF associated with those three production sites that employed supplemental irrigation is estimated using the irrigated, rather than rainfed, crop yield. The effect of this can be seen most clearly in the case of Free State, South Africa (Table 7); this farm had the highest green WF when estimated using the rainfed yield (followed by Ialomiţa, Romania and Kansas, USA). However, the irrigated crop yield is 45% higher in Free State, South Africa when compared to Ialomiţa, Romania. As a result, the green WF under irrigated conditions in South Africa decreases by 910 m^3 and is, therefore, no longer the largest seen.

The volume of $Blue_w$ consumed in irrigated agriculture ranges from 1,911 m^3/hectare in Free State, South Africa, where $Blue_w$ only accounts for 24% of total CWU, to 4,815 m^3 in Kansas, USA, where $Blue_w$ accounts for 52% of CWU. Accordingly, the blue WF – which is estimated by dividing CWU_{blue} (m3/hectare) by the crop yield in irrigated agriculture (tonnes/hectare) – ranges from 201 m^3/tonne (Free State, South Africa) to 388 m^3 tonne (Kansas, USA). The sum of the blue and green WF of maize grown under irrigated conditions ranges from 739 m^3/tonne (Kansas, USA) to 1,016 m^3/tonne (Ialomiţa, Romania).

Across the 19 maize production sites included here (13 rainfed and three employing both rainfall *and* rainfall and supplemental irrigation), the average WF (green, or green and blue) was 694 m^3/tonne. This is less than the WF of generic maize cultivation estimated by Mekonnen and Hoekstra (2010) (1,028 m^3/tonne). However, this is likely due to the scale and productivity of the farms included in this study (Section 3).

4.3. The economic value of $Green_w$ and $Blue_w$

The economic value of $Green_w$ ranged between \$-0.041 m^3 and \$0.115 m^3 (Tables 8 and 9).[8] Maize cultivated under rainfed conditions in Wielkopolskie, Poland and Ialomiţa, Romania both exhibit negative $Green_w$ values. These negative values are caused by relatively low commodity prices and moderate yield levels for those farms during the time period considered here, as well as the absence of the coupled/decoupled payments that we excluded from our analysis (Section 2.2.2). In the case of Ialomiţa, Romania, this is offset when irrigation water is introduced and accordingly, $Blue_w$ has a positive economic value (as we discuss in what follows).

The highest value of $Green_w$ was found in the Kursk Oblast, Russia. This arises because this farm exhibited the second-lowest total costs across the 16 farms (Table A3.1), together with the lowest volume of $Green_w$ consumption per hectare (Table 6). This combination helped to maximise the residual (by minimising costs) and ensure that this residual was apportioned across the lowest volume of water (Eq.8). Similarly, the farm in Huron County, Canada, enjoyed the second-highest revenue per hectare from rainfed cultivation. Consequently, these revenues helped to maximise the residual, which was apportioned over a volume of $Green_w$ consumption that was below the average for the 16 farms.

The economic value of $Blue_w$ consumed in the three farms that employed irrigation water ranges between \$0.08 m^3 and \$0.328 m^3. The value at the upper end of this range (Free State, South Africa) is the largest unit value estimated here. This value arises because irrigation boosts yields by 5.6 tonnes per hectare in Free State (compared to 5.24 tonnes/ha in Kansas and 1.33 tonnes in Ialomiţa). In turn, increased yields boost revenue by ~ 160%; this compares with increased costs associated with irrigation of ~ 70%.

The importance of valuing $Green_w$ and $Blue_w$ is not just in the absolute values estimated, though. As we move on now to discuss, the economic values estimated here also provide signals regarding the global allocation of crop production and the local trade-offs this raises.

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[8] Water volumes in cubic metres per hectare were used to derive the economic values presented here (see tables 6 and 7).

Table 10
Economic water productivity compared to economic value – rainfed locations.

Farm (Country)	Farm (Region)	$Green_w$ EWP $/m^3	$Green_w$ $/m$^{3\ a}$	Difference $/m^3
Argentina	North Buenos Aires	0.144	0.055	0.089
Argentina	South Buenos Aires	0.154	0.063	0.091
Argentina	West Buenos Aires	0.118	0.042	0.076
Canada	Huron County	0.308	0.107	0.201
Hungary	Tolna	0.283	0.044	0.239
Hungary	Balaton	0.305	0.074	0.232
Poland	Wielkopolskie	0.365	−0.041	0.406
Russia	Kursk Oblast	0.261	0.115	0.146
Russia	Labinsk, Krasnodar Krai	0.195	0.038	0.157
Ukraine	Khmelnytsky region	0.216	0.094	0.122
Ukraine	Poltava region	0.285	0.092	0.193
USA	Eastern central North Dakota	0.231	0.040	0.192
USA	North central Iowa	0.272	0.066	0.206
AVERAGE		**0.241**	**0.061**	**0.181**

Note: EWP = economic water productivity. [a] See Table 8.

5. Discussion

In the last section, we showed that whilst $Green_w$ does not have a price, it nonetheless has a value. On average, across the 16 representative farms cultivating maize, the value of $Green_w$ was $0.05 m^3. By way of a crude example to illustrate the potential contribution that $Green_w$ makes, worldwide production of maize (of all varieties) in 2017 was 1.1 bn tonnes (Table 5). Mekonnen and Hoekstra (2010) estimate that the global average green WF of generic maize is 947 m^3/tonne. Therefore, if we use the average value of $Green_w$ estimated across the locations analysed here, then the total annual value of $Green_w$ employed in the global cultivation of maize is ~$52bn. Whilst growers are certainly aware of the crucial role that rainfall plays in plant growth, this contribution is not currently being recognised in economic terms in the sense that the monetary value of rainfall itself is not estimated or utilised in decision making.

Recognising the positive economic contribution of $Green_w$ *in toto* may, in itself, provide an incentive for the virtual water trade given the dominant role of $Green_w$ in this. However, the focus here is geographical variations in unit economic values and how these values differ between $Green_w$ and $Blue_w$. As we move on now to discuss, these values can provide signals to inform the global allocation of crop cultivation between irrigated and rainfed conditions and, crucially, inform the suitability of any ensuing trade-offs between agricultural production and local ecosystem services.

5.1. *Fostering the virtual green-water-trade – Substituting $Green_w$ for $Blue_w$*

The virtual green-water trade proposition refers to the export of crops cultivated in often water abundant and productive rainfed locations, to areas that would otherwise have employed local $Blue_w$ resources for irrigation. As estimated here, the economic values reported in Table 8 and 9 provide some support to this proposition as they suggest an economic rationale for assigning production in a manner that favours rainfed cultivation. However, crucially, this depends on our understanding of what we mean by 'economic value' and thus what this concept signals.

In this context, economic value is not being used to adjudicate between competing uses in a single location, and nor is it being viewed from the farmer's perspective as a value to maximise. On the contrary, value is being used here as an indicator of *relative* water scarcity across different locations. Therefore, it seems reasonable to suggest that the most favoured sourcing locations would be those with a *lower*, not higher, value of water. In other words, production should be allocated to where water is the *least* scarce. The residual value framework used here reflects water scarcity in two principal ways. First, crop prices per tonne may be higher in regions where the water used to produce them is scarce; second, crop inputs as a whole may be used more efficiently in regions where water inputs are scarce, and thus crop costs may be lower.[9] The result of both factors is that the residual attributable to water would increase, as would the final economic value that is deduced.

If we follow this logic, Free State, South Africa, appears to be the most favoured sourcing location. This is because the economic value of a unit of $Green_w$ is the lowest *positive* value in evidence across the maize production sites, irrespective of the water type (i.e. $Green_w$ or $Blue_w$). In other words, in this location maize is profitable, but water is the least scarce economically. Furthermore, there are ten maize production sites where the estimated economic value of a unit of $Green_w$ is positive but lower than the economic value of $Blue_w$ in Ialomița, Romania (the location with the lowest value $Blue_w$). This is based on a small sample of farms, particularly those employing supplemental irrigation. Nonetheless, it suggests a rationale, in some instances, for the intentional allocation of crop cultivation in favour of rainfed locations.

One implication of such an allocation is that the value of $Blue_w$ is, in effect, contributing to its substitution with $Green_w$ even if the value of $Blue_w$ is not strictly being 'internalised' (i.e. incorporated into the price of the crop itself). In so doing, this avoids externalities associated with irrigation such as water depletion, salinisation, waterlogging, overexploitation of groundwater and soil degradation, all of which can incur substantial environmental damage costs (Aldaya et al., 2010; Fader et al., 2011). Indeed, Hart et al. (2011) estimated the annual costs of implementing management practices to address soil salinisation alone as ~ €310 per hectare. However, because there is only a small disparity between the evapotranspiration that occurs from the crop field under rainfed conditions, and that which would occur if the field were covered in natural vegetation, the externalities associated with $Green_w$ are comparatively few (Aldaya et al., 2010).[10] As a result, $Green_w$ does not change catchment hydrology, unlike $Blue_w$. Additionally, given that the withdrawal and transportation of water for all purposes accounts for a substantial share of global energy use with all this means for carbon emissions (United Nations World Water Assessment Programme, 2014), the use of $Green_w$ also alleviates some of this burden.

However, if production were reallocated from Ialomița, Romania (irrigated) to rainfed conditions in Free State, South Africa, to keep production volumes constant, there would need to be an expansion of agricultural land in Free State given the lower rainfed yield (Fig. 3). Therefore, the acceptability of local trade-offs between the increased use of rainfall to produce biomass, as opposed to leaving the rainfall to provide other ecosystem services based on natural vegetation, would need to be established. The estimates of the economic value of $Green_w$ deduced here would help inform just such a determination between competing uses i.e. the unit economic value of water used to cultivate maize could be compared with the unit value of water used to provide ecosystem services. Nonetheless, the analysis here raises the question of whether increased virtual green-water trade would lead to the horizontal expansion of arable land, which is problematic, not least from a greenhouse gas perspective. As shown by Fader et al. (2011), water productivity tends to be higher under current global trade patterns and saves ~ 263 km^3 and 41 Mha of water and land, respectively. Nonetheless, in Section 5.4, we set out those countries, beyond the case study,

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[9] In Eq. (8) and (9), the denominators are both measures of water consumption (i.e. CWU). However, whilst $Green_w$ is consumptive by definition, irrigation water can also be measured in terms of the volume of water withdrawn from a water source. In this scenario, we might also expect the volume of water withdrawn to be used more efficiently in water scarce areas i.e. irrigation efficiency would be higher.

[10] Although $Green_w$ use does change natural environments and can lead to water quality impairment through non-point pollution.

Table 11
Economic water productivity compared to economic value – rainfed and irrigated locations.

Farm (Country)	Farm (Region)	Green$_w$ EWP \$/m^3	Green$_w$ \$/m^3 [a]	Difference \$/m^3	EWP under irrigated conditions (Green$_w$ and Blue$_w$) \$/m^3 [b]
Romania	Ialomița	0.179	−0.014	0.194	0.159
South Africa	Western Free State	0.123	0.006	0.117	0.227
USA	Northwest Kansas	0.233	0.030	0.203	0.208
AVERAGE		**0.178**	**0.007**	**0.171**	**0.198**

Note: EWP = economic water productivity. [a] See Table 9. [b] Calculated using the combined green water footprint (under irrigated conditions) and blue water footprint (Table 7).

Table 12
Comparison of optimal rainfed sourcing locations and water types suggested by different approaches.

	Economic value	Economic water productivity	Physical water productivity
Preference 1	Western Free State (South Africa) Green$_w$	Wielkopolskie (Poland) Green$_w$	Wielkopolskie (Poland) Green$_w$
Preference 2	North West Kansas (USA) Green$_w$	Huron County (Canada) Green$_w$	Kursk Oblast (Russia) Green$_w$
Preference 3	Labinsk, Krasnodar Krai (Russia) Green$_w$	Balaton (Hungary) Green$_w$	Huron County (Canada) Green$_w$

Table 13
The sensitised economic value of Green$_w$ – rainfed locations.

Farm (Country)	Farm (Region)	Green$_w$ \$/m^3 [a]	Green$_w$ \$/m^3 (sensitised)	Difference \$/m^3
Argentina	North Buenos Aires	0.055	0.017	0.039
Argentina	South Buenos Aires	0.063	0.042	0.021
Argentina	West Buenos Aires	0.042	0.018	0.024
Canada	Huron County	0.107	0.035	0.072
Hungary	Tolna	0.044	0.039	0.005
Hungary	Balaton	0.074	0.073	0.001
Poland	Wielkopolskie	−0.041	−0.064	0.023
Russia	Kursk Oblast	0.115	0.111	0.004
Russia	Labinsk, Krasnodar Krai,	0.038	0.024	0.014
Ukraine	Khmelnytsky region	0.094	0.081	0.013
Ukraine	Poltava region	0.092	0.064	0.027
USA	Eastern central North Dakota	0.040	−0.001	0.040
USA	North central Iowa	0.066	−0.032	0.098
AVERAGE		**0.061**	**0.031**	**0.029**

Note: [a] See Table 8.

which may be best placed to expand green virtual water exports and those which may have an incentive to increase virtual water imports. Ultimately, the relative productivity of water in these exporting and importing locations will determine whether an expansion of arable land is necessary. If such an expansion is necessary, as Rockström et al. (2007) and Rockström et al. (2009) ultimately conclude, then the approach described here can guide the determination of where this expansion might best take place and thus inform sustainability and sourcing decisions. Indeed, as discussed in the next section, this guidance may in some cases contradict established productivity-based indicators such as the WF, which will be familiar to consumers and supply chain managers alike (Hoekstra et al., 2011; Ercin et al., 2012; Vanham et al., 2013; Mekonnen and Hoekstra, 2014).

However, the logical extension of this work might ultimately be, as te Wierik et al. (2020, p.14) posit, a global food-water trading scheme "that divides the world into agricultural exporters and importers based on their relative water availability." However, the very real challenges associated with the virtual water trade that are covered in Section 5.6 would need to be addressed to make this a reality. More broadly still, according to Falkenmark and Rockström (2006, p.131), the "ultimate task" for the water-resource planners and managers of tomorrow is "to manage the partitioning of rainfall [into green and blue water] for humans and ecosystems across spatial and temporal scales. Similarly, van Noordwijk and Ellison (2019) talk about moving beyond watershed governance to precipitationshed governance given the spatial dependencies (or teleconnections) which see, for example, the "dependence of Blue Nile rainfall and runoff to the Nile River on White Nile and Congo basin [evapotranspiration]." Indeed, te Wierik et al. (2020) have called for water governance to be revisited in view of this wider hydrological perspective that extends beyond the basin scale and a focus on Blue$_W$. This analysis here is a first attempt to introduce environmental economics to this emerging interdisciplinary debate.

5.2. *Comparison with traditional water productivity indicators*

It is informative to compare the prescriptions offered by a perspective that focuses on geographical variations in economic value with those offered by physical water productivity (the WF) and economic water productivity (EWP) indicators. EWP (\$/m^3) is estimated by dividing the local market price of maize (\$/tonne) by the *total* WF (m^3/tonne). Therefore, EWP can be reported for Green$_W$ when this is the only component of the WF (i.e. rainfed production sites). However, where the WF also includes Blue$_W$ (i.e. sites which use supplemental irrigation) it is not possible to report the EWP of Blue$_W$; instead, EWP refers to the combined impact of Green$_W$ and Blue$_W$. EWP has been included here because it is an increasingly common indicator in virtual water studies

Table 15
Correct and incorrect estimation of the economic value of Blue$_w$.

Farm (Country)	Farm (Region)	(1) Correct estimation \$/m^3	(2) Incorrect estimation blue only \$/m^3	(3) Incorrect estimation blue and green \$/m^3
Romania	Ialomița	0.080	0.050	0.016
South Africa	Western Free State	0.328	0.346	0.083
USA	Northwest Kansas	0.099	0.126	0.066
AVERAGE		**0.169**	**0.174**	**0.055**

Table 14
The sensitised economic value of Green$_w$ and Blue$_w$ – rainfed and irrigated locations.

Farm (Country)	Farm (Region)	Green$_w$ \$/m^3 [a]	Green$_w$ \$/m^3 (sensitised)	Difference \$/m^3	Blue$_w$ \$/m^3 [a]	Blue$_w$ \$/m^3 (sensitised)	Difference \$/m^3
Romania	Ialomița	−0.014	−0.008	0.006	0.080	0.080	0
South Africa	Western Free State	0.006	−0.008	0.013	0.328	0.328	0
USA	Northwest Kansas	0.030	0.009	0.021	0.099	0.110	0.011
AVERAGE		**0.007**	**−0.002**	**0.009**	**0.169**	**0.173**	**−0.004**

Note: [a] See Table 9.

(e.g. Chouchane et al., 2015; Owusu-Sekyere et al., 2017).

As shown in Tables 10 and 11, there is a substantial disparity between estimates of economic value and estimates of EWP. On average, across the 13 farm locations that only employed Green_w, the difference between the two measures was \$0.18 m^3. On those three farms that employ rainfed and irrigated conditions, the average difference between the economic value of Green_w and EWP was \$0.17 m^3. Of the three sites employing supplemental irrigation, the highest EWP was Free State, South Africa.

Therefore, care should be taken when using and interpreting this approach. Whilst EWP may refer to a 'value,' it is not a genuine welfare measure. EWP does not consider any of the costs associated with crop cultivation and how these vary between locations, and thus inflates any 'value' associated with a unit of water.

Nevertheless, from an EWP perspective, which is traditionally interpreted as a value to be maximised, the optimum sourcing location is rainfed cultivation in Wielkopolskie, Poland. The same prescription follows from a physical productivity perspective (Tables 6 and 7). However, as summarised in Table 12, whilst all three approaches favour the use of rainfed cultivation in all three instances, the prescriptions from an economic value perspective diverge from economic and physical water productivity. Most obviously, the negative economic value in Wielkopolskie, Poland (Table 8) indicates that cultivation in this location is not economically sustainable, a factor not captured by the two other approaches. In addition, Table 12 indicates that an approach based on economic value may not allocate in favour of the most productive locations, which seems counterintuitive.

Nonetheless, economic values represent a yardstick against which the potential productivity of water can be measured. Whilst this is also true with the WF and EWP indicators, as mentioned, neither considers both crop revenues *and* costs and thus provides a genuine welfare signal. Therefore, an economic value perspective may be of most use when it comes to incentivising actions to intensify rainfed agriculture. These actions would focus on addressing the well-studied 'yield gap' (boosting the amount of crop per drop) by the more effective use of Green_w i.e. promoting vapour shift whereby non-beneficial evaporation from the soil is translated into productive transpiration that promotes biomass development (Falkenmark and Rockström, 2006; Schyns et al., 2019). Depending on any relative increases in the cost of cultivation, this would have the effect of boosting crop revenue and therefore the residual imputed to water. Thus, whilst water should be sourced from the lowest value location, this would be with the expectation that the return to water in this location has the *potential* to move toward that of the highest valued location. However, where this potential does not exist (i.e. where agro-climatic conditions are not suitable for productive cultivation) and the economic value of water is low because of this rather than because of low water scarcity, this would need to be established. Doing so may require the use of additional productivity-based indicators and thus cautions against a reductionist approach. This is particularly true when considering wider social and environmental dimensions of sustainability which are beyond the scope of this work (Hoekstra et al., 2011).

5.3. *Sensitivity analysis – Adding back land costs and farm support payments*

Tables 13 and 14 set out the sensitised economic values of Green_w and Blue_w after adding back land costs and farm support payments (coupled and decoupled payments). On average, the net effect across the 16 rainfed production sites is that the value of Green_w falls by ~ 50%. There are also now five sites (previously two) that exhibit negative unit values. This outcome reflects the greater influence of land costs by comparison to the extra income from farm support payments in all but one case. The exception was rainfed cultivation in Ialomița, Romania where farm support payments were greater than land costs leading to a higher sensitised unit value of Green_w, albeit still negative. Consequently, there are now nine production sites where the economic value of Green_w (sensitised) is positive but less than the economic value of Blue_w in Ialomița, Romania (the location with the lowest sensitised value of Blue_w).

The sensitised unit value of Blue_w is unchanged at two of the three irrigated production sites. This arose because identical land costs and/or farm support payments per hectare are applied to both rainfed and irrigated scenarios. Therefore, there is no change in net income attributable to Blue_w.

The top three sourcing locations are again all rainfed but now consist of North West Kansas (USA), North Buenos Aires (Argentina), and West Buenos Aires (Argentina), which demonstrates how sensitive the overall conclusions are to the cost and revenue items that are included in the analysis.

5.4. *Beyond the maize case study*

So far, the potential for an economic value-based perspective to allocate crop cultivation between locations and between water types has been discussed in the context of the case study. To an extent, this case study was governed by the unique data set that enabled the analysis here, but which also imposed some limitations. These limitations – which will be discussed in full in Section 5.6 – mainly stemmed from the lack of data to derive the value of irrigation, which was itself a product of the approach to valuing Blue_w adopted here. This approach required the crop to be grown under rainfed and irrigated conditions on the same farm and at the same time, and understandably there were not many farms that did this in the *agri benchmark* database. Therefore, if the analysis here was re-run in an ideal scenario, what would this look like?

The answer to this comes in two parts: which countries currently export virtual water and could increase these exports, and which countries import virtual water or may have a reason to do so. However, first, it is important to recognise that whilst there are locations where Green_w is over utilised, at the global level, ~56% of the sustainably available Green_w flow has been allocated to human activities (Schyns et al., 2019). Therefore, in principle, there would appear to be at least some scope, in some locations, to explore the expansion of green water-based export crop cultivation.

Regarding the countries that export large quantities of virtual water (the majority of which as mentioned earlier, is Green_w), these tend to have certain favourable characteristics. These characteristics include a large area of cropland on a per capita basis, fertile soil, favourable terrain slopes, and favourable agro-climatic conditions (Aldaya et al., 2010; Liu and Yang, 2010; Fader et al., 2011). Countries that enjoy these conditions are mainly located in North America, Oceania and South America, and include the USA, Canada, Argentina and Australia (Fader et al., 2011). Therefore, these countries – or regions within these countries – seem to be candidates for increased Green_w exports, provided they are also self-sufficient in water. If horizontal expansion of agriculture is necessary to expand production in countries exporting virtual water, as mentioned earlier, estimating the economic value of Green_w would also help inform local trade-offs between the increased use of rainfall to produce biomass, and other ecosystem services.

In terms of the countries that would benefit from increased international food trade and the Green_w that this is predominantly based on, the work of Rockström et al. (2009) and Fader et al. (2011) would suggest that these countries fall into four categories: 1) countries that have absolute and per capita Blue_w scarcity (e.g. Pakistan and Iran), 2) countries that export substantial Blue_w but that nevertheless experience some degree of scarcity in some locations (e.g. Pakistan, Spain and India), 3) countries that import large volumes of Blue_w and contribute to environmental degradation in other countries (e.g. Indonesia and Brazil), and 4) countries where spatial constraints mean that Blue_w only passes through part of the country (e.g. Egypt).

However, as several authors have noted, virtual water trade is not always best explained by relative water endowments between importing and exporting countries: other factors such as land productivity, labour costs, and political considerations can be more important (Allan, 2003; Kumar and Singh, 2005; Zhao et al., 2019). Whilst Green_w has not been accounted for in all these studies just mentioned, in addressing questions of allocation from a water scarcity perspective, the optimal solution discussed here may not ultimately be feasible in every instance.

5.5. *Implications for the residual value approach and agricultural water policy*

The results from the case study have also highlighted the importance of applying the RVM correctly when valuing supplemental irrigation water (Blue_w). This means assigning the change in net income (between rainfed and irrigated agriculture) to irrigation water, and not the total residual value (or return over costs), some of which may be attributable to Green_w. The implications of this are shown in Table 15. Column one shows the economic values of Blue_w estimated here; columns two and three show how this value changes if the total residual value is attributed to Blue_w, or if the residual is attributable to Green_w *and* Blue_w combined. The result is either an artificially high value in the first instance or an artificially low value in the second instance.

The danger of using incorrect estimation procedures is particularly evident when we are comparing irrigation water values in a global context. For example, consider two countries:

- Country A has abundant water and uses supplemental irrigation simply to boost yield.
- Country B is water-scarce but uses irrigation water to ensure crop viability.

If irrigation water values were estimated in Country A using the incorrect approach whereby the total residual value was assigned to the smaller volume of irrigation water, then this could potentially lead to a higher value estimate than that which would apply in Country B. If we interpret economic value as the intensity of Willingness to Pay, we would, therefore, allocate production to Country B even though water is scarcer.

5.6. *Limitations*

Several limitations apply to the results presented here. These limitations can be grouped into three areas: 1) modelling water use in crop cultivation, 2) the economic values estimated, and 3) the assumptions behind virtual water trade.

Beginning with the methods used to model water use, the crop parameters used in the *CROPWAT* model (Appendix 2) were the same for both rainfed and irrigated conditions. In reality, this would not be the case; some crop parameters, for example, rooting depth, would differ. This approach was necessary due to a lack of more detailed data. In addition, though, even slightly different crop parameters may have increased the level of Green_w for *those fields that employed supplemental irrigation*. In turn, the implication of this would have been that some of the change in net income (Eq.9) would have been attributable to any such increase in Green_w, and our focus in this paper was on trying to isolate the economic value of Green_w. A second modelling limitation refers to the FAO *CROPWAT* model that was used to estimate CWU and the climatic data it relies on from the FAO *CLIMWAT* database. Specifically, average climate data is provided by *CLIMWAT* over at least a 15-year time horizon. However, the cost and revenue data provided by *agri benchmark* referred to specific years (2015 to 2017). Therefore, we have assumed here that the climatic conditions during 2015 to 2017 did not deviate from the long-run trends reflected in the climate datasets utilised. Similarly, we have assumed that precipitation and soil moisture conditions between 2015 and 2017 did not deviate from the long-run trends suggested by the historic datasets that were used in the analysis.

Regarding the second area of limitation, the RVM provides an *average* value of a unit of water; the residual value (or change in net income) is apportioned equally across the volume of water consumed during cultivation (Eq. (8) and (9)). Strictly speaking, however, allocation decisions should be driven by *marginal* values. In effect, therefore, we are making the assumption here of constant returns to scale when setting out the policy recommendations described earlier. This assumption is in keeping with the strong assumptions that underpin the RVM whereby the underlying production function is homogeneous of degree one, and a perfectly competitive market is assumed for both input and output markets. However, in reality, reallocating crop cultivation may impact yields, production costs and crop revenue, which would, in turn, impact the value of water deduced and thus the associated policy recommendations.

Nevertheless, these factors are counterbalanced by the detailed dataset provided by *agri benchmark* that is based on representative farms in specific major growing regions, and that effectively enabled the approach described. Absent this dataset, it would have been problematic to apply more complex environmental valuation techniques (such as the production function approach) that would have provided estimates of the marginal value of water. The reason for this is that providing directly comparable estimates of the marginal value of water in 16 different locations would have been prohibitively time-consuming. Alternatively, these estimates would have been less spatially specific, which was the approach that Grammatikopoulou et al., (2019) took in their work on the economic value of Green_w. Therefore, whilst it is a limitation that the approach used here provides an average rather than marginal value of water and that it relies on a static analysis, this may be the only realistic means of indicating the economic value of Green_w across regions, at the same point in time, and at a reasonable spatial scale. Similarly, the analysis was also limited in terms of the number of Blue_w (or irrigation) values that were feasible to estimate. However, again, the detailed dataset provided by *agri benchmark* may well be the only realistic means of illuminating the spatially variable economic value of Blue_w and Green_w at present, and thus points the way forward for future research. Any such research may also want to consider the water employed in multiple crop rotations – encompassing different crops – to gain a fuller picture of the economic value in each location, as well as the opportunity costs of different crop cultivation decisions.

The final area of limitation concerns the promotion of virtual water trade itself. There are challenges associated with reallocating agricultural production to take advantage of conditions in different countries that are relevant here (Falkenmark and Rockström, 2006; Yang et al., 2006; Siebert and Döll, 2010; Fader et al., 2011). These challenges include low purchasing power amongst countries facing the largest growth in demand for food, a risk that food imports may increase dependency on exporting countries, and that the basis of high-water productivities in exporting countries may, in fact, be high input use, amongst others. In addition, in the context of virtual green-water trade specifically, the idea of displacing irrigation ignores, as Siebert and Döll (2010) point out, that the benefits of irrigation are greatest in arid and semi-arid areas, many of which include developing countries where irrigation provides a vital source of income. One could add to this that climatic change is predicted to increase the variability of rainfall in the future (Rockström et al., 2007; Rockström et al., 2009) and that any expansion in the use of Green_w can detrimentally impact Blue_w flows (Schyns et al., 2019). These challenges are all relevant; virtual water trade will not be a panacea for all water issues. However, as multiple authors have already ultimately concluded, it is necessary to identify strategies to increase virtual water trade (and the Green_w this is predominantly based on) to address pressing global challenges (Rockström et al., 2007; Rockström et al., 2009; Siebert and Döll, 2010). This paper contributes to that end.

6. Conclusion and future research

To conclude, this study utilised the case of maize cultivation on 16 representative farms (across nine countries) and an adapted form of the RVM to show the substantial economic value attributable to Green_w that is currently going uncommunicated (on average \$0.05 m^3). The economic value of Green_w has been a blind spot in the literature, no doubt because Green_w is largely unseen and thus often treated as an exogenous variable. However, estimating the economic value of Green_w can help to inform important water allocation decisions, which have a bearing on pressing global challenges such as population growth and the alleviation of hunger (Rockström et al., 2007, Rockström et al., 2009).

The first of these allocation decisions – and the main focus of this paper – occurs at the global level where Green_w can be allocated to a greater or lesser extent depending on the spatial allocation of agricultural production that is then traded internationally. This virtual water trade typically sees the cultivation of crops in water abundant rainfed locations, which are then exported to regions that would otherwise have employed local irrigation resources. As a result, there is a displacement (or reduction) of Blue_w, which in turn has the potential to: 1) cut the negative environmental externalities that are usually associated with irrigation, and 2) reflect the higher opportunity cost associated with Blue_w in allocation decisions. The analysis presented here suggested that there was a clear rationale for incentive designs that reflect this pattern and which in effect (if not fact) contribute to the 'internalisation' of Blue_w. Moreover, irrespective of whether Blue_w is involved, the very act of communicating the monetary value of Green_w may also provide an added incentive to the virtual water trade, given the dominance of Green_w in this trade.

However, our analysis required a re-evaluation of what we understand by 'value.' Here, it was suggested that when viewing *different* drops of water in *different* locations, value should be conceived as an indicator of *relative* scarcity or impact. Nevertheless, when deciding on the *local* implications of global-level sourcing decisions, it was stressed that the economic value of Green_w could also be used in a more traditional sense, i.e. to adjudicate between competing uses for the *same* drop of water. In this guise, the economic value of Green_w can help inform the acceptability of any local trade-offs between the increased use of rainfall to produce biomass and other ecosystem services based on natural vegetation. Indeed, the use of the economic value of Green_w to inform the horizontal expansion (and intensification) of rainfed agriculture was suggested as the second allocation decision that this approach can inform which impacts on the pressing global challenges referred to earlier.

The sensitivity analysis that was conducted showed that the relative value of Green_w in different locations is extremely sensitive to the precise decisions regarding which cost and income categories to include in the residual value framework. There is clearly a trade-off between excluding certain categories to enable a fairer comparison between locations and artificial inflation of the residual attributable to water. Finally, future research will need to focus on extending the case study used here (and other revelatory cases like it) and reviewing the economic value of Green_w and Blue_w in the group of countries that are most likely to benefit from, and be able to provide, increased virtual water trade.

7. Data statement

The data supplied by *agri benchmark* is confidential but may be available upon request.

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CRediT authorship contribution statement

Benjamin H. Lowe: Conceptualization, Formal analysis, Funding acquisition, Project administration, Investigation, Methodology, Writing – original draft, Writing – review & editing, Visualization. **Yelto Zimmer:** Data curation, Writing – review & editing. **David R. Oglethorpe:** Writing – review & editing.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Yelto Zimmer reports a relationship with *agri benchmark* that includes: employment. YZ is employed by Thünen Institute/*agri benchmark* who provided data for use in this study. There is no conflict of interest with other activities.

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Appendix 1

Table A1
Definition of categories used in farm budgets.

Category	Definition
Yield (tonnes/hectare)	Amount of harvested good at the usual moisture content for a commercial product.
Price (tonne)	Farm gate prices that growers receive.
Seeds	All cost for seeds whether they are purchased commercial seeds or opportunity cost for farm saved seeds.
Fertiliser	All cost for fertilizer including purchased as well as manure coming from livestock. Prices for single nutrients are estimated on a per kg element basis.
Pesticides	Expenses for herbicides, fungicides, insecticides and other crop care products
Dry energy cost	Contains cash energy expenses such as heating oil and gas used for drying the harvested product.
Crop insurance net cost	Net insurance cost e.g. against hail for the individual crop.
Other direct cost	e.g. service fees to trim hedges
Finance cost field inventory	Includes the finance cash costs for debt in current assets (e.g. short-term loans) and the opportunity cost of equity in current assets. It is assumed that all direct cost needs to be financed for 6 months.
Hired labour	Cost for wages paid plus social security cost as well as any insurance costs directly related to the individual labour force. The cost allocation to the crop enterprise and the individual crops follows the approach used for family labour.
Family labour	Accounts for the opportunity cost of family labour, which is allocated to individual crops either by using machine runtime-hours, or revenue shares of individual crops in the total revenue. The opportunity cost is defined in the setup of the representative farm according to the specific conditions in the region and the farms and reflects the forgone alternatives of family members to earn money outside the farm.
Contractor	Third party services to manage crops; represents the total amount paid to the contractor, hence it covers labour cost, machinery cost and diesel cost.
Machinery depreciation cost	Straight line depreciation of investments according to the economic lifetime expectancy, using current repurchase prices for machines rather than historical purchase prices.
Machinery finance	Interest paid for debt plus opportunity cost for equity used to finance machinery.
Machinery repairs	Expenses for the maintenance of machinery.
Diesel	Total diesel cost (field operations, transport, other).
Other energy	Electric power, natural gas and alike
Buildings depreciation	See machinery.
Buildings finance cost	See machinery.
Building repairs	See machinery.
Land improvement	Expenses associated with installing and cleaning drainage.
Farm tax	Land taxes and alike (does not include taxes on profits).
Farm insurance	Against fire and alike
Farm advisory cost	Third party services to improve the management of crops and the farm
Farm accounting cost	Bookkeeping, tax reporting and alike
Farm office cost	Office space, equipment, material
Other farm cost	

Note: Source: Adapted from agri benchmark (2020).

Appendix 2

Table A2
Crop parameters used in CROPWAT.

Parameter	Value
Planting/harvesting dates	Local data in each location.
Kc Values	0.30, 1.20, 0.35.
Stage (days)	Horizontally adjusted based on local seeding and harvesting dates.
Rooting depth (m)	0.30, 1.00.
Critical depletion fraction	0.55, 0.55, 0.80.
Yield response factor	0.40 (initial), 0.40 (development), 1.30 (mid-season), 0.50 (late season), 1.25 (total).
Crop height (m)	2.00

Note: Source: FAO (2009).

Appendix 3

Table A3.1
Summary of revenues and costs – rainfed locations.

Farm (Country)	Farm (Region)	Rainfed revenue ($/ha)	Rainfed direct costs ($/ha)	Rainfed operating costs ($/ha)	Rainfed additional costs ($/ha)	Rainfed total costs ($/ha) [a]
Argentina	North Buenos Aires	988	322	160	127	609
Argentina	South Buenos Aires	930	311	144	95	550
Argentina	West Buenos Aires	806	302	137	79	518
Canada	Huron County	1,550	579	330	104	1,013
Hungary	Tolna	1,399	792	333	59	1,183
Hungary	Balaton	1,403	523	470	70	1,064
Poland	Wielkopolskie	1,486	685	856	112	1,653
Russia	Kursk Oblast	941	262	253	10	524
Russia	Labinsk, Krasnodar Krai	922	266	430	43	740
Ukraine	Khmelnytsky region	1,000	275	242	46	563
Ukraine	Poltava region	1,101	350	358	30	738
USA	Eastern central North Dakota	1,230	632	336	51	1,020
USA	North central Iowa	1,722	673	540	92	1,304
AVERAGE		**1,191**	**459**	**353**	**71**	**883**

Note: [a] Calculated as the sum of direct, operating and additional costs.

Table A3.2
Summary of revenues and costs – rainfed and irrigated locations.

Farm (Country)	Farm (Region)	Rainfed revenue ($/ha)	Rainfed direct costs ($/ha)	Rainfed operating costs ($/ha)	Rainfed additional costs ($/ha)	Rainfed total costs ($/ha) [a]	Irrigated revenue ($/ha)	Irrigated direct costs ($/ha)	Irrigated operating costs ($/ha)	Irrigated additional costs ($/ha)	Irrigated total costs ($/ha) [b]
Romania	Ialomița	832	330	476	91	896	1,043	341	483	114	937
South Africa	Western Free State	696	311	321	29	661	1,807	624	446	76	1,146
USA	Northwest Kansas	1,015	575	267	43	885	1,906	829	391	80	1,300
AVERAGE		**848**	**405**	**355**	**54**	**814**	**1,585**	**598**	**440**	**90**	**1,128**

Note: [a] Calculated as the sum of direct, operating and additional costs (rainfed). [b] Calculated as the sum of direct, operating and additional costs (irrigated).

Appendix 4

Table A4
Climate characteristics of different farm locations.

Farm (Country)	Farm (Region)	Annual rainfall [a] (mm)	Temperature (°C) [b]		Length of growing period in days (seeding and harvesting dates) [c]	Average ET_0 (Jan – Dec) (mm/day) [d]
			Maximum (°C)	Minimum (°C)		
Argentina	North Buenos Aires	971	30.2 (Jan)	4.2 (July)	226 (Sep-Apr)	2.95
Argentina	South Buenos Aires	817	29.9 (Jan)	2.9 (July)	226 (Sep-Apr)	3.19
Argentina	West Buenos Aires	803	31.6 (Jan)	3.3 (July)	226 (Sep-Apr)	3.53
Canada	Huron County	1,008	26.4 (July)	−10.7 (Jan)	185 (Apr-Nov)	2.17
Hungary	Tolna	545	26.3 (July)	−4.0 (Jan)	183 (Apr-Oct)	2.67
Hungary	Balaton	595	25.9 (July)	−4.6 (Jan)	153 (Apr-Sept)	2.27
Poland	Wielkopolskie	519	23.5 (July)	−4.8 (Jan)	185 (Apr-Nov)	1.95
Romania	Ialomița	452	27.5 (July)	−4.4 (Jan)	182 (Apr-Sept)	2.50
Russia	Kursk Oblast	601	25 (July)	−12.3 (Jan)	138 (May-Sept)	1.96
Russia	Labinsk, Krasnodar Krai	752	29.4 (July)	−6.7 (Feb)	153 (Apr-Sept)	2.41
South Africa	Western Free State	540	30.9 (Jan)	0.6 (July)	181 (Nov-May)	4.52
Ukraine	Khmelnytsky region	640	24.4 (July)	−8.0 (Jan)	154 (Apr-Oct)	2.01
Ukraine	Poltava region	567	25.9 (July)	−11.7 (Jan)	154 (Apr-Oct)	1.81
USA	Eastern central North Dakota	484	28.6 (July)	−19.8 (Jan)	167 (May-Oct)	2.89
USA	North central Iowa	818	30.4 (July)	−11.8 (Jan)	183 (Apr-Oct)	3.05
USA	Northwest Kansas	491	−10.3 (Jan)	32.5 (July)	183 (May-Nov)	4.30

Note: [a] Source: Fick and Hijmans, 2017. Annualised average monthly precipitation data between 1970 and 2000. [b] Source: FAO (2006). Based on the procedure for selecting climate data noted in the main text. [c] Source: data supplied by *agri benchmark*. [d] As estimated by the climate module in the CROPWAT model (FAO, 2009).

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